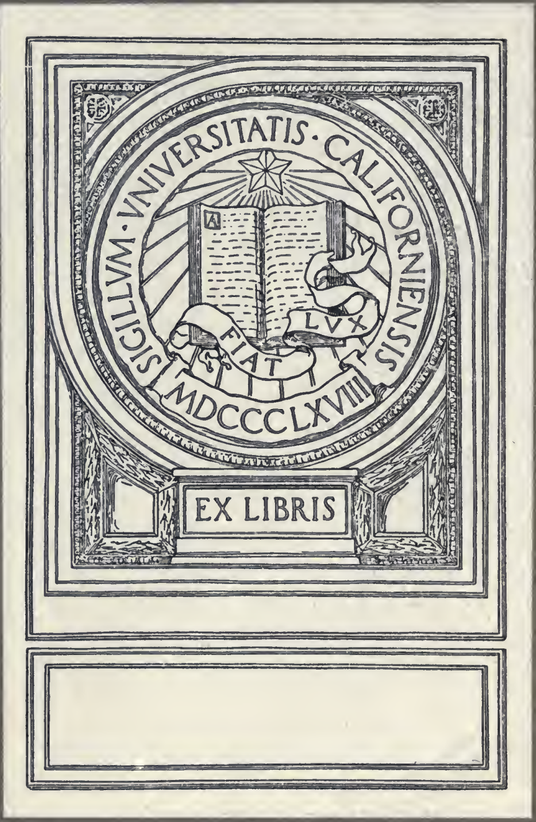
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TEXT-BOOK

OF THE

MATERIALS OF ENGINEERING

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OF THE

MATERIALS OF ENGINEERING

BY

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WITH A CHAPTER ON CONCRETE

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PREFACE TO SECOND EDITION

The principal change made in revising this text for the second edition is in the chapter on concrete, which has been entirely rewritten by Prof. Harrison F. Gonnerman. A short chapter has been added on rubber, leather, and hemp rope, considerable material has been added to the chapter on strain and stress, and to the chapter on inspection and testing, a separate chapter has been given to the subject of specifications, and tables, figures, and references have been thoroughly revised.

HERBERT F. MOORE.

URBANA, ILLINOIS,
January, 20, 1920.

PREFACE TO FIRST EDITION

The object of this text-book is to furnish a concise presentation of the physical properties of the common materials used in structures and machines, together with brief descriptions of their manufacture and fabrication. The book is intended primarily for use in technical schools in connection with courses in the Mechanics of Materials, or in connection with courses in the Materials Testing Laboratory. It is hoped, however, that the book may prove to be of use to draftsmen, inspectors, machinists, and others who, dealing with the materials of engineering in their daily work, wish to become familiar in an elementary way with the properties of those materials.

The text is distinctly elementary in character, and for the reader who may wish to pursue his studies further there is given at the end of each chapter a list of selected references. The books and periodicals named in these lists will be found in nearly all technical school libraries, and in many city libraries. For the convenience of teachers who may use this book as a text, a list of questions on the various chapters is given at the end of the last chapter.

This work is, of necessity, a compilation of data from various sources, and the author has endeavored to give credit where it is due. He acknowledges his indebtedness to the references given in the lists and to the various individuals who have assisted him.

HERBERT F. MOORE.

URBANA, ILLINOIS,
August, 5, 1917.

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TEXT-BOOK OF THE MATERIALS OF ENGINEERING

CHAPTER I

INTRODUCTORY

Scope of Subject.—The study of the materials used by engineers in the construction of buildings, bridges, motors, machine tools, and other structures and machines includes a consideration of: (*a*) the methods of manufacture and of fabrication into structures or machines of the material in common use; (*b*) the properties of these materials; (*c*) the requirements of service which these materials must meet; and (*d*) methods of testing and inspection which are used to insure that these service requirements shall be met. Before taking up a detailed study of different materials, the effects on materials of stress and strain will be discussed in a general way.

General Properties of Materials, Strength.—For all structures and machines the materials used must have sufficient strength to prevent the actual breaking of parts and the consequent failure of the structure or machine. In some cases strength is the prime requisite of the materials used (*e.g.*, bridges, cranes, punch and shear frames); in other cases strength of the materials is a secondary consideration. The strength of a material is a measure of its ability to resist the application of load without rupture, collapse, or undue distortion. The application of load to a part of a machine or structure causes internal resisting forces or *stress* to be set up in that part. There are three kinds of elementary stress: *tension* (*e.g.*, the stress in a rope holding up a weight); *compression* (*e.g.*, the stress in the pillars holding up a floor); and *shear* (*e.g.*, the stress in the rivets splicing together two plates under tension). Fig. 1 illustrates these elementary stresses. Flexure or bending stress (*e.g.*, the stress set up in a loaded beam) is a combination of tension and compression; bearing stress (*e.g.*, the stress on the floor directly under the legs of a table) is largely compression; and torsion (*e.g.*, the stress in a shaft transmitting power) is a special case of shear.

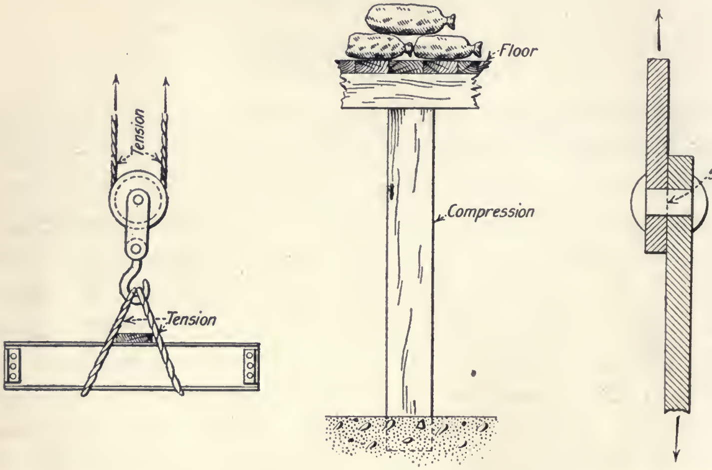

Fig. 1.—Illustrations of elementary stress.

Stiffness.—Stiffness and strength of materials are sometimes confused, they are, however, two distinct properties. If any stress is set up in a part of a machine or structure the form of that part is slightly changed. This change of form is called *strain* or deformation. The stiffness of a material is measured by the magnitude of the change of form under stress. Stiffness is frequently a very important property of a material. For example, in a machine tool there should be very slight deflection of parts under normal conditions of working, else the machine tool will fail to produce work of a sufficient degree of precision. In this case material of high stiffness is desirable. On the other hand, it is desirable that railway ties should yield under load so as to minimize shock, and for this service a material with a low degree of stiffness, such as timber, is preferable to one with a high degree of stiffness.

Elasticity and Plasticity.—Materials under low stresses do not suffer any appreciable permanent change of form, assuming their original form after the removal of load. Under such conditions they are said to be *elastic.* Under high stresses materials do suffer a permanent change of form, and become somewhat *plastic.* A perfectly plastic body after the removal of load would retain the form assumed under load. Under increasing load the change from a condition of nearly perfect elasticity to one of a considerable degree of plasticity ocurs suddenly for some materials, especially for steel, wrought iron, and most rolled or hammered metals; such materials are said to have a well-defined *yield point.* Other materials, such as timber, concrete, cast iron, do not become plastic to any noticeable extent. For nearly all engineering purposes it is desirable that the materials used should remain elastic under working conditions.

Toughness and Brittleness.—Some materials will withstand great deformation together with high stress without actual rupture; such materials possess great *toughness.* Other materials shatter before much deformation is noticeable; such materials are *brittle.* Rolled steel and rubber are examples of tough materials, cast iron and glass of brittle materials. Toughness is a highly desirable quality in materials for structures and machines in which sudden shattering rupture is especially disastrous; *e.g.,* it is quite necessary that car couplers and car frames should be able to resist the severe shocks of service, and possibly of minor accidents, without actual rupture, even if considerable permanent distortion takes place.

Ductility and Malleability.—Some materials under tension will suffer a considerable elongation before actual rupture takes place, such materials are *ductile.* A ductile material which can be stretched out only under high stress is tough. A material which can be hammered out into thin sheets is *malleable*. Lead is malleable and ductile, but not tough.

Adaptability to Engineering Construction and Facility in Fabrication.—It is evident that even material possessing desirable qualities could not be used in construction if it was extremely costly, if it could not be worked into the desired shapes, or if it could not be transported to or handled at the place where the structure or machine was to be built.

Uniformity and Reliability.—Some materials can be produced with a high degree of uniformity of properties, such as strength, stiffness, etc., while the properties of other materials can not be foretold within wide limits. For engineering work material which is uniform in quality is always desirable. Materials whose structure is uniform throughout resist repeated stress better than materials with non-uniform structure. Under the action of repeated stress, minute cracks are liable to start at points where the structure is not uniform, and the material is sometimes fractured by the spread of these minute cracks.

Hardness.—In common language hardness means resistance to abrasion. Technically the term is usually used to denote resistance to plastic deformation.

Durability.—It is desirable that during the period of use of any structure or machine the material in it should not deteriorate in quality. Destructive agencies not infrequently act on the materials of construction; *e.g.*, corrosion attacks steel and iron, bacterial growths cause wood to decay, electrolytic action sometimes destroys concrete. Mechanical wear of parts may destroy the usefulness of a machine. For any given construction the durability of the materials to be used must be considered.

Electric and Magnetic Properties.—For the materials used in machines and structures for generating, transmitting, and utilizing electric energy or for the material in structures located near high-power electric circuits the electric and magnetic properties are frequently of prime importance.

Classification of Materials.—The materials of construction used in engineering work may be divided into two general classes: (*a*) metallic, and (*b*) non-metallic.

Under metallic materials we may classify:

I. THE FERROUS METALS-IRON AND STEEL

1. Cast iron, including pig iron, cast iron in castings, and "semi-steel." These are all fusible, but not malleable, not weldable (except by actual fusion) and not temperable; they all contain a large percentage of carbon (high carbon content), are brittle and have a crystalline structure. They are used in cases where the metal is to be cast directly into shape, and where ductility is not a requisite. Malleable cast iron is cast iron with its carbon content and crystalline structure transformed by heating and slow cooling (annealing). It has a considerable degree of ductility.

2. Wrought iron is manufactured from pig iron by the "puddling" process without fusion of the final product. It has a fibrous structure, fibers of slag extending through crystals of iron, it has a very low carbon content, it is ductile, weldable, fusible only with great difficulty, and is not temperable. It is used where ease of welding or hot working is desirable, *e.g.*, in small blacksmith shops, and is claimed by some metallurgists to resist corrosion better than steel. Wrought iron is widely used for water pipes.

3. Steel is manufactured from pig iron by the open-hearth process, the Bessemer process, or the electric furnace process, or by a combination of these processes. Special high grades of steel are manufactured from wrought iron by the crucible process. All these methods involve *fusion*. They are described in succeeding chapters. All grades of steel are fusible and malleable. The carbon content of commercial steel varies from almost zero to 1.25 per cent. Steel with not more than 0.25 per cent. carbon is *mild* steel; 0.25 to 0.60 per cent. carbon, *medium*-carbon steel; more than 0.60 per cent. carbon, *high*-carbon steel. Mild steel and, to a less degree, medium steel are weldable, non-temperable, tough, and ductile. Mild steel and medium

steel are probably the most important metallic materials of engineering construction. They are used in all kinds of structural and machine work. High-carbon steel is weldable with difficulty, temperable to a high degree and of low ductility. It is used for tools, springs, and in cases where great strength is necessary.

As used in engineering work steel may be cast in molds into shape (steel castings) or into blocks (ingots) of cast steel which are rolled or hammered into shape. Rolled or hammered steel is, in general, stronger, more ductile and tougher than are steel castings of the same chemical composition.

Carbon and iron are the principal ingredients in steel, but special steels of great strength and toughness are made by alloying carbon and iron with other elements. Common alloy steels are: nickel steel, chrome-nickel steel, tungsten steel, vanadium steel, and manganese steel.

II. THE NON-FERROUS METALS

1. *Copper.*—Copper is manufactured from copper ores, and rolled or drawn into sheets and wires. Both its strength and its ductility are somewhat lower than the strength and the ductility of steel. Its conductivity for electric currents is very high. The principal use of copper is for electric wires, and it is used to a limited extent for roofing, pipes, etc., where resistance to corrosion is of prime importance.

2. *Aluminum.*—Aluminum is manufactured from ores by removal of oxygen from the oxides of the metals (reduction). Aluminum is the lightest metal in commercial use: rolled into sheets or drawn into wires it has considerable strength, and is a good conductor of electricity. It is used for small machine parts in which lightness is of great importance, and, sometimes alloyed with copper it is used for electric wires, especially for long spans on electric transmission lines. Aluminum resists corrosion and is used for kitchen ware and for tanks for certain chemicals.

3. *Lead Tin Zinc.*—Lead, tin, and zinc are manufactured

from ores by reduction. These metals are used in special cases in which strength is not a prime requisite and in which resistance to chemical action is necessary. They are used in alloys for bearings for shafting.

4. *Brass.*—Brass is an alloy of zinc and copper. It is used for small machine parts in which resistance to corrosion is of importance, it is also used as a bearing metal.

5. *Bronze.*—Bronze is an alloy of copper and tin. It is used where resistance to corrosion is necessary, and where strength is also necessary. Bronze may be made almost as strong as steel. Bronze is used as a bearing metal in the highest grade of bearings. It is very expensive as compared with steel and is used only in special cases. Various alloys of copper, tin, zinc, aluminum, and other metals are sometimes spoken of as "bronze" and are used for special constructions.

NON-METALLIC MATERIALS

1. *Wood.*—Wood is very easily shaped and fastened together for temporary construction. When new or if carefully preserved from decaying, wood is, in most cases, the material which furnishes a given strength with the least weight. It is used for house and ship construction and finish, for railway ties, temporary trestles, bridges and other structures, for patterns for castings, and forms for concrete construction. Wood frequently deteriorates with age on account of decay.

2. *Brick and Terra-cotta.*—Brick and terro-cotta are made by burning clay. They are used widely for walls and piers of buildings, paving and drain tile. Terra-cotta tiles are used for roofs. Brick and terra-cotta are brittle, but possess considerable compressive strength.

3. *Concrete.*—Concrete is made by mixing some cementing material, usually Portland cement, with water and sand and stone (or gravel). Concrete can be poured into molds, which are removed after the concrete has hardened. Concrete is used for all kinds of massive structures. It has considerable compressive strength, but very low tensile

strength. Where tensile strength is necessary, steel rods are imbedded in the concrete to take the tensile stress, this combination being known as reinforced concrete. Concrete is used for paving, for sidewalks, for walls, floors, and columns, and for foundations for houses and machinery.

4. *Mortar.*—Mortar is made by mixing cement or lime with fine sand and with water. It is used as a surface for walls, for the outside finish of houses, and for cementing together the individual pieces of brick and stone work.

5. *Gypsum.*—Gypsum when mixed with water hardens into a solid mass which is lighter than concrete and which possesses less strength. Gypsum is used for light walls and for roofing.

6. *Natural Stone.*—Natural stone is quarried and cut to shape. It is used for walls, buildings, and bridges. It is regarded as the most nearly permanent form of construction, but is very expensive.

7. *Rubber.*—Rubber is made from the juice of a tropical tree. Its salient characteristic as a material of construction is its enormous capacity for stretch, and, to a less extent for compression, without permanent change of form. It is used for tires, hose, belting, and "buffers" for absorbing the energy of shock in machines.

8. *Leather and Rawhide.*—Leather and rawhide are made from the hides of animals, the former being put through a process known as "tanning." Leather is used for belts and for hydraulic packings. Rawhide is used for gears where silent operation is especially desirable.

9. *Hemp and Cotton.*—Ropes made of the fibers of hemp and cotton are in very common use. They cannot, of course, be used for carrying any stress but tensile stress.

Tests of Materials.—*Chemical Tests.*—Chemical analyses of materials whose quality is under investigation are usually made on small representative samples of the material and have for their chief object the determination of the quantity of various ingredients present in the material. They are frequently used to detect the presence of an injurious amount of an undesirable ingredient, or to detect unevenness of distribution of ingredients through a mass of material (segregation).

Physical Tests.—The physical tests commonly performed to determine the quality of materials of construction include: tests of strength (tension, compression, shear, bending, torsion), of ductility (elongation, bending), of brittleness (impact tests), of resistance to repeated stress (endurance tests), of hardness, of resistance to abrasion, and of the internal structure (microscopic examination). Physical tests are made, sometimes on a small sample of the material and sometimes on the material in its finished form. Physical tests may be tests to destruction (*e.g.*, a tension test to rupture of a small test piece made from a sample taken from a shipment of steel) or tests under working load (*e.g.*, a test of the floor of a building under the load it is supposed to carry in service). Tests to destruction, in general, give relative results rather than absolute results and are useful in determining the properties of a material in comparison with the properties of material of proven quality in service.

CHAPTER II

STRAIN AND STRESS

Preliminary.—In discussing the properties of materials it is necessary to refer to their ability to withstand deformation and to resist forces. It is necessary to define and discuss various terms which are used in connection with the behavior of materials when forces are applied to them in order that these terms may be intelligible when used in the succeeding chapters.

Strain, Unit Strain.—Whenever a force is applied to any member of a machine or a structure—to a beam in a house, a shaft in a machine shop, a rail in a railroad track—the shape of the member is altered. If the member has been properly designed to withstand the force the change of shape is small, usually not directly visible to the eye; on the removal of the force the member returns almost exactly to its original shape. If the force is too large for the member to carry without structural injury, there usually occurs a considerable change of shape. If this overload is removed, the body does not return to its original shape, but remains permanently distorted. The change in any linear dimension is called the *strain,* or deformation, and the change per unit of linear dimension is called the *unit strain* or unit deformation (measuring in inches per inch, using the units common in engineering practice).

Stress, Unit Stress.—If a machine part or structural member, Fig. 2*a*, is acted on by forces, P, P', there must be set up within the body internal forces called *stresses* or *fiber stresses* which resist the tendency of the external forces to tear apart or to crush the body. Imagine the part of the body at one side of any section *mn* to be cut away, then to represent the fiber stresses at the section *mn* there must be forces S to balance the force P (Fig. 2*b*).

The summation of the forces S make up the total stress at the section mn. If the stress over a very small portion of the section is denoted by ΔS and the area of the very small section is denoted by ΔA, then for that small area $\frac{\Delta S}{\Delta A}$ is the *intensity of stress,* or the *stress per unit area,* or, more briefly, the *unit stress.* If the stress is uniformly distributed over the whole area of cross-section mn, then the unit stress is $\frac{P}{A}$ in which P is the resultant force acting on one side of that section, and A is the area of the section. Note that this is true only *if the stress is uniformly distributed.* In general, the stress per unit area will be different at different locations on the cross-section mn. The mathematical analysis of stress distribution forms the subject matter of mechaincs of materials. While no extended discussion of the mathematical analysis of stress distribution will be attempted in this book, there are given in this chapter some of the common formulas for stress and strain, together with comment on their limitations and application.

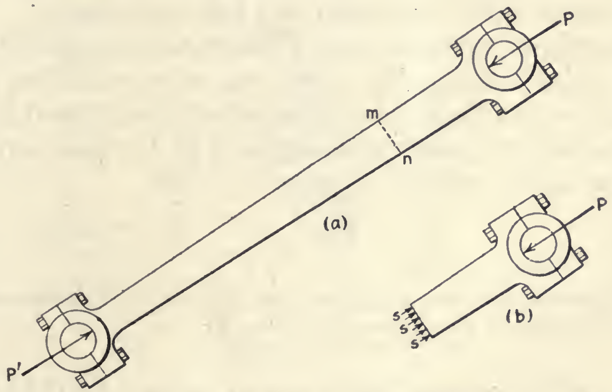

FIG. 2.—Machine part under stress.

Hooke's Law.—Under working conditions for the materials commonly used to carry load in structures and machines *stress is proportional to strain.* This statement is *Hooke's law,* and is named after the English scientist who first stated it. Hooke's law does not hold for high stresses, and for any material the lowest stress for which deviations from this law can be detected is an index of the elastic strength of the material (see paragraph following on elastic limit, proportional limit, and yield point). Under working conditions Hooke's law agrees very closely with the observed action of rolled metals, and also of steel castings; it is a fairly close approximation for cast metals in general, for concrete, for brick, and for wood; it is a rough approximation for such materials as rubber, leather, and hemp rope. The mathematical analyses of stress-distribution commonly used by engineers assume that Hooke's law holds, *and do not apply for stresses above the "proportional limit" discussed in a later paragraph.*

Uniformly-distributed Stress; Tension, Compression, Shear. Under axial loading the stress on a cross-section of a machine or structural part is uniformly distributed across the cross-section, and the magnitude of the unit stress is given by the formula:

$$S = \frac{P}{A} \qquad (1)$$

in which S is the unit stress in lb. per sq. in., P is the axial load in pounds, and A is the area of the cross-section in sq. in.

Such a uniform stress-distribution is assumed for the bodies of eyebars, for tie rods, for bolts under tension, for ropes, for belts, for guy wires, for short posts, for bearing blocks, etc. The stress-distribution in long compression members is discussed in a later paragraph. In considering any actual structural or machine part the use of the above formula neglects many localized stresses, especially near the points of attachment to other parts,—for example the bearing stresses between an eyebar and the pin to which it is attached. Except for parts subjected to oft-repeated loading these localized stresses are usually not important. A fuller discussion of the significance of such localized stresses is given in Chapter III.

For parts subjected to transverse forces whose lines of action are parallel and so close together that there is no appreciable bending action (see Fig. 3), such as plates riveted or bolted together the magnitude of the shearing unit stress is frequently assumed as:

$$S_s = \frac{P_s}{A} \tag{2}$$

in which S_s is the shearing unit stress in lb. per sq. in., assumed to be uniformly distributed over the surface of the cross-section; P_s is the shearing load in pounds; and A is the area of the cross-section in sq. in.

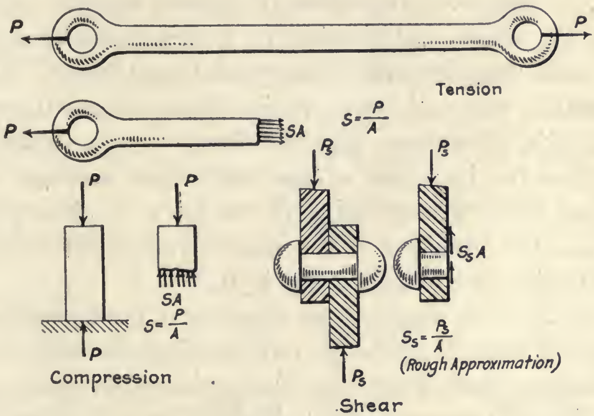

FIG. 3.—Uniformly distributed stress.

This formula is a rough approximation rather than an exact statement. There are always present heavy bearing stresses at points of contact of adjacent parts, with a resulting cutting action at the surfaces of the bolts or

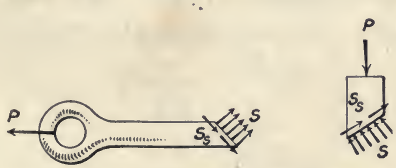

FIG. 4.—Stress on oblique section.

rivets and an intensified shearing stress. However, the foregoing formula is fairly reliable for computing the load necessary to shear off a bolt, rivet, or pin.

In any machine or structural member under axial load, on any plane oblique to the action line of the load there are both tensile (or compressive) and shearing stresses (see Fig. 4). For any oblique plane the tensile (or compressive) unit stress is less than $\frac{P}{A}$. The shearing unit stress is maximum for a plane at 45 degrees with the axis; for this plane the shearing unit stress is $0.5\frac{P}{A}$.

Non-Uniform Stress Distribution.—Under flexure, under torsion, or under combinations of flexure, torsion, and axial loading the stress-distribution in a structural or machine part is more complex than under axial load alone. On any cross-section the unit stress varies from surface to surface, or from axis to surface, and the study of the stress-distribution has for its main object the determination of the maximum unit stress existing in the part, or, as it is sometimes put, the location of the most-stressed fiber, and the determination of the unit stress in it.

Flexure.—In a machine or structural part under cross-bending or flexure the external bending moment at any cross-section, caused by the loads, reactions, and couples at one side of the section is balanced by the internal moment of the fiber stresses. The stress varies from tension at one edge of the member to compression at the opposite edge. On an axis passing through the center of gravity (centroid) of the cross-section the stress is zero, and within the proportional limit the unit stress in any fiber is proportional to the distance of the fiber from this *neutral axis* as it is called. For any fiber the stress is given by the formula:

$$S = \frac{Mv}{I} \tag{3}$$

in which S is the unit stress in lb. per sq. in. (tension for the side of the member made convex by flexure, compression for the side made concave); M is the bending moment in inch-pounds of the forces and couples on one side of the section; v is the distance in inches of the fiber from the neutral axis; and I is the so-called "moment of inertia" of the cross-section about the neutral axis in (inches).[4]

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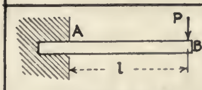
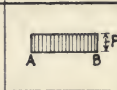
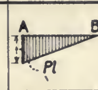
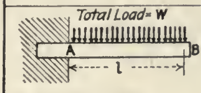
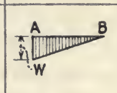
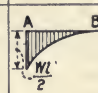
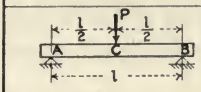
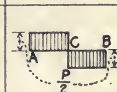
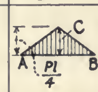
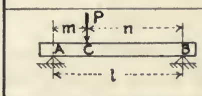
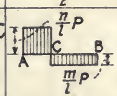
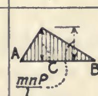
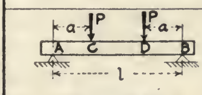
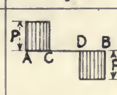
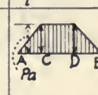
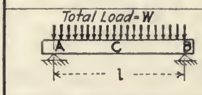
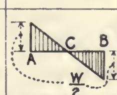
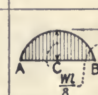
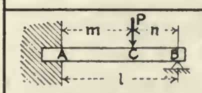
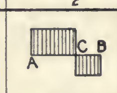
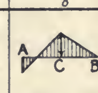
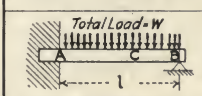
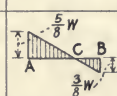
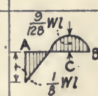
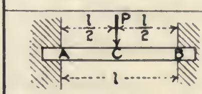
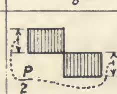
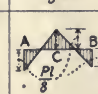
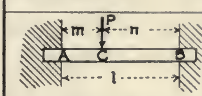
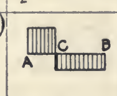
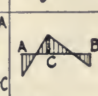
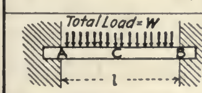
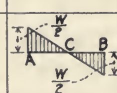
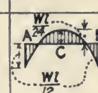
	A to B	P		A	Pl	
	A	W		A	$\frac{Wl}{2}$	
	A to C C to B	$\frac{P}{2}$		C	$\frac{Pl}{4}$	
	A to C or C to B	$\frac{n}{l}P$ from A to C $\frac{m}{l}P$ from C to B		C	$\frac{mn}{l}P$	
	A to C D to B	P		C to D	Pa	
	A & B	$\frac{W}{2}$		C	$\frac{Wl}{8}$	
	B to C or C to A	$P\left(1-\frac{3n}{2l}+\frac{n^3}{2l^3}\right)$ from B to C $P\left(\frac{3n}{2l}-\frac{n^3}{2l^3}\right)$ from C to A		C or A	$Pn\left(1-\frac{3n}{2l}+\frac{n^3}{2l^3}\right)$ at C $\frac{P}{2}\left(n-\frac{n^3}{l^2}\right)$ at A	
	A	$\frac{5}{8}W$ (Shear at B $= \frac{3}{8}W$)		A	$\frac{Wl}{8}$ (Moment at C $= \frac{9}{128}Wl$)	
	A to C and C to B	$\frac{P}{2}$		A, B, and C	$\frac{Pl}{8}$	
	A to C or C to B	$P\left(1-\frac{3m^2}{l^2}+2\frac{m^3}{l^3}\right)$ from A to C $P\frac{m^2}{l^2}\left(3-2\frac{m}{l}\right)$ from C to B		A, B or C	$Pm\left(1-\frac{2m}{l}+\frac{m^2}{l^2}\right)$ at A $\frac{Pm^2}{l}\left(1-\frac{m}{l}\right)$ at B $\frac{Pm^2}{l}\left(2-\frac{4m}{l}+\frac{2m^2}{l^2}\right)$ at C	
	A & B	$\frac{W}{2}$		A and B	$\frac{Wl}{12}$ Moment at C $= \frac{Wl}{24}$	

FIG. 5.—Bending moments and shears for beams.

For the fiber farthest distant from the neutral axis this formula becomes:

$$S = \frac{Mc}{I} \tag{3a}$$

in which c is the distance of the most remote fiber from the neutral axis.

In using formulas (3) and (3a) it is necessary to compute M the moment at the cross-section of the forces and couples on one side of the cross-section (either side may be taken). If the forces acting on the member can all be determined by the common equations of statics[1] this is a simple matter and the member is said to be "statically determinate." If the forces acting cannot be so readily found, as for example in the case of a beam with more than two supports, the member is said to be "statically indeterminate," and to determine the moment at any cross-section the elastic deformation of the member must be considered. Fig. 5 gives the magnitude and location of maximum bending moments for a number of common cases of flexure.

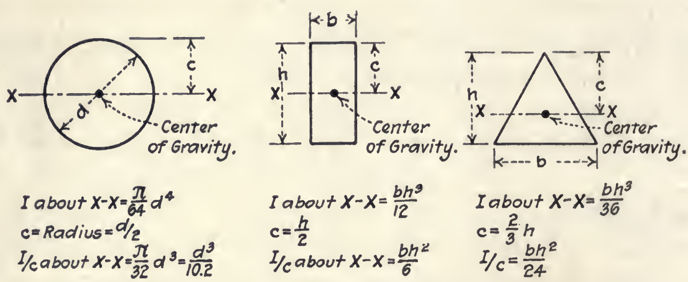


FIG. 6.—Moment of inertia for circle, rectangle, and triangle.

In using formula (3a) it is necessary to determine the value of I and of c for each case under consideration. Fig. 6 gives the value of I, of c, and of I/c (called the section modulus) for the circle, the rectangle, and the triangle. The value of I/c for more complicated shapes can be com-

[1] Sum of vertical forces for whole body = 0.
Sum of horizontal forces for whole body = 0.
Sum of bending moments for whole body = 0.

puted by dividing the shape into approximate rectangles and triangles. First the center of gravity of the composite figure is found, then the fiber most remote from the axis drawn through the center of gravity perpendicular to the plane of bending can be determined by inspection, and c measured directly. The I of the composite section is the sum of the I's of the component rectangles and triangles about the neutral axis of the whole section. For any component rectangle or triangle the I about the neutral axis is given by the formula:

$$I = \bar{I} + Ad^2 \tag{4}$$

in which $\bar{I}$ is the moment of inertia of the rectangle or triangle about its own centroidal axis (see Fig. 6); A is the area of the rectangle or triangle; d is the distance from the center of gravity of the rectangle or triangle to the neutral axis of the whole figure; and I is the moment of inertia of the rectangle or triangle about the neutral axis of the composite figure.

Fig. 7 shows the working out of this method for determining I and I/c of a cross-section of a punch frame.

Special graphical methods for determining the value of I for irregular sections are given in many texts on mechanics of materials.

Formulas (3) and (3*a*) are true only when a "principal axis" (axis for which the I of a cross-section is a maximum or a minimum) lies in the plane of the loads causing the bending. This is the case for members whose cross-sections have an axis of symmetry either in the plane of bending or at right angles to that plane. The large majority of flexure-resisting members are loaded so as to fulfil this condition. Fig. 8 shows several such sections together with some which do not fulfill the above condition, and for which formulas (3) and (3*a*) cannot be used. The stresses for these unusual cases may be widely different from the stresses given by the use of formulas (3) and (3*a*). Examples of such obliquely loaded flexure members are: roof purlins, and railroad rails. In this connection attention is called to the references given at the end of this chapter.

For beams whose axes are curved lines, such as hooks elliptical springs, chain links, etc., formulas (3) and (3*a*) are inexact. The neutral axis is between the center of gravity of the cross-section and the concave side of the curved beam, the unit stress on the concave side is increased

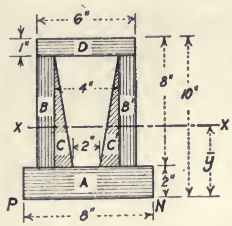


FIG. 7.—Moment of inertia for composite figure.

PROBLEM.—Find the distance $\bar{y}$ of the gravity axis *XX* from the base *PN* of the cross-section shown, and find $\bar{I}$ and I/c for the cross-section.

The composite figure is divided into elementary rectangles and triangles, *A*, *B*, *B′*, *C*, *C′*, and *D*. The area of each elementary part and moment of that area about *PN* are determined. Then $\bar{y}$ is equal to the sum of the elementary moments divided by the sum of the elementary areas. The sum of the moments of inertia about the axis *XX* of the elementary parts gives the moment of inertia of the whole cross-section.

For each elementary part, $I = \bar{I} + Ad^2$

Part	Width (in.) b	Height (in.) h	Area (sq. in.) A	Distance of center of gravity of part from *PN* (in.) q	Moment of part about *PN* (in.)³ $M = Aq$	Distance of center of gravity of part from *XX* (in.) d	d^2 (sq. in.)	Ad^2 (in.)⁴	I of part about its own gravity axis (in.)⁴ $\bar{I}$
A	8.0	2.0	16.0	1.00	16.00	−3.19	10.18	162.9	5.3
B	1.0	7.0	7.0	5.50	38.50	+1.31	1.72	12.0	28.6
B′	1.0	7.0	7.0	5.50	38.50	+1.31	1.72	12.0	28.6
C	1.0	7.0	3.5	4.33	15.17	+0.14	0.02	0.1	9.5
C′	1.0	7.0	3.5	4.33	15.17	+0.14	0.02	0.1	9.5
D	6.0	1.0	6.0	9.50	57.00	+5.31	28.20	169.2	0.5

Sum of elementary areas $(\Sigma A) = 43.0$

Sum of elementary moments $(\Sigma M) = 180.34$

Distance of center of gravity of whole cross-section from $PN = \frac{180.34}{43.0} = 4.19$ in.

Sum of $Ad^2 (\Sigma Ad^2) = 356.3$

Sum of $\bar{I}$'s $(\Sigma \bar{I}) = 82.0$

$\bar{I}$ for whole cross-section $= 356.3 + 82.0 = 438.3$ (in.)⁴

$c = 10.00 - 4.19 = 5.81$ in.

$I/c = \frac{438.3}{5.81} = 75.4$ (in.)³

and the unit stress on the convex side is decreased. The less the radius of curvature of the axis of the beam the greater is the variation of unit stresses from the values given by formula (3*a*). In this connection attention is called to the special references given at the end of the chapter. Formula (3*a*) is, however, frequently used to give a rough approximation for stress in curved beams.

There are shearing stresses in members subjected to flexure, and the distribution of these shearing stresses is discussed briefly in a succeeding paragraph.

Formula (3*a*) is sometimes used to give comparative values for tests of materials to fracture. The value of S determined from the load at fracture for a flexure test is called the *Modulus of Rupture.*

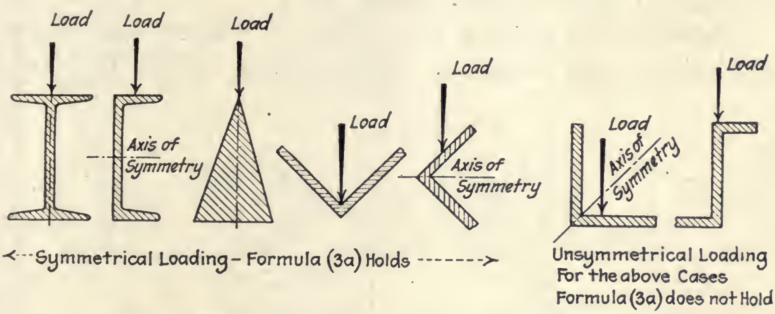


FIG. 8.—Symmetrical and non-symmetrical loading for beams.

Torsion.—The formula commonly used for computing shearing unit stresses in structural and machine parts under torsion applies only within the proportional limit and only to members whose cross-section is either a circle or a hollow circle. For such members the fiber stress is a shearing stress varying from zero at the axis of the member to a maximum at the surface. At any point in the member there is a shearing unit stress parallel to the axis and a shearing unit stress of equal magnitude perpendicular to the axis. These stresses are called the longitudinal shearing stress and the transverse shearing stress respectively. The relation between twisting moment and maximum shearing unit stress (either longitudinal or transverse) is given by the formula:

$$S_s = \frac{Tc}{J} \tag{5}$$

in which T is the twisting moment in inch-pounds on one side of the cross-section; S_s is the maximum shearing unit stress in lb. per sq. in. J is the polar moment of inertia of the cross-section in (inches)^4; and c is the radius of the cross-section.

Values of J and $\frac{J}{c}$ for a circle and for a hollow circle are given in Fig. 9. The twisting moment at any cross-section of a member under torsion is given by the algebraic sum of the twisting moments on one side of that section (either side may be considered). For a shaft transmitting hp horse power at N revolutions per minute the twisting moment in inch-pounds is 63000 hp/N.

The shearing stresses in a shaft of non-circular cross-section are very complex. Approximate values for maxi-

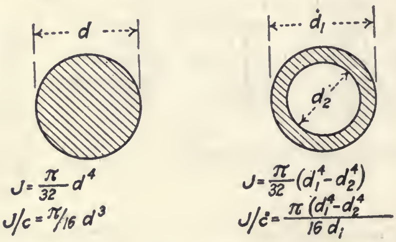


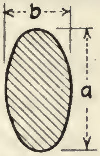
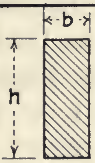
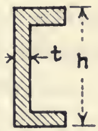
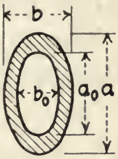
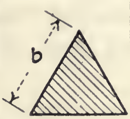
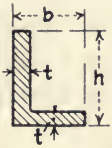
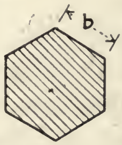
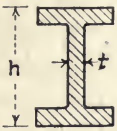
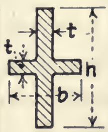
FIG. 9.—Polar moment of inertia for circle and hollow circle.

mum shearing unit stress for various cross-sections are given in Fig. 10 these values are based on the experimental work of Bach and of Kommers.

In using formula (5) or the formulas given in Fig. 10 it must be borne in mind that the unit stress determined is a *shearing* stress and that for any material the safe shearing unit stress is different from the safe tensile or compressive stress. This consideration is further discussed in Chapter IV. On any oblique cross-section of a member under torsion there are, in general, both shearing stresses and tensile (or compressive) stresses (see Fig. 11). On a cross-section perpendicular to the axis or in a direction parallel to the axis the shearing stress reaches its maximum value, and the tensile (or compressive) stress is zero. On a 45-degree section the shearing stress is zero, and the tensile (or compressive) stress reaches a maximum value. On a 45-degree section the value of the unit tensile (or compressive) stress is equal to the value of the unit shear-

$S_s = T/Z$ in which S_s = max. unit shearing stress (lb. per sq. in.); T = twisting moment (inch-pounds); Z = torsional section modulus..

The values of Z given in this figure are based on the experimental work of Bach and of Kommers.

Cross-section	Z (in inches³)	Cross-section	Z (in inches³)	Cross-section	Z (in inches³)
	$\frac{\pi}{16} ab^2$ $a > b$		$\frac{2}{9} b^2 h$ $b < h$		$\frac{2}{9} t^2 h$*
	$\frac{\pi}{16} \frac{ab^3 - a_0 b_0^3}{b}$ $a > b$		$\frac{b^3}{20}$		$\frac{2}{9}(h+b-t)t^2$
	$\frac{b^3}{1.09}$		$\frac{2}{9} t^2 h$*		$\frac{2}{9}(h+b-t)t^2$

*Kommers' Tests indicate that the flanges of I and channel sections add very little to the value of Z.

Fig. 10.—Torsion constants for non-circular sections.

ing stress on a cross-section at right angles to the axis of the member: that is for a circular shaft on a 45-degree section the maximum tensile (or compressive) unit stress is equal to $\frac{Tc}{J}$. This is of importance in computing unit stresses for members in torsion which are made of materials which are weaker in tension than they are in shear, such as cast iron and most brittle materials. For such materials under torsion no computed unit shearing

Fig. 11.—Stresses on oblique cross-section of a torsion member.

stress should be allowed greater than the safe unit stress in tension.

Combined Stresses.—The formulas given in the following paragraphs on combined stress are based, as are the preceding paragraphs, on the common theory of elastic action. These formulas serve satisfactorily for general practice, although somewhat more exact formulas have been developed that taken into account the lateral strain, which always accompanies stress. These more exact formulas are very briefly treated in succeeding paragraphs on lateral strain under load and on Poisson's ratio.

Axial Load Combined with Flexure.—Axial load and flexure in a member set up stresses which act in the same direction or in opposite directions, hence the resulting combined unit stress may be determined by adding algebraically the stresses caused by each action. The unit stress at the extreme fibers due to the combination of axial load and flexure is:

$$S = \frac{P}{A} \pm \frac{Mc}{I} \qquad (6)$$

in which the nomenclature is the same as for formulas (1) and (3*a*).

For the fibers along which the axial stress and the stress due to flexure are in the same direction the plus sign is used; for the fibers along which the axial stress and the stress due to flexura are in opposite directions the minus sign is used. A common case of combined axial stress and flexural stress occurs in a member which is subjected to a load parallel to the axis at a distance e from that axis. For such a member M is equal to Pe, and formula (6) becomes:

$$S = P/A + \frac{Pec}{I}$$

If r denotes the radius of gyration of the cross-section, measured in inches, $I = Ar^2$ and the above equation may be written:

$$S = \frac{P}{A}\left(1 + \frac{ec}{r^2}\right) \qquad (7)$$

For long bars at the center of their length M differs from

Pe on account of the deflection of the bar under eccentric load, and formula (7) becomes inexact. For long bars under tension the deflection diminishes the value of e at the middle of the length, and consequently, Pe and S are diminished, and formula (7) errs on the side of safety. For compression members the bending increases c and consequently Pe and S, and formula (7) errs on the side of danger. For bars in compression whose length is more than four or five times the smallest dimension of the cross-section formula (7) should not be used (see succeeding paragraph on long columns).

Tensile (or Compressive) Stress combined with Shearing Stress.[1]—When there is present in a machine or structural member tensile stress, caused either by axial load or by flexure, and at the same time there is present shearing stress, caused either by direct shear or by torsion there are set up both tensile stresses and shearing stresses in the member. The maximum tensile unit stress occurs, in general, on some oblique plane, and on that plane the unit shearing stress is zero: the mimimum unit tensile stress occurs on a plane at right angles to that for the maximum unit tensile stress, and on the plane of minimum unit tensile stress the unit shearing stress is also zero (it must be borne in mind that compressive stresses are regarded as negative tensile stresses in this section and: minimum tensile stress may have a negative value, that is may be a compressive stress.) The maximum shearing unit stress occurs on some oblique plane between the plane for maximum unit tensile stress and the plane for minimum unit tensile stress. The maximum unit tensile stress is given by the formula:

$$S^1 = \frac{S_t}{2} + \sqrt{S_s^2 + \left(\frac{S_t}{2}\right)^2} \qquad (8)$$

The maximum unit shearing stress is given by the formula:

$$S_s^1 = \sqrt{S_s^2 + \left(\frac{S_t}{2}\right)^2} \qquad (9)$$

[1] In this paragraph compressive stress is regarded as negative tensile stress, and the terms maximum and minimum are used algebraically.

In formulas (8) and (9) S^1 is the maximum tensile (or compressive) unit stress resulting from the combined stress, measured in lb. per sq. in.; S_t is the tensile (or compressive) unit stress caused by flexure or axial stress on the fiber under consideration, measured in lb. per sq. in.; S_s is the shearing unit stress caused by direct shear or by torsion on the fiber under consideration, measured in lb. per sq. in.; and S'_s is the maximum shearing unit stress resulting from the combined stress, measured in lb. per sq. in.

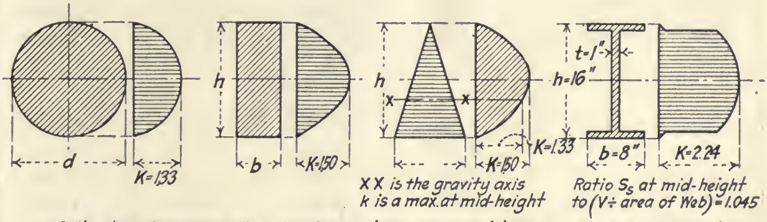
In using formulas (8) and (9) it must be borne in mind that the allowable unit shearing stress for any material is different from the allowable unit stress in tension or compression. Computation may show S^1_s to be less than S^1, yet if the material is weaker in shear than in tension, as is the case with most ductile metals, the danger of failure by shear may be greater than the danger of failure by tension. In general, both S^1 and S^1_s should be computed, and the safety of the member determined both against shearing failure, and against failure by tension or compression.

Shear in Beams.—Beams are subjected to shearing action as well as to flexure. The shearing stress for any cross-section of a beam is computed by equating the summation of the internal shearing stresses on that cross-section to the external shear set up by the loads acting on one side of that section (either side may be considered). At any point on the cross-section of the beam there are shearing unit stress in the plane of the loads and *perpendicular* to the axis of the beam is equal in magnitude to the shearing unit stress in the plane of the loads and *parallel* to the axis of the beam, or, as it is frequently expressed, the vertical shearing unit stress is equal in magnitude to the horizontal shearing unit stress. The magnitude of the vertical or the horizontal shearing unit stress at any point of a cross-section of a beam is given by the formula:

$$S_s = \frac{V}{Ib} vA \qquad (10)$$

in which S_s is the shearing unit stress at the given point, measured in lb. per sq. in.; V is the shear at the section, measured in pounds, A is the area of that part of the cross-section between a line passing through the given point parallel to the neutral axis of the section and the nearest extreme fiber of the cross-section (see Fig. 13); v is the distance of the center of gravity of the above part of the cross-section from the neutral axis (vA is the "static moment" of the above part of the cross-section about the neutral axis, measured in (inches)^3); I is the moment of inertia of the cross-section in (inches)^4; and b is the width of the cross-section at the point considered.

S_s is evidently zero at the extreme fiber where A is equal to zero: for many forms of beams, including rectangular beams, circular beams, and beams of I, H, T, and channel section, S_s is a maximum at the neutral axis, but this is not true for all sections of beams. Fig. 12 shows the varia-



In the above figures K is the ratio of S_s as given by formula (10) to the average shearing unit stress for the whole cross-section (V/A)

FIG. 12.—Distribution of shearing stress for various cross-sections.

tion of S_s across the cross-section for several common cross-sections of beams. For the I-beam it is seen that the value of S_s is nearly constant over the whole depth of the web, whence the common practice of finding the approximate value of S_s for an I-beam by dividing the shear V by the area of the web. Fig. 13 illustrates the computation of S_s for a point in a cross-section of somewhat complex shape.

Since the maximum tensile (or compressive) stress S due to flexure occurs at an extreme fiber where S_s is zero, and the maximum value of S_s occurs at or near the neutral axis where S is zero it is very rarely necessary to consider the effect of combined flexural and shearing stresses at other points in the cross-section. For I-beams and girders with thin webs the combined shearing and flexural stresses at the junction of web and flange may, however, cause a resulting stress greater than S at the extreme fiber.

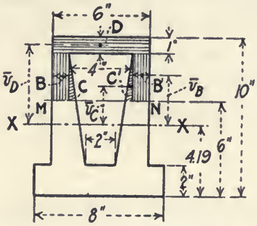


FIG. 13.—Determination of shearing stress for a beam whose cross-section is a composite figure.

PROBLEM.—For the same cross-section as is shown in Fig. 7 determine the shearing unit stress (S_s)—horizontal and vertical—at MN, in terms of the vertical shear V at the section.

$$S_s = \frac{V}{Ib}vA$$

From Fig. 7: $I = 438.3$ (in.)^4

$$b(\text{at } MN) = 1.00 + 0.43 + 0.43 + 1.00$$
$$= 2.86 \text{ in.}$$

Part above MN	Width (in.) b	Height (in.) h	Area of part above MN (sq. in.) A	Distance of center of gravity of part from XX (in.) $\bar{v}$	Static moment of part about XX (in.)^3 $\bar{v}A$
B	1.00	3.00	3.00	3.31	9.93
B'	1.00	3.00	3.00	3.31	9.93
C	0.43	3.00	0.64	2.81	1.80
C'	0.43	3.00	0.64	2.81	1.80
D	6.00	1.00	6.00	5.31	31.86

Sum of $\bar{v}A$'s ($\Sigma\bar{v}A$) 55.32. This is vA of the formula above.

$$S_s = V\frac{55.32}{438.3 \times 2.86} = 0.0441V$$

Long Compression Members, Columns, Pillars, Struts.—In any actual structural or machine member nominally under axial load there is always present bending action due to accidental eccentricity of load and non-homogeniety of material. In tension members the bending action tends to decrease under load and formula (1) can be used for any length of member. In compression members the bending action tends to increase under load, and for members whose length is more than four or five times their smallest transverse dimension formula (1) is not safe to use. As the eccentricities and irregularities which cause bending action in compression members with nominal axial loading are necessarily uncertain in amount, formulas for long compression members are necessarily empirical.

For long compression members it is customary to reduce P/A, the average unit stress allowed on the cross-section, by an amount depending on the length of the member, the manner in which it is fastened at the ends, and the form and size of the cross-section. The two column formulas most used are the "straight line" formula, and the Rankine-Gordon formula. The straight line formula is:

$$P/A = S - k\frac{l}{r} \tag{11}$$

in which P is the safe axial load in pounds; A is the area of the cross-section in sq. in.; S is the safe unit stress in compression at the concave edge of the column, measured in lb. per sq. in.; l is the length of the column in inches; r is the least radius of gyration of the area of the cross-section of the column, measured in inches (l/r is called the slanderness ratio for the column), and k is a constant determined from tests of columns to failure.

The Rankine-Gordon formula is

$$P/A = \frac{S}{1 + q(l/r)^2} \tag{12}$$

in which q is a constant determined from tests of columns to failure (not the same constant as k in the straight line formula) and the other symbols are the same as for the straight line formula.

Values for the constants k, q, and S are given in various engineering handbooks for special cases: average values for general use are given in Table 1.

TABLE 1.—CONSTANTS FOR USE WITH COLUMN FORMULAS

These constants are for *working unit stress* in columns. See Chapter IV for discussion of working stress.

Material of column	S	Pin-ended columns		Fixed-ended columns[1]	
		k	q	k	q
Structural steel........	15,000	70	0.00012	40	0.000030
Structural nickel steel..	20,000	100	0.00017	60	0.000042
Cast iron.............	10,000	75	0.00040	45	0.000100
Timber...............	1,000	10	0.00050	5	0.000125

[1] For actual columns the ends are never absolutely fixed, and the general practice is to use values somewhat larger than those given in this column.

Lateral Strain Under Load; Poisson's Ratio.—Accompanying tensile or compressive stress in any direction there is a strain in the direction of the stress and also a strain at right angles to that direction. A round bar placed under axial tension diminishes slightly in diameter, and a round bar in compression increases slightly in diameter. Members with other shapes of cross-section undergo corresponding changes of transverse dimensions under axial load. Within the proportional limit for a member under axial load the change in a transverse dimension divided by that dimension is called the *lateral unit strain.* The ratio of lateral unit strain produced by an axial load to the axial unit strain produced by the same load is called *Poisson's ratio.* Values of Poisson's ratio for common materials are:

Steel and wrought iron	0.30
Cast iron	0.25
Brass	0.25
Concrete	0.10

Comparatively little experimental work has been done on the determination of Poisson's ratio for other materials used in structures and machines.

Effect of Lateral Strain on Strength; Three Theories of Failure of Materials.—Under the action of two stresses at right angles, or under the combined action of axial stress and shearing stress the lateral *strains* set up have no effect on the *stresses* developed, but they do affect the *strains* developed at any point. For example, a boiler shell is subjected to circumferential tensile stress due to the bursting action of the steam pressure, and also to axial stress due to the pull of the boiler heads. The lateral contraction due to the axial stress acts to diminish the circumferential stretch due to bursting pressure, and the resulting *maximum circumferential unit strain* at a point in the shell is *less* than the *circumferential unit strain* due to bursting pressure alone. The *maximum circumferential unit stress* is unaffected by the axial stress. If the shell were subjected to axial compression from any source this axial compression would *increase* the circumferential stretch over that due to bursting pressure alone.

Which action, strain or stress, produces structural *damage* in the material of a member? Or, as some claim, is it really the shearing stress (on some oblique plane) which tends to cause failure in the material? The answer to these questions is still a matter of debate, and there are three common theories for the cause of failure of material, namely the *maximum strain theory*, the *maximum stress theory*, and the *maximum shear theory*. Perhaps the most recent investigations are those of Becker at the University of Illinois and those of Matsumura and Hamabe at Kyoto Imperial University. These investigations taken together seem to indicate that strain rather than stress is the cause of failure, but that shearing stress must also be taken into account. For a complete analysis of the strength of any structural or machine member it is necessary to compute *both* the maximum unit strain, and the maximum unit shearing stress. The common theory of strength of materials as given in elementary text-books on the mechanics of materials is the maximum stress theory, and in such books no account is taken of the effect of lateral strain, or the "Poisson's ratio effect" as it is sometimes called, this is equivalent to assuming a value of zero for Poisson's ratio. For most cases met in practice the common theory gives results of sufficient accuracy.

Unit strain is measured in inches per inch length, and is consequently an abstract number, but it has become so fixed a habit to think and write of strength of materials in pounds per square inch that in using the maximum strain theory the value of the unit strain is usually multiplied by the modulus of elasticity of the material, giving a value proportional to unit strain but expressed in pounds per square inch. This value is denoted by the symbol $E\delta$ and in this text will be called the *strain equivalent*.

Elementary Formulas Involving the Consideration of Lateral Strain.— If two stresses act at right angles to each other the maximum unit strain is in the direction of the larger stress, and the magnitude of the strain equivalent $E\delta$ is:

$$E\delta = S_1 - \sigma S_2 \tag{13}$$

in which S_1 is the (numerically) larger stress (tensile or compressive); S_2 is the numerically smaller stress (tensile or compressive); and σ is the value of Poisson's ratio for the material. In using formula (13) tensile stresses are considered plus and compressive stresses are considered minus. This applies to formulas (14) and (14*a*) also.

The strain equivalent $E\delta'$ in the direction of S_2 is:

$$E\delta' = S_2 - \sigma S_1 \tag{13a}$$

The maximum unit shearing stress S_s' on any oblique plane is:

$$S'_s = S_1/2 \tag{14}$$

if S_1 and S_2 are of the same sign, and

$$S_s' = \frac{S_1 - S_2}{2} \tag{14a}$$

if S_1 and S_2 are of opposite sign. The reason for the difference between formula (14) and formula (14*a*) involves analysis in three-dimensional mechanics which will not be given here.

If there is acting at a point in the cross-section of a member an axial unit stress S (caused either by direct axial load or by flexure) combined with a shearing unit stress S_s (caused either by direct shearing action or by torsion) the resulting strain equivalent $E\delta$ is:

$$E\delta = (1 - \sigma)\frac{S}{2} + (1 + \sigma)\sqrt{S_s^2 + \left(\frac{S}{2}\right)^2}$$

Formula (15) is the maximum strain theory formula corresponding to the maximum stress theory formula (8) on page 23.

Under the combined action of axial stress and shearing stress the maximum shearing unit stress is given by formula (9) for either the maximum stress theory or the maximum strain theory.

The maximum strain theory is sometimes called St. Venant's theory; the maximum stress theory is sometimes called Rankine's theory; and the maximum shear theory is sometimes called Guest's theory. As noted above the theory commonly used in engineering computations is the maximum stress theory, with occasional computation of shearing stress. This procedure is of sufficient accuracy for most engineering computations, and the foregoing paragraphs on the maximum strain theory are not intended to disparage the use of the common theory, but to serve as an introduction to the more exact theory for cases where an unusually high degree of accuracy is desirable.

Stress-strain Diagrams for Materials.—The relation of stress to strain for any material is conveniently shown by

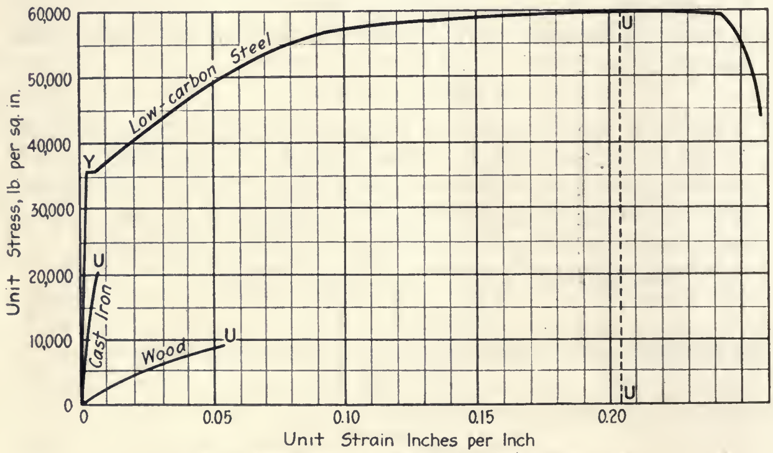


FIG. 14.—Typical stress-strain diagrams.

a *stress-strain diagram*, such as is given in Figs. 14 and 15. Such a diagram is obtained as follows: A series of known loads is applied to a specimen of the material by means of a testing machine (see page 267), and the corresponding strains measured by means of some form of micrometer. The unit stresses and unit strains corresponding respectively to the loads and strains are computed and plotted, usually representing unit stresses as ordinates (vertical distances on the diagram) and unit strains as abscissas (horizontal distances). A curve drawn through the plotted points gives the stress-strain diagram. Figs. 14 and 15 give typical stress-strain diagrams for steel, cast iron, and wood which are representative stress-strain diagrams for ductile materials, brittle materials, and fibrous materials, respectively.

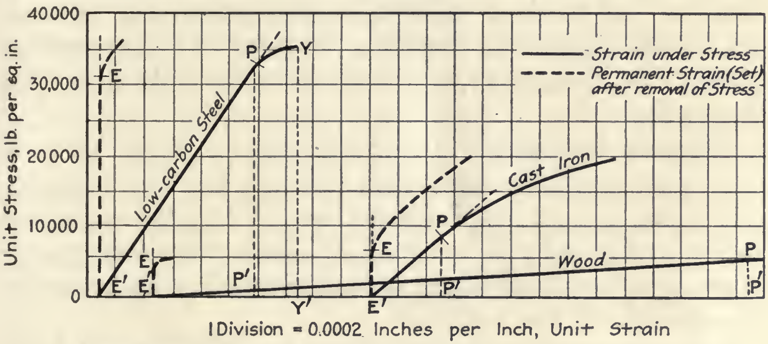


FIG. 15.—Typical stress-strain diagrams for small strains.

Elastic Limit, Proportional Limit, Yield Point.—In Fig. 15 solid lines indicate strain when the specimen is stressed and broken lines indicate strain remaining after stress is removed (permanent set). In the stress-strain diagrams obtained for most materials, it is seen (broken-line diagrams, Fig. 15) that up to a certain unit stress there is no measurable permanent set after the removal of load. For any material the lowest unit stress at which there can be detected permanent set is called the *elastic limit* of the material. In Fig. 15 the elastic limits are shown at E.

For most material up to a certain unit stress the stress-strain diagram does not deviate appreciably from a straight line, and Hooke's law holds. For any material the lowest unit stress at which there can be detected a deviation from Hooke's law is called the *limit of proportionality of stress to strain,* or more briefly, the *proportional limit.* In Fig. 15 proportional limits are denoted by P.

For ductile materials, such as mild steel, soft brass, etc., especially for rolled or forged materials, the stress-strain diagram frequently shows a sharp break as at Y (Figs. 14 and 15). If in making a test of such material the load is applied continuously the scale beam of the testing machine "drops" at a stress corresponding to the sharp break in the stress-strain diagram and strain can be detected by direct measurement with a pair of dividers. The unit stress (Y, Fig. 15) at which a very sudden change takes place in the strain is called the *yield point.* In general, only ductile materials show a yield point. In commercial testing the yield point is sometimes erroneously called the elastic limit.

Ultimate Strength.—In tension tests or shear tests of materials, and in compression tests of non-ductile materials there is found a well-defined load which is the maximum carried before rupture occurs. The unit stress corresponding to this load is called the *ultimate strength* or, more briefly the *ultimate* for the material.

Significance of the Elastic Limit, the Proportional Limit and the Yield Point.—For any material the values determined for the elastic limit and the proportional limit are dependent upon the precision of the measuring instruments and methods used in their determination. Tests are rarely made to determine the elastic limit, since such tests involve repeated application and release of stress and take a very long time. The elastic limit of a material is an indication of the stress which the material will withstand without appreciable permanent distortion. This is of value in the study of materials for machine tools in which any appreciable permanent distortion would mean very serious damage to the machine.

The elastic limit has been defined by some writers on Mechanics of Materials, to be the unit stress below which any material was perfectly elastic, and below which the material would be able to withstand without rupture an infinite number of repetitions of stress. Whether in a test under static load—such a test as is made in a testing machine—with instruments of higher precision than those now available there could be found an *absolute* elastic limit for any actual material is doubtful. Under repeated stresses rupture has occurred at computed unit stresses considerably lower than the proportional limit as determined in the ordinary laboratory test.

Some physicists and some testing engineers maintain that for most materials the elastic limit and the proportional limit occur at identically the same stress; others dispute this statement; while still others claim that, if instruments of sufficient precision were available, for actual materials some extremely minute permanent set and some very slight deviation from Hooke's law would be found for any stress, however, small. However, *for practical purposes the two limits are identical* and they will be so regarded in this book, and the term *proportional limit* commonly used. Practically the proportional limit of a material is the criterion of its elastic strength *under static loading.*

As suggested above the exact location of the proportional limit depends on the precision of the instruments used in measuring loads and strains, and on the accuracy of plotting the stress-strain diagram. Following the practice recommended by the Committee on Standard Methods of Testing, appointed by the American Society for Testing Materials, the proportional limit will be located at that stress for which the stress-strain diagram shows the first deviation from a straight line, the measurements of strain being made with a micrometer reading to 0.0001 in.

The yield point indicates a sudden change from a condition of nearly perfect elasticity to one of a high degree of plasticity. Below the yield point Hooke's law is a very close approximation to the truth, and permanent sets are very small. If the material of a structure or a machine is stressed beyond the yield point, the resulting distortion is so great that the usefulness of the structure or machine is usually at an end, unless the overstressed area is very small. For ductile materials, the yield point should, in general, be regarded as the *practical ultimate strength* under static loads for tension as well as for compression. Brittle materials have no yield point, and the ultimate strength is probably the most reliable limit of strength for static loads. The yield point is much more readily determined than is the proportional limit, and specifications for rolled materials usually contain requirements for the yield point rather than for the proportional limit.

Behavior of Materials in a Partially Plastic State.— In most cases the material of structures and machines is subjected to stresses so low that the action is almost perfectly elastic. The behavior of material under stresses so high that plastic action is set up is of interest for two reasons: (1) In the process of shaping and fabricating the material it is not infrequently necessary to bend, to stretch, or to punch the material cold; (2) the behavior of the material under accidental overloads is frequently of importance, and for some members, such as ball and roller bearings, the stresses at points of contact are above the proportional limit.

In fabricating members of steel structures, such as beams and columns, it is frequently necessary to bend them to shape or to punch holes in them. Those processes involve local stresses beyond the yield point of the material. Material which possesses high ductility is not seriously injured by such treatment, but brittle material under such conditions would be shattered.

In selecting the material to be used for a structure or a machine, it is frequently of importance to consider the effects of accidental overload. An excellent example is furnished in the selection of material for parts of railway rolling stock, such as car couplers, draft rigging, side frames, etc. For such parts it is evident that a tough material which, even after it is badly distorted, still possesses considerable strength is preferable to a brittle material which, though it may stand a higher unit stress before rupture, snaps suddenly with very little strain or other warning of approaching failure, if rupture does occur. A material which after severe distortion still possesses high strength is called "tough." Fig. 16 gives stress-strain diagrams for a tough material, and for two others less tough. The toughness of a material may be measured by the area under the complete stress-strain diagram.

The desirability of insuring the parts of railway cars against sudden, shattering failure has caused the very general replacement of cast-iron parts by steel castings. For a similar reason cast-iron columns for buildings have been generally discarded in the best practice. It is a general rule in machine design not to use a brittle material in direct tension if it can be avoided.

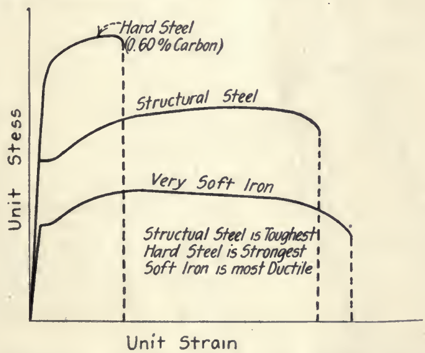


FIG. 16.—Stress-strain diagrams showing different degrees of toughness.

In parts of machines which involve the carrying of heavy loads on spherical or cylindrical surfaces—such as ball bearings, roller bearings, car and wagon wheels, chain links—there are set up in, in service, stresses beyond the proportional limit of the material. Such parts do not last indefinitely; they wear out, and their length of life is dependent on the properties of the material when stressed beyond the proportional limit. In wire rope, band saws, and other flexible machine parts which, in use, are repeatedly bent as they pass round pulleys and sheaves, the yield point of the material is frequently exceeded, and such members show considerable permanent distortion after a short time in service, and finally wear out.

Effect of Stress Beyond the Yield Point.—In 1881, Johann Bauschinger of Munich published the results of a long series of experiments which demonstrated that, if a ductile material was stressed in one direction beyond its yield point, for subsequent stress *in the same direction*, the yield point and the proportional limit were raised, that for subsequent stresses in the *reverse* direction the yield point and the proportional limit were lowered, and that in any case the toughness of the material was diminished. Fig. 17 illustrates the properties of material stressed beyond the yield point. Bauschinger also showed that time was necessary for the particles of the material to adjust themselves after overstress, and that for subsequent stresses in either

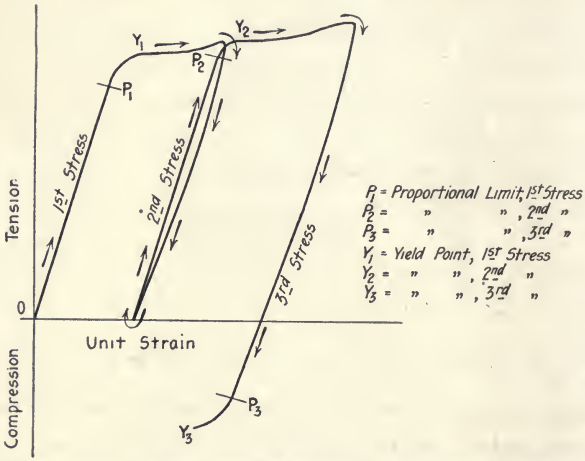


FIG. 17.—Stress-strain diagram showing effect of repetition of stress beyond the proportional limit.

direction the yield point and the limit of proportionality of overstressed materials were raised by rest.

The properties of cold-rolled steel and of cold-drawn wire are explained by Bauschinger's tests, as is the "springiness" of hammered steel or brass plates. In the process of cold-drawing or cold-rolling the material is stretched well beyond its yield point. Steel, iron, copper, brass, aluminum and zinc are rendered stronger by cold-rolling, cold-drawing or cold-hammering. The cold-working of metal generally decreases its ductility and its toughness. To a large degree heating followed by slow cooling (annealing) removes the effects—beneficial and injurious alike—of cold-working. The resistance of metal to repeated stress is probably not increased by cold-working.

Resistance of Materials to Impact.—In selecting materials for members which must resist impact, it must be borne in mind that there are two factors to be considered: total *stress* allowable in the member, and total *strain* allowable. Resistance to impact is a function of *both* these factors. In this connection it may be noted that "the force of a blow" can not be computed unless not only the *energy* of the blow is known, but also the rigidity of the body striking the blow and of the parts on which the blow is delivered, for example, a piece of iron weighing 100 lb. falling from a height of 20 ft. would deliver 2,000 ft.-lb. of energy when it struck a body, but the *force* set up if it struck soft earth would be much less than the force set up if it struck a rigid concrete foundation.

For materials which must withstand heavy accidental impact without actual rupture, *toughness* is the prime requisite. Toughness has been defined on page 3 and it may be noted here that the toughness of a material may be measured by the *area under the stress-strain diagram* for that material (see Fig. 14). A striking illustration of the resistance of materials to rupture under impact is furnished by comparing the action of oak with that of cast iron. Under static load cast iron is about three times as strong as oak, but the *strain* which oak will stand before it is ruptured is about nine times the strain which cast iron will stand. The area under the stress-strain diagram for oak is about three times that for cast iron, and under impact loads oak is about three times as strong as cast iron.

The ability of a material to resist impact without permanent distortion is measured by the area under the stress-strain diagram up to the elastic limit (for practical purposes up to the proportional limit). If elastic resistance to impact is desired a material with a high proportional limit or a low modulus of elasticity should be used. A good illustration of the difference between elastic resistance to impact and resistance to rupture under impact is furnished by a comparison of the action of high-carbon steel with that of low-carbon steel. High-carbon steel has the higher proportional limit and has a greater area under its stress-strain diagram up to the proportional limit. It is superior to low-carbon steel in its *elastic* resistance to impact and is used for such members as springs. Low-carbon steel, however, has a greater area under the *whole* of its *stress-strain* diagram than has high-carbon steel (see Fig. 16), on account of its much greater ductility, and low-carbon steel offers greater resistance to *rupture* under impact than does high-carbon steel, and is used for such members as chains and car couplers in which ability to withstand occasional heavy shock without rupture is of great importance. Wrought iron has a low elastic resistance to impact, but, like low-carbon steel has a high resistance to rupture under impact. In this respect it does not show any marked superiority to the better grades of low-carbon steel, but is superior to the poorer grades.

In considering resistance to static load, it is, in general, necessary to consider only the unit stresses set up in the most stressed fibers of a member—in the smallest cross-section of a rod in tension, for example. If a machine or a structure is to withstand impact, the *total deformation* of any part is effective in increasing the resistance to impact. Two rods of the same material with equal cross-section have the same static strength in tension irrespective of their relative lengths; but their ability to withstand impact varies directly as their length.

Stiffness, Significance of the Modulus of Elasticity.—The modulus of elasticity of a material is an index of its stiffness or rigidity and is the ratio of unit stress within the proportional limit to the corresponding unit strain. The stiffness or rigidity of a strong material under working loads may be no higher than the rigidity of a weaker material. The best illustration of the distinction between strength and stiffness is found in the action of steel. All grades of steel from the softest rivet steel to the hardest tool steel have about the same modulus of elasticity—30,000,000 lb. per square inch. This is illustrated in Fig., 18 which shows typical stress-strain diagrams for various grades of steel. In Fig. 18 the slope of the line *OA* indicates the value of the modulus of elasticity for all the steel specimens. If the unit stresses actually set up in a machine member or structural part are within the limit of

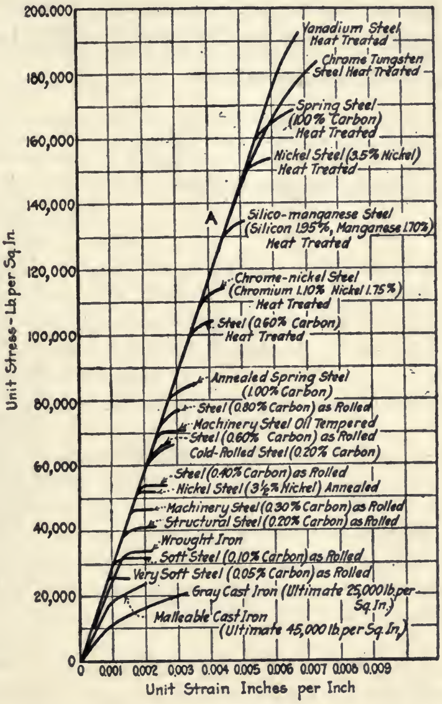


FIG. 18.—Stress-strain diagrams for various grades of iron and steel.

proportionality, it makes no difference in the rigidity whether soft steel or hard steel is used. In machine tools it has been sometimes proposed to remedy too great deflection by replacing the flexible parts with others made of a stronger, harder steel; this usually does no good, as the stresses in machine tool parts are usually low, and it is the modulus of elasticity of the steel rather than the strength which counts. The use of high-strength nickel steel for long-span bridges will allow the use of smaller structural members, but the stiffness of the bridge will be somewhat diminished by the use of these smaller members.

Coefficient of Expansion; Stresses due to Temperature.—The application of heat expands all solids. The amount of expansion per inch of length per degree of rise of temperature in an unrestrained piece of material is called the *coefficient of expansion* for the material. In Table 2 are given average values for the coefficient of expansion of some of the common materials based on the Fahrenheit scale of temperature.

TABLE 2.—COEFFICIENTS OF EXPANSION

The value given is for the "linear" coefficient of expansion; that is, is the expansion per inch length per degree (Fahr.) rise of temperature.

Material	Coefficient of expansion (Fahrenheit)
Aluminum	0.0000130
Brass	0.0000101
Bronze	0.0000098
Copper	0.0000089
Cast iron	0.0000056
Wrought iron	0.0000065
Steel	0.0000066
Zinc	0.0000141
Brick	0.0000031
Concrete	0.0000079
Marble from	0.0000031
Marble to	0.0000079
Plaster (white)	0.0000092
Porcelain	0.0000020
Slate	0.0000058
Wood	0.0000028
Brick masonry	0.0000040

If a machine or structural member is restrained from free expansion under application of heat there is set up a stress in the member. If x' is the expansion which would take place if the member were unrestrained and x is the expansion which actually does take place due to rise of temperature the unit stress S set up is:

$$S = \frac{x' - x}{l} E$$

in which l is the length of the member and E is the modulus of elasticity of the material.

Selected References for Further Study

TEXTS ON THE MECHANICS OF MATERIALS

1. Elementary texts which do not require a knowledge of calculus:
   - MURDOCK: "Strength of Materials," New York, 1911.
   - MERRIMAN: "Strength of Materials" (to be distinguished from "Mechanics of Materials" by the same author), New York, 1912.
   - SLOCUM: "Resistance of Materials," Boston, 1914.
2. Elementary texts which require a knowledge of the calculus:
   - BOYD: "Strength of Materials," New York, 1917.
   - ANDREWS: "The Strength of Materials," New York, 1916.
   - FULLER AND JOHNSON: "Applied Mechanics," Vol. II, New York, 1919.
   - HOUGHTON: "The Elements of Mechanics of Materials," New York, 1909.
   - SLOCUM AND HANCOCK: "Text-book on the Strength of Materials," Boston, 1906.
3. More comprehensive texts:
   - MERRIMAN: "Mechanics of Materials," New York, 1915.
   - MORLEY: "Strength of Materials," London, 1913.
   - CHURCH: "Mechanics of Engineering," New York, 1908.
   - BURR: "The Elasticity and Resistance of the Materials of Engineering," New York, 1915.
   - LANZA: "Applied Mechanics," New York, 1910.
4. Special references:
   - ANDREWS: "The Strength of Materials," New York, 1908. Chap. VI. gives a discussion of graphical methods for determining moment of inertia.
   - WATERBURY: "Stresses in Structural Steel Angles," New York, 1917, and L. J. Johnson, Trans. Am. Soc. C. E., Vol. LVI, p. 169 (1906), give discussions of stresses in beams when the loading is not parallel to a "principal axis" of the cross-section of the beam.
   - BOYD: "Strength of Materials," New York, 1917, Chap. XVIII, gives a discussion of curved beams and hooks.
   - LANZA: "Applied Mechanics," New York, 1910, Chap. X gives a discussion of the strains and stresses in bodies, taking lateral strain into account. A knowledge of calculus is necessary to enable a student to follow the discussion.
   - LOVE: "A Treatise on the Mathematical Theory of Elasticity," Cambridge (England), 1906, is a very elaborate treatise on strain and stress. A knowledge of advanced mathematics is required.

CHAPTER III

THE RESISTANCE OF MATERIALS TO REPEATED STRESS

Importance of Resistance to Repeated Stress.—The strength of materials is commonly determined by tests under a load gradually increasing from zero to the ultimate of the test specimen. In nearly all computations of stress and strain the basis of the computation is the action produced by a steady load applied but once. For more than half a century it has been recognized that under loads repeated many thousands of times the behavior of material might be quite different from the behavior under a single application of load. The growing use of high-speed machinery has been especially influential in necessitating the consideration of the strength of material under repeated stress.

In a general way the difference in the behavior of material under repeated loads and under a single load (or a load applied but a few times) is shown by the tendency toward gradual breakdown of the material under repeated load. Under a single application of load the material of a structure either withstands the load or it fails; under load repeated many thousands of times the material may withstand the load for awhile, and then fail by the gradual spread of cracks or other local injuries to the material. Under repeated load local strains which would be of no importance if but one loading were to be applied may form a nucleus for damage which gradually spreads until the whole member fails.

Loss of Energy during Application and Release of Load. If stress is applied to any member of a machine or a structure and then is released, that member is said to have been carried through a *cycle* of stress. If the action of the member were perfectly elastic the stress-strain diagram for such a cycle would be a straight line as shown at OA, Fig 19. If there is inelastic action the stress-strain diagram for the cycle of stress will not be a straight line, but will enclose a small area as shown at $O'A'$, Fig. 19. The area enclosed within the stress-strain diagram for a cycle of stress represents energy lost, and this lost energy is called *mechanical hysteresis*.

The minute amount of energy lost during a cycle of stress is, presumably, transformed into heat, and this heat is accompanied by microscopic wear on the small particles

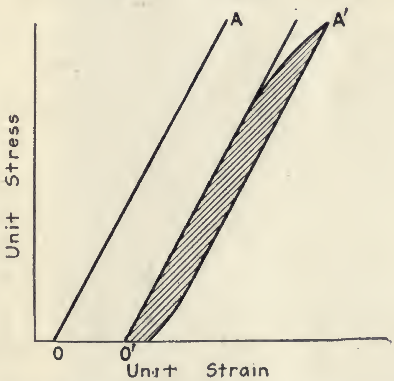


FIG. 19.—Stress-strain diagrams for one cycle of stress. OA, No appreciable inelastic action; $O'A'$, inelastic action evident.

of the material as they slide over each other. If the cycle of stress is repeated a great many times the cumulative effect of this wearing action so weakens the material that small cracks begin to form; these cracks spread and finally cause the material to rupture. The growth of microscopic cracks, or "slip lines," in metals was very beautifully shown in 1899 by Ewing and Rosenhain. Fig. 20 shows the development of these "slip lines," as the microscopic flaws were called by their discoverers, for a test piece of pure iron subjected to repeated stress of considerable magnitude (well beyond the yield point). The first slip lines appear between particles of metal *within* a crystal as these particles slide one on another; as further repeti-

a. Before application of stress. *b.* After several hundred applications of stress "slip lines" developed. *c.* Just before failure, crack opens.

Fig. 20.—Iron under repeated stress.

Photomicrograph by H. R. Thomas. Magnification 75 times.

tions of stress occur larger cracks open and finally, cause rupture.

The view of failure of metals under repeated stress formerly common was that under repeated stress metal "crystallized," and that failure took place at the junction of the crystals formed. This view has been generally discarded by metallurgists; all metals are crystalline in structure under the first stress as well as after many stresses; moreover, as shown by the experiments of Ewing and Rosenhain, the first evidences of failure are usually seen not at the junction of crystals, but *within* the crystals. The theory of the gradual development of microscopic cracks—the "micro-flaw" theory—is generally held today rather than the "crystallization" theory.

Mechanical Hysteresis at Low Stresses.—If the elastic limit of a material as determined by ordinary static tests were an *absolute* elastic limit, there would be no loss of energy and no wear during cycle of stress within this limit and the material might be expected to withstand an infinite number of repetitions of stress without failure. For actual materials this is not true. The elastic limit determined in static test depends on the precision of the apparatus used in determining it; moreover, actual material is never perfectly homogeneous, nor are the members of any actual machine or structure free from high localized stresses. While these local stresses might not appreciably affect the *static* strength of the machine or structure, under *repeated* loads these high local stresses may start cracks which, spreading, may ultimately cause failure.

Localized Stress in Structural and Machine Members.—Localized stress in structural and machine parts may be caused either by external irregularities of outline, uneven application of load, or internal non-homogeniety. Such localized stresses are neglected in the ordinary formulas of mechanics of materials, such as are given in Chapter II., and may reach magnitudes several times those of the computed unit stresses. Sudden changes in cross-section, sharp corners, especially inward-projecting corners, and rough surface finish are among the common external factors which cause high localized stress. Sharp corners of bearing blocks, and poor fit of pin bearings are among the common factors causing high localized stress at points of contact of adjacent structural or machine parts. Small particles of slag or of oxidized iron, and imperfectly joined crystals are among the common internal irregularities of structure which cause high localized stress. While these high localized stresses are not given by the common formulas of mechanics of materials yet when the ordinary computed stresses are increased, in general these localized stresses also increase, so that their destructive effect may be lessened by reducing the computed stress on the member. As has been noted in a preceding paragraph these localized stresses act over such minute areas that they affect the *static* strength of the member but little. They are not negligible, however, in their effect on the strength of members subjected to repeated stress. High localized stress may cause a crack to start either directly or by cold-working the metal (see p. 36) until it becomes brittle where the localized stress exists. This crack itself extends the discontinuity of the metal, and at its root the localized-stress effect is still further increased. As the crack extends the effect on the piece is as if a minute saw cut were being made further and further into the piece, until the member under the repeated load snaps short off. Not every localized stress develops a crack to failure of the piece, but every high localized stress is a potential source of progressive structural failure. Homogeneity of internal structure, smoothness of internal surface, and avoidance of sharp corners and sudden changes of cross-section may be more important in the design of machine parts than is high static strength of material.

Shoulders of crankshafts and of axles, corners of keyways in shafts, the root of screw threads, and rivet holes are examples of locations where high localized stress is likely to occur.

Both in laboratory tests and in actual service (*e.g.*, torpedo-boat shafts and car axles) materials have failed under computed repeated stresses lower than the elastic limit as determined by static tests.

Repeated Stress Tests.—There is at the present time no entirely satisfactory standard for measuring the resistance of materials to repeated stress. The standard most nearly satisfactory is found in the result of laboratory tests to failure of materials under repeated stress, supplemented by a study of the successes and failures of materials subjected to repeated stress in practice. The earliest and the most extensive series of repeated stress tests is the series

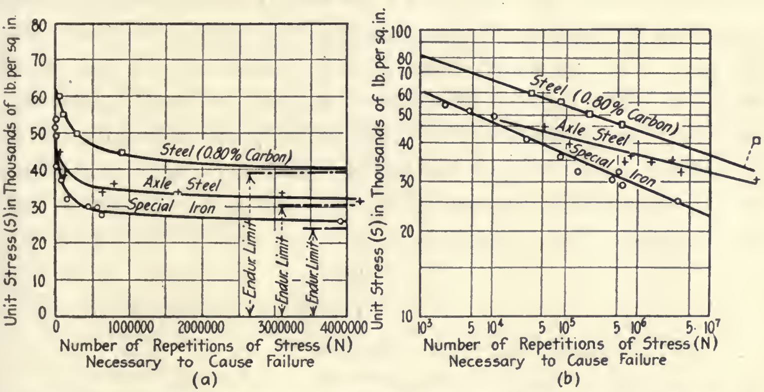


FIG. 21.—Typical diagrams of results of repeated stress tests. Diagram (*a*) drawn to ordinary coördinates. Diagram (*b*) gives same test results as diagram (*a*) drawn to logarithmic coördinates.

made by Wöhler for the Prussian Government from 1858 to 1870. Many other investigators have made tests, none, however, making tests so extensive as those of Wöhler.

Fig. 21 shows the results of several typical series of tests on materials under repeated stress.[1] In this figure, plotted with unit stress as ordinates and number of repetitions to cause failure as abscissas, it is seen that the curves have a steep downward slope at the beginning, and become nearly horizontal for about 3,000,000 repetitions of stress. By earlier writers on mechanics of materials it was assumed

[1] See p. 284 for description of testing machines for testing of the strength of materials under repeated stress.

that the curves became so nearly horizontal after a few million repetitions that the corresponding unit stress might be assumed as the strength of the material under an infinite number of repetitions of stress. The unit stress corresponding to the ordinate of the curve after it had become horizontal was called the *endurance limit* of the material. In many cases, the endurance limit as thus found for a material is roughly proportionel to the ultimate static strength though there are exceptions to this, especially for cold-worked metal. If material was subjected to repetition of stress varying from zero to a maximum the endurance limit, was found to be not far from one-half the ultimate strength. If the material was subjected to stress varying from a maximum in one direction to an equal stress in the opposite direction (complete reversal of stress) the endurance limit was found to be from one-quarter to one-third the ultimate strength. Based on the researches of Weyrauch and Launhardt, the following formula was proposed by J. B. Johnson:

$$S_e = \frac{\frac{1}{2}S_u}{1 - \frac{1}{2}Q} \tag{1}$$

S_e = the endurance limit for the material.
S_u = the (static) ultimate of the material.
Q = the ratio of minimum stress to maximum stress during a cycle of stress (for stress varying from zero to a maximum, $Q = 0$; for completely reversed stress, $Q = -1$).

The use of the endurance limit gives fairly reliable results for members which will not have to withstand more than a few million repititions of stress, but in view of the fact that the most extensive laboratory tests have been carried only to a few million repititions, and that in service such members as shafts, car axles, and piston rods are frequently required to withstand several hundreds of millions of repetitions of stress before wearing out, it seems doubtful whether the endurance limit as determined above is entirely reliable for such members.

In 1910 O. H. Basquin of Northwestern University pointed out that an examination of the results of numerous series of repeated stress tests indicated that for nearly all the range covered by such tests the law of resistance to repeated stress might be expressed by the equation

$$S = KN^m \qquad (2)$$

in which S = the maximum unit stress developed in the test piece.
N = the number of repetitions of stress necessary to cause failure.
K and m are constants depending on the material and somewhat on the manner of making the test.

This is known as the *exponential equation for repeated stress.* Another form of expression for the above equation, frequently more convenient is

$$\log S = \log K + m \log N \qquad (3)$$

If the logarithms of S and N are plotted, or if values of S and N are plotted on logarithmic cross-section paper equation (3) is represented by a straight line. Fig. 21*b* shows the results of the same series of tests as is given in Fig. 21*a* but in Fig. 21*b* the coördinates are logarithmic. For large values of N the exponential equation gives in many cases values of S smaller than the observed values, in other words the exponential hypothesis seems to err on the side of safety.[1]

[1] A possible explanation of the increased endurance of materials under repetitions of low stress and consequent high values of N is as follows: For high stresses the damage done per cycle of stress covers a considerable area of cross-section in the member and the progress of structural injury proceeds regularly. For low stresses little isolated areas are damaged, and the rapidity with which damage proceeds is a "probability" function of the grouping of the damaged areas. It has been suggested in a paper presented by Moore and Seely before the American Society for Testing Materials that for iron and steel members of structures and machines whose failure would not endanger life the values of the stress found by the application of the exponential hypothesis, equation (4) or equation (5), page 51, may be multiplied by a "probability factor" greater than unity.

$$1 + e\left(\frac{-20,000,000}{N}\right)$$

is here suggested as a suitable probability factor, in which the constant e is 2.718 the base of the hyperbolic system of logarithms. Values of this probability factor are given in the table at the bottom of p. 50.

In view of the fact that there have been very few repeated stress tests made in which the number of repetitions of stress exceeded 5,000,000, that up to 1,000,000 repetitions of stress the exponential equation seems to follow test results fairly closely, and that for greater numbers of repetitions the exponential equation seems to yield results on the safe side, it is recommended as the best equation we possess at present for computing the probable strength of materials under repeated stress.

Effect of Range of Stress.—Wöhler in his investigations of the effect of repeated stress discovered that the number of repetitions of stress necessary to cause rupture depended on the *range* of unit stress during each cycle. If the range of unit stress was from zero to 40,000 lb. per square inch fewer repetitions were necessary to cause rupture than if the range was from 20,000 lb. per square inch to 40,000 lb. per square inch (note that for each of the above cases the *maximum* stress is the same). Various formulas have been proposed for the effect of range of stress on the resistance to repeated stress. From a study of the work of Wöhler and the supplementary work of Bauschinger the effect of range of stress seems to be fairly well expressed by the following modification of equations (2) and (3): For the constant K substitute the expression $\frac{B}{1 - Q}$ in which B is a constant for any given material determined from repeated stress tests and Q is the ratio of the minimum unit stress during a cycle to the maximum. For a range of

N Number of repetitions of stress	Probability factor
1,000,000	1.000
10,000,000	1.135
20,000,000	1.368
50,000,000	1.670
100,000,000	1.818
500,000,000	1.960
Infinity	2.000

unit stress from zero to a maximum, Q is zero, for completely reversed stress Q is -1. In the case of a bridge chord, in which the unit stress due to live load is four times the unit stress due to dead load and is in the same direction, Q is $+0.2$.

The exponential equations for repeated stress then become:

$$S = \frac{B}{1 - Q} N^m$$

or

$$\log S = \log B - \log (1 - Q) + m \log N \qquad (4)$$

Constants for the Exponential Equations for Repeated Stress.—As our experimental data for repeated stress tests are very few, values of constants for formulas should be regarded as tentative, and the stresses allowed in practice should be very low. The repeated stress test most often made is of a rotating shaft under a bending load; this test causes complete reversal of bending stress. Fig. 110 shows, in diagram, testing machines for reversed bending stress. The results of a large number of such tests of specimens with well-finished surface and without sharp corners at points of high stress are fairly well expressed by the formula:

$$S = \frac{BN^{-0.125}}{1 - Q}$$

or

$$\log S = \log B - \log (1 - Q) - 0.125 \log N \qquad (5)$$

in which B is a constant which must be determined experimentally for various metals. Some values of B obtained from experiments are given in Table 3. Poor surface finish, internal cracks or flakes, and deep scratches or tool marks may be expected to have the effect of numerically increasing the exponent of M above the value 0.125.[1]

[1] See footnote, page 49, for suggested modification of formulas for low stresses in structures whose failure does not involve danger to life.

TABLE 3.—VALUES OF THE CONSTANT B IN THE EXPONENTIAL FORMULA FOR REPEATED STRESS

$$S = \frac{BN^{-0.125}}{1 - Q} \text{ or } \log S = \log B - 0.125 \log N - \log (1 - Q)^1$$

This equation gives rather conservative values for S for members with shop-polished surface, and with all corners at points of high stress generously filleted. The values are based on the results of tests from various laboratories.

Material	B	Log B
Structural steel and soft machinery steel	250,000	5.39794
Wrought iron	250,000	5.39794
Steel 0.45 per cent. carbon	350,000	5.54407
Cold-rolled steel shafting	400,000	5.60206
Tempered spring steel	400,000 to 800,000	5.60206 to 5.90309
Hard-steel wire	600,000	5.77815
Gray cast iron	100,000	5.00000
Cast aluminum	80,000	4.90309
Hard-drawn copper	140,000	5.14613

For tests involving repetitions of direct tension or direct compression we have even less data than for reversed bending tests. Such data as we have indicate that the value of m in equations (4) and (5) is numerically slightly larger than that given by repeated bending tests. However, from the scanty data available it would seem that for members of structures or machines subjected to repetition of direct tension or direct compression equation (5) with the constants given in Table 3 furnishes a fairly safe guide.

[1] In the formula given S is the unit stress (lb. per sq. in.), N is the number of repetitions of stress necessary to cause failure, and Q is the ratio of the minimum stress applied to the maximum stress (for a stress varying from zero to a maximum, $Q = 0$; for a completely reversed stress, $Q = -1.0$).

This equation gives results for unit stress lower than that given in some tests in which N had a value greater than 1,000,000. The exponential formula seems to err somewhat on the side of safety for a large number of repetitions of stress. On page 49 in a footnote is given a suggested "probability factor" which may be used in connection with values of S obtained by the above equations. It is recommended that for structural parts or machine members whose failure would endanger life that the exponential equation be used unmodified by any probability factor.

In using the exponential equations for repeated stress it must always be borne in mind that under no consideration may the safe *static* stress be exceeded. The safe static stress is a criterion independent of the strength under repeated stress. As an illustration suppose that N be taken as less than 100 for structural steel, and that Q be taken as 0.1, the application of equation (5) would give a value of S higher than the ultimate static strength of the material. This would mean that for the conditions given static strength would govern rather than strength under repeated stress.

Diagrams for the Exponential Equations for Repeated Stress.—For solving the exponential equation (5) above, the diagram shown in Fig. 22 may be used. The manner of using the diagram is as follows:

Enter the diagram at the lower edge with the desired value of N as abscissa; pass verticaly to the diagonal line for the value of B for the given material (if the exact value of B for the material is not plotted the location of its line can be judged by interpolation with a sufficient degree of accuracy); then pass horizontally to the diagnoal line for the value of Q corresponding to the given range of stress; then vertically to the upper edge of the diagram where the value of S for failure under repeated stress may be read from the scale.

Wrought Iron versus Steel.—In general, the resistance of a material to repeated stress is high or low as its proportional limit is high or low, though there seem to be exceptions to this rule, due largely to the greater sensitiveness of special alloys to slight defects in heat-treating. Wrought iron has a lower proportional limit than does structural steel, and the resistance to repeated stress is, in general, less for wrought iron than for steel. However, the uniformity and reliability of wrought iron makes it superior to some or the cheaper grades of steel—for example steel which is marked as "tank steel," for which there are no standard specifications, and which is very variable in quality.

Effect of Rapidity of Repetition of Stress.—A certain amount of time is required for any member of a machine or structure to assume the deformation corresponding to any given load, and if repetitions of load follow each other at intervals shorter than this time, the deformation in the

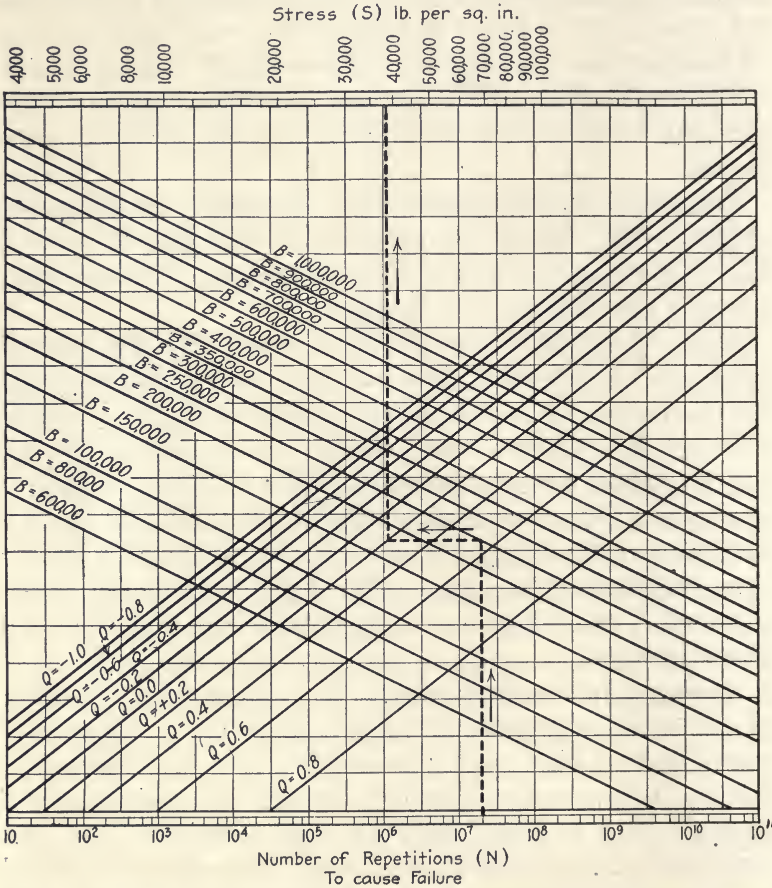


FIG. 22.—Diagran for solving the exponential equation for repeated stress.

$$S = \frac{BN^{-0.125}}{1 - Q}$$

member, the stress set up, and the number of repetitions it will withstand may be appreciably affected. A few recent British tests of material under repeated stress seem to indicate that for small members there is no appreciable effect produced by varying the rapidity of repetition of stress below about 2,000 repetitions per minute.

Effect of Rest on Resistance to Repeated Stress.—If metal is stressed *beyond the yield point* so that plastic action is set up, its strength and its elastic action are improved under subsequent stress, if the material is allowed to rest (see page 36). Recent experiments by British investigators and by Mr. W. J. Putnam of the University of Illinois seem to indicate that, for steel and iron at least, any effect of rest on the resistance to repeated stress is doubtful for unit stresses below the yield point of the material.

Effect of Sudden Change of Outline of Member.—Every sharp corner in a piece subjected to repeated stress facilitates the formation of micro-flaws in the piece. Results of repeated stress tests made by Stanton and Bairstow at the British National Physical Laboratory on test pieces

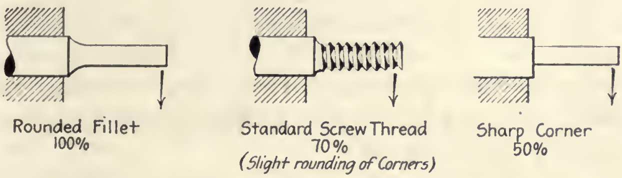


FIG. 23.—Effect of sharp corners on strength under repeated stress.

of varying shape gave the following relative values for strength under repeated stress for the shapes tested:

Rounded fillet	100
Standard screw thread	70
Sharp corner	50

Fig. 23 shows the shapes tested: the importance of avoiding sharp corners where local stresses of great intensity are set up is very great for members subjected to repeated stress on account of the danger of minute cracks forming and spreading.

Effect of Surface Finish.—Rough surface finish of a part subjected to repeated stress affords opportunity for minute cracks to start at the bottom of scratches, tool marks, or irregularities due to scale. Rough surface finish may reduce the stress causing failure under a large number of repetitions by as much as 30 per cent.

Effect of Internal Flaws in Structure.—Internal flaws also seem to reduce the resisting power of metals for repeated stress. No definite quantitative statement can be made for this reduction, but metal showing flakes and other irregularities in fracture should be looked on with suspicion if intended for use in members subjected to millions of repetitions of high stress.

Service Expected from Various Machine and Structural Parts.—We do not know certainly whether any material can resist an infinite number of repetitions of any stress however small. The safest view for an engineer to take seems to be that under repeated stress materials of construction have a limited "life." The exponential equation for resistance to repeated stress gives results in accordance with this view. If this view is held the number of repetitions which a member is required to withstand in normal service becomes of importance. The following list gives the number of repetitions for various structural and machine members. The list is intended to be suggestive rather than to serve as an exact guide.

The chord members of a railway bridge carrying 100 trains per day for a period of 50 years would sustain about 1,826,000 repetitions of stress. The stress would vary from the dead-load stress to a live-load averaging somewhat below that caused by the passage of the heaviest locomotives.

The floor beams in an elevated railway structure during a period of service of forty years are subjected to about 40,000,000 repetitions of stress; the variation is mainly from zero to a maximum.

A railroad rail over which 250,000,000 tons of traffic passes would sustain something like 500,000 repetitions of locomotive-wheel loads, the stress being slightly more severe than a repetition from zero to a maximum. The rail would have to stand in addition to the locomotive-wheel loads something like 15,000,000 repetitions of stress caused by car-wheel loads. The stresses set up by car-wheel loads would be about half as great as the stresses set up by the locomotive-wheel load.

A mine-hoist rope bent over three sheave wheels and operating a hoist 100 times a day, in a term of service of 5 years would sustain

550,000 repetitions of stress. If the sheave wheels are so placed that they reverse the direction of the bending of the rope they would nearly cause a complete reversal of stress; if bending takes place in one direction only the range of stress is from nearly zero to a maximum.

The piston rod and the connecting rod of a steam engine running at 300 r.p.m. for 10 hr. per day, 300 days per year for 10 years sustains 540,000,000 repetitions of stress, and the range of stress involves almost complete reversal.

A band saw in hard service for 2 months sustains about 10,000,000 repetitions of stress varying from nearly zero to a maximum.

A line shaft running at 250 r.p.m. for 10 hr. a day, 300 days per year, sustains during a service of 20 years 900,000,000 repetitions of bending stress due to force transmitted by belts, gears, and driving chains. The stress is completely reversed. It should be noted that for the line shaft the *torsional* stress is not repeated nearly so often as is the bending stress.

The shaft of a horizontal steam turbine running at 3,000 r.p.m. for 24 hr. per day, 365 days in a year during 10 years' service sustains 15,768,000,000 reversals of bending stress caused by the weight of rotating parts and the tangential force of the inrushing steam.

The crankshaft of an automobile engine is subjected to about 120,000,000 cycles of stress by the time the car has run 50,000 miles, and the stress is nearly complete reversal.

The crankshaft of an airplane engine in 150 hours of actual flying is subjected to about 18,000,000 cycles of stress, the stress being almost completely reversed. An airplane engine runs at nearly full power all the time, and this makes the reversals of stress especially destructive.

It should be noted that other factors than breakdown of the material by repeated stress tend to cause parts of machines and structures to have a limited "life." Wear caused by friction of rubbing parts is a very common cause limiting the "life" of a machine part. An illustration of this action is furnished by railroad rails in which the head usually wears out under the action of car and locomotive wheels before the rail is in danger of failure by repeated stress.

The foregoing discussion concerns itself with stresses which by their repeated application cause failure. Safe working stresses for members subjected to repeated stress are discussed in Chapter IV.

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CHAPTER IV

WORKING STRESS; FACTOR OF SAFETY; SELECTION OF MATERIALS

Working Stress.—In the study of mechanics of materials *stress* is considered as an internal force in a body which resists external forces acting on the body. In dealing with members of structures and machines it is needful to hold this in view, and to consider also the destructive effect of stress, and the accompanying strain, on the materials used. Two questions must be answered: (1) What is the maximum unit stress set up in the body? This is a question to be answered by mathematical analysis. (2) Does this unit stress exceed the safe stress for the material used? This question demands for its answer a knowledge of the physical properties of materials.

In considering the safety under load of a structure or a machine, several viewpoints are possible. The designer wishes to know how large the members must be to carry the given load; the purchaser wishes to know how great a load can be safely carried by the machine or the structure; the inspector wishes to know how great stresses are set up by the loads actually imposed on the structure or the machine. All these viewpoints involve a consideration of the stress set up by the working load, that is, of the working stress. A *safe working stress* for the material in a structure or a machine may be defined as a unit stress (measured in pounds per square inch) which under the conditions of operation or use will not cause structural damage.

The maximum safe working stress for any material is always less, much less, than the ultimate strength of the material (as determined by tests of sample test specimens). Four general reasons may be given for this fact:

1. A structure or machine would not give satisfactory service if it were on the point of failure. Nearly all materials show marked distortion before failure, and the stiffness is greatly reduced.

2. Complete information as to the properties of the material in any actual machine or structure is never available. Sometimes the process of manufacture of the material is not known (for example, it may not be known whether steel is Bessemer steel or open-hearth steel; whether concrete is hand-mixed or machine-mixed). The thoroughness of testing and of inspection of material varies widely for different classes of work. If the material is a part of a large shipment the inspection and testing may have been very thorough; if the shipment was a small one there may have been no inspection at all. The process of fabrication of the material may have weakened it, as is the case with steel plates or shapes in which holes have been punched for rivets, or which have been bent or hammered into position without being heated. The material may suffer deterioration as time elapses; for example, steel exposed to moist air or to smoke corrodes unless kept thoroughly covered with a coat of paint; concrete may be weakened by electrolysis from stray currents from street-car power circuits; wood decays.

3. The magnitude of the loads actually applied to a machine or a structure, and the magnitude of the stresses set up are never known exactly. The loading actually placed on the floor of a building or on the roadway of a bridge, or the actual working load on a machine will not, in general, be exactly that assumed in the design. The fitting of members to each other is never perfectly done, and the distribution of stress among members is not infrequently markedly different from that assumed in the design. For example, for a group of eyebars making up a bridge chord, the load is generally assumed to be equally distributed among them, actual measurements of strain sometimes show considerable differences between the loads carried by different eyebars of the group. The uncertainty

of distribution of stress between members is especially marked in "statically indeterminate" structures, such as fixed-ended beams, trusses with "redundant" members, and the like.

The science of the mechanics of materials is not yet completely developed. The laws of stress in many common structural members are not yet fully known; for example, the equations commonly used in designing columns are still largely of an empirical nature, different methods of computing stresses in curved beams or in thick cylinders yield varying results.

Different kinds of loading produce varying degrees of structural distress. A load repeated millions of times is far more disastrous than is a steady load, and to some materials (notably wood) a long-continued load is more destructive than is one of short duration. The damage caused by shock incident to the operation of machines very often can not be computed with any degree of exactness.

4. Any machine or structure is liable to be subjected to an accidental or a temporary overload, and some margin of safety should be left to provide for this contingency. A good illustration of such overloads is furnished by hoisting chains and ropes, which frequently are subjected to excessive load on account of the slipping of hooks and hitches.

Consequence of Failure of Material.—In determining the maximum safe working stress for any machine member or structural part, the consequences of failure should be taken into consideration. If failure of the piece endangers human life, the allowable working stress is to be taken less than for a similar piece whose failure involves merely material damage. If the failure of a particular piece will not cause complete collapse of the structure, and if it can be readily replaced, a relatively high working stress may be allowed.

Certain types of machine and structural members do not normally carry any great amount of stress in service, but are provided for the purpose of insuring the machine or structure against sudden, destructive collapse if the main members fail. Spiral-steel reinforcement in concrete columns furnishes an excellent illustration of this "insurance" under a load. If a non-reinforced concrete column is loaded to the ultimate, a shattering collapse takes place, while if the column is reinforced by a spiral of steel the same load causes a large distortion, but the failure is a gradual one instead of sudden, complete collapse.

Factor of Safety.—A method which has been widely employed for determining the maximum allowable working stress for a material consists in dividing the ultimate strength of the material (as determined by laboratory tests of specimens) by a "factor of safety." Values of this factor in common use vary all the way from 2.5 for steel under steady load to 15 or 20 for timber under repeated load or shock. The use of this term "factor of safety" not infrequently gives the designer or the purchaser a false sense of security. If a structure is designed with a factor of safety of 5 it is by no means certain that it will stand up under five times the working load. The factor of safety is really more of a factor of *uncertainty* than a factor of safety.

Standard Allowable Working Stresses.—In the drafting room of a machine-building plant or of a large structural firm allowable working stresses for the common materials become fixed by experience. For example, it has become very general practice to allow under steady load a working tensile stress of 16,000 lb. per square inch for structural steel rolled into rods, plates, or beams. In building construction, standardization of working stresses has proceeded so far that in the building laws of most large cities the maximum allowable working stresses for the common structural materials are definitely fixed. Table 4 gives a summarized statement of some such allowable stresses. Technical committees composed of members of the leading engineering societies have also formulated codes giving allowable stresses for some structural materials.

Table 4.—Working Stresses for Structural Materials

The values given in this table are based on a comparison of the values given in the building ordinances of New York, Chicago, Philadelphia and Boston.

Material	Kind of stress	Allowable stress, lb. per sq. in.
Ordinary rubble masonry:		
Portland-cement mortar	Compression (bearing)	100
Lime mortar	Compression (bearing)	60
Coursed rubble masonry;		
Portland-cement mortar	Compression (bearing)	200
Lime mortar	Compression (bearing)	120
Squared masonry, Portland-cement mortar:		
Granite	Compression (bearing)	600
Limestone or sandstone	Compression (bearing)	400
Portland-cement concrete:		
1 cement; 6 aggregate, machine-mixed	Compression (bearing)	400
1 cement; 6 aggregate, hand-mixed	Compression (bearing)	350
1 cement; 9 aggregate, machine-mixed	Compression (bearing)	300
1 cement; 9 aggregate, hand-mixed	Compression (bearing)	250
Brick masonry:		
Paving brick, Portland-cement mortar	Compression (bearing)	350
Pressed brick, Portland-cement mortar	Compression (bearing)	250
Common brick, lime mortar	Compression (bearing)	100
Common brick, Portland-cement mortar	Compression (bearing)	175
Wood:		
Yellow pine	Tension fibers in beams	1,100
Yellow pine	Compression along grain	1,000
Yellow pine	Compression across grain	250
Yellow pine	Shear along grain	100
Douglas fir	Tension fibers in beams	1,300
Douglas fir	Compression along grain	1,100
Douglas fir	Compression across grain	250
Douglas fir	Shear along grain	115
Norway pine, white pine, spruce	Tension fibers in beams	900
Norway pine, white pine, spruce	Compression along grain	750
Norway pine, white pine, spruce	Compression across grain	250
Norway pine, white pine, spruce	Shear along grain	60
Hemlock	Tension fibers in beams	750
Hemlock	Compression along grain	500
Hemlock	Compression across grain	150
Hemlock	Shear, along grain	50
Structural steel	Tension	16,000
Structural steel	Compression	15,000
Structural steel	Shear	10,000
Rivet steel	Shear	9,000
Steel of rivets and pins	Bearing	25,000
Steel of rivets and pins	Extreme stress in bending	25,000
Steel castings	Tension	16,000
Steel castings	Compression	15,000
Wrought iron	Tension	12,000
Wrought iron	Compression	11,000
Wrought iron	Shear	6,000
Cast iron	Tension in beams	3,000
Cast iron	Compression	13,000
Cast iron	Shear	3,000

In machine building, standardization of working stresses is more difficult than in structural work; the variety of materials used is greater, and the conditions of service less certain. In a large manufacturing establishment certain standard allowable stresses are soon developed for its particular line of work. The tables of allowable stresses and of working formulas given in the various handbooks for machine and structural designers give valuable information as to allowable stresses, but such tables must not be used blindly without any consideration of their limitations. The study of the proportions of and probable stresses in successful machines is often the best guide for the machine designer or the purchaser in cases where practice has not yet standardized allowable working stresses.

Working Stresses for Material Subjected to Repeated Loading.—For structural or machine parts subjected to repeated loading the working stresses allowed must evidently be less than the unit stresses given by equation (1) or equation (5) Chapter III, which are stresses for failure.

In choosing working stresses for members subjected to repeated stress it should be remembered that a small reduction in stress very greatly increases the number of repetitions of stress which the material can withstand. For metals it seems from test results that a decrease of 9 per cent. in stress nearly doubles the "life" of the material. Since the endurance of a material is so sensitive to changes in the magnitude of stress, it seems more logical for repeated-stress problems to apply the "factor of safety" used to the number of repetitions rather than to the stress, computing the probable stress at failure for a number of repetitions many times greater than the number which the member is expected to withstand in service. If the factor of safety is applied to N, then it should be very much larger than the factors commonly applied to stresses in static-stress problems. The test data for repeated stress is very much less extensive than the test data for static strength, and the test results show wide variation in N for small change in S; and while the equations given yield results a little lower than the average results of tests, yet for some few tests failure occurred at lower values of N than the equations would indicate. To guard against this variation, and against the large variation in N which would be caused by slight variations in the stress actually applied to the material, a factor of safety of 100 would not seem too large, if applied to the number of repetitions of stress.

In problems involving static strength it is customary to apply the factor of safety to the stress which will cause failure. If this practice is followed for repeated-stress problems (remembering always that under any conditions the stress allowed must not be greater than the safe static working stress for the material) a factor of safety of 1.8 would correspond to an increase of endurance of something over 100 times.

Materials for Various Classes of Machines or Structures.—Some illustrations of the selection of materials for machine and structural parts will be given in this section. The selections noted are to be regarded as typical rather than as furnishing anything like a complete list.

Bridges.—The materials usually available for bridge work are timber, concrete, steel, and stone. For short-span bridges timber usually is the cheapest, the lightest and the least durable material. For temporary structures, military bridges and bridges on roads to logging camps or contractors' camps, timber is the material usually used. For permanent bridges timber is now rarely used. If the bridge is long-span bridge, steel is in nearly all cases the best material to use, since in a long-span bridge the dead weight of the material furnishes a large part of the total load, and for a given strength a steel structure is lighter than one of concrete or stone. For very long spans nickel steel or other special steel of high strength is frequently used. For short-span bridges both steel and concrete are used. The relative cost and the degree of permanence of the work varies with the location, the surroundings, and the character of the traffic. A well-made reinforced-concrete bridge suffers less deterioration and costs less for upkeep than does a steel bridge, and is subject to less vibration under heavy loads. For the floor of the bridge, timber and reinforced concrete are used; the use of reinforced concrete is becoming more and more common. A combination of bridge materials frequently used is steel for the main trusses or beams, and for floor beams; and reinforced concrete for the floor of the bridge. Stone masonry bridges are built for locations involving short spans, where appearance and permanence are factors overbalancing first cost.

Buildings.—Timber is used for temporary construction, and for buildings for which low cost is the prime consideration. For the framework of very high buildings steel is the material nearly always used. For the beams of factories, warehouses, and public buildings steel, reinforced concrete, and timber are used. For the columns the above materials are used, also for short columns, terra-cotta, brick, and cast iron. For walls brick, concrete blocks and stone masonry are used and for light walls which do not have to carry much stress timber with plaster on laths, terra-cotta and gypsum are used. As in the case of bridges, stone masonry is used where fine appearance and permanence overbalance considerations of first cost.

Shafting.—Strength, stiffness, and compactness are very necessary properties in shafting, and steel is the material in almost universal use. Cold-rolled steel is very widely used on account of the ease and cheapness with which it can be rolled true to shape and to size. For shafting to be used in machine tools or other machines in which accuracy of motion is of prime importance, cold-rolled shafting is too liable to "spring" out of shape if machined, on account of the heavy internal stresses set up in it by the cold-rolling process. For such machines turned steel shafting is used. For very hard service, automobile shafts, screws for screw presses, etc., special alloy steels of high strength are used. It should be remembered, however, that if the working stresses are low, a shaft of ordinary low-carbon steel is as *stiff* as one of high-carbon steel or of special alloy steel (see page 38).

Railway Equipment.—Couplers, yokes (for holding the couplers) and bolsters (for carrying the bearings) are usually made from steel castings. The complicated shape required makes it expensive to use pieces built up of rolled steel, and under the repeated pounding of railroad service every joint in a built-up member is a source of possible weakness. The recent improvements in the process of casting and heat-treating steel places this material in a position of first importance for railway appliances. Locomotive frames are sometimes steel castings and sometimes forgings. Brake beams for locomotives and cars are usually built up from rolled shapes, and rods. For railway service toughness is an important quality for materials on account of the frequent heavy shocks to which equipment is subjected.

Car Wheels.—The requirements for the material in the different parts of a railway car wheel are diverse. The tire must be hard to resist wear; the hub and plate (or spokes) should not be brittle on account of the shock which must be withstood. Two solutions for these diverse requirements are common: (1) the wheel is made of cast iron, the hub and plate being soft gray iron, while the rim is "chilled" and consequently hard; and (2) the wheel is made of rolled steel of a grade which combines considerable hardness with a fair degree of ductility. Both cast-iron car wheels and steel car wheels have their advocates, and both are in extensive use.

Machine Frames.—For machine frames in which stiffness and steadiness against vibration are the prime requisites and in which weight is not objectionable (for example, the frame of a steam engine or of a machine tool) cast iron is the material usually used on account of its low cost. For machine frames carrying heavy stresses (for example, punch and shear frames) cast iron is sometimes used, frequently the special cast iron known as "semi-steel" is used, and sometimes steel castings are used. The use of steel castings for heavily stressed frames is constantly increasing.

Engine, Pump, and Hydraulic-press Cylinders.—For cylinders carrying low pressures—engine cylinders, air-compressor cylinders, and low-pressure pump cylinders—cast iron is the material commonly used. For such cylinders the thickness is determined not by considerations of strength but by considerations of foundry practice—it is not possible to cast a very thin cylinder. Cast iron makes a much better bearing metal for the rubbing of the piston than does steel. For high-pressure cylinders, for example, cylinders for hydraulic presses, steel castings or steel forgings are used because of their ability to resist the high stresses which are set up. For such cylinders the speed of rubbing of piston over cylinder is usually low and the effect of the high friction of steel on steel is not so important. Where there is great danger of corrosion, brass or bronze linings are frequently used with steel cylinders, and the small cylinders of high-pressure hydraulic pumps are frequently made of bronze castings. Bronze is expensive, but it combines strength, good bearing qualities and resistance to corrosion.

Bearings.—The material for bearings usually is chosen for it smooth-wearing qualities rather than for its strength, though for bearings in machines subjected to heavy static loads, or to severe impact, bearings must be made of material having a good degree of compressive strength. Steel makes a poor bearing material for steel shafts or slides. Steel rubbing on steel develops a rough, torn surface which soon becomes hot. Cast iron makes a much better bearing metal for steel shafts than does steel, though its brittleness limits its use to bearings not subjected to shock. Bronze is an excellent bearing metal especially for heavy loads. Numerous "soft" bearing alloys are in use. Prominent among these is Babbitt metal, an alloy of antimony, tin, and copper. Other alloys contain varying proportions of antimony, tin, and lead. These soft bearing metals are widely used for bearings which run under light steady pressure. These soft alloys can be readily melted and cast in place round a shaft, and in case the metal becomes accidentally overheated and melted out it can be readily replaced. The soft bearing metals are not suitable for use under heavy pressures, which cause them to "flow."

Selected References for Further Study

Any detailed list of references for allowable stresses in structures and machines would cover several pages of this book. In general, such references would include: Pocket Books and Hand Books for Civil, Mechanical and Architectural Engineers; Building Ordinances of Cities; Handbooks of Steel Manufacturing Companies; and Reports of Committees of Engineering Societies.

CHAPTER V

THE MANUFACTURE OF PIG IRON

Occurrence of Iron in Nature.—Iron is found in nature in the form of vast deposits of iron ores, most of which are *iron oxide.* It is possible to produce nearly pure iron directly from the ore by the removal of oxygen from iron oxide[1] (this process is called *reduction* of the ore); it has been found more economical, however, to first reduce the ore to an impure iron containing a high percentage of carbon. This reduction takes place in a tall stack known as a blast furnace. The impure iron produced in a blast furnace is known as *pig iron;* and this pig iron may be further refined by means of an open-hearth furnace, a Bessemer converter, a puddling furnace, or an electric furnace. Descriptions of these refining processes are given in succeeding chapters.

Ores of Iron.—The principal ore of iron is hematite (ferric oxide Fe_2O_3); other ores are magnetite (Fe_3O_4) and siderite or spathic ore ($FeCO_3$). The value of an iron ore is determined largely by the percentage of iron it contains. Ores carrying 50 per cent. or more of iron are known as *high-grade ores.* Ores carrying less than 50 per cent. of iron are called *low-grade ores.* The value of an ore is also affected by the nature of the impurities it carries. Common impurities present in iron ore are sulphur (as sulphides), phosphorus (as phosphates) silica and earthy matter. Sulphur and phosphorus are especially undesirable elements in iron ore.

Fig. 24 shows the location of the principal iron ore deposits in the United States. About 85 per cent. of the ore

[1] In earlier times direct reduction of ore to nearly pure iron was the common method used in producing iron, and today there is some promise of commercial usefulness for a process producing pure iron direct from iron ore by means of the electric furnace (see page 107). The direct production of iron from ore is, however, mainly of historical interest.

mined in this country comes from the Lake Superior region and is red hematite. The ore of the Alabama region is of

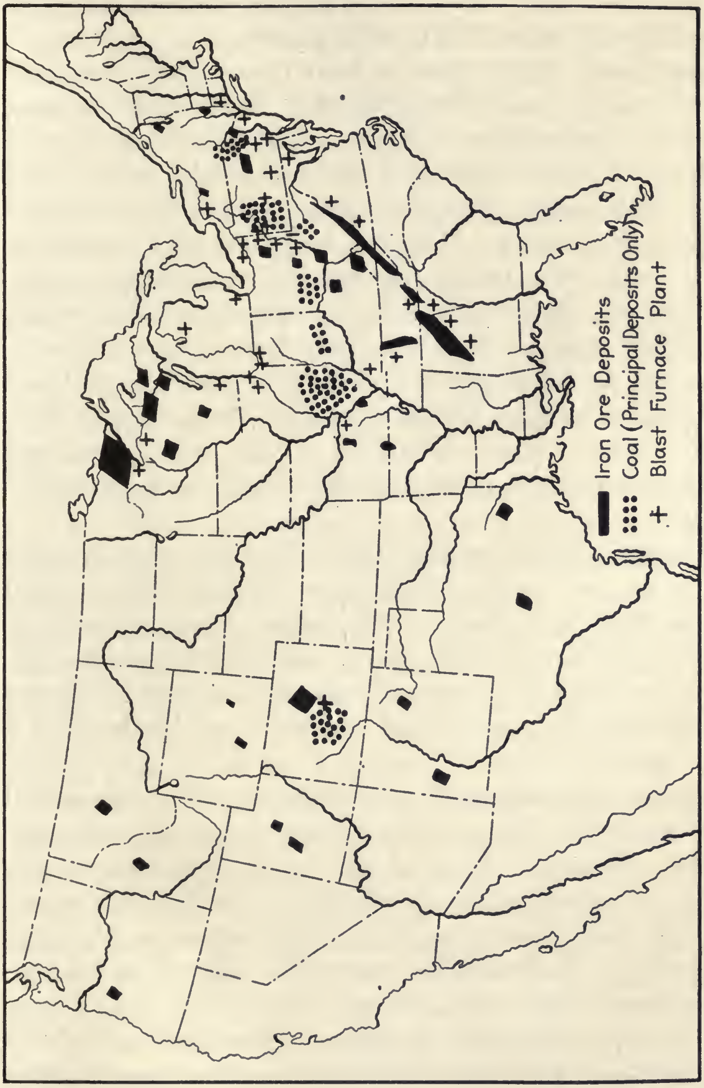


FIG. 24.—Iron ore deposits, coal deposits and blast furnaces in the United States.

lower grade than that from the Lake Superior region, but the Alabama region is the next in importance to the Lake Superior region in amount of production. The purest ores in the world are found in Sweden, and the pig iron and pure iron reduced from those ores is of the highest quality. The annual output of iron ore for the United States in normal times is about thirty million tons.

Mining and Preparation of Iron Ore.—Most American ores of iron lie near the surface of the ground, and are mined by open-surface mining. The red hematite ores, which are the most important, are soft earthy ores and are mined with steam shovels. Some harder ores require drilling and blasting. The red hematite ores require no special preparation before they are fed to the blast furnace for reduction. Other ores carrying more impurities require preliminary treatment. Ores in the form of iron carbonate are usually transformed to iron oxide by heating, and ores containing a high percentage of water are heated to drive off this water. Ores containing a high sulphur content are roasted at a temperature high enough to burn off the sulphur.

Reduction of Ore to Pig Iron.—Iron ore is, in general, iron oxide and to be changed to metallic iron it must be deoxidized or reduced. The reducing agent is carbon, which is also used as fuel, and in the reducing process the iron is produced in a molten condition, in which state it takes up carbon from the fuel, and the resulting product is highly carbonized iron.

Fuel for the Reduction of Iron Ore.—The carbon fuel for the reduction of iron ore is usually supplied in the form of *coke.* Formerly most of the coke produced in this country was produced by the distillation of bituminous coal in closed retorts known as "bee-hive" ovens, in which all the products of distillation except the coke were wasted. At the present time about 60 per cent. of the coke is produced in ovens designed to utilize or recover the products of distillation which include the hydrocarbon gases and the tar and ammonia products produced.

In some pig-iron producing plants anthracite coal is used as a fuel. In a few furnaces producing a very high grade of pig iron charcoal is used. Charcoal contains fewer contaminating ingredients than does coke, but is very expensive. Sulphur is an ingredient which is especially troublesome in coke.

Flux Used in Reducing Iron Ore.—In addition to ore and fuel it is necessary in the reduction of iron ore to provide some material which will unite with the impurities of the ore forming a fusible mixture. This material is called a *flux* and must itself be free from undesirable ingredients, especially sulphur and phosphorus, and since most of the impurities found in iron ore give an acid reaction in the reducing process, the flux should be strongly basic. Limestone is the flux generally used, and the combination formed of flux and impurities, known as *slag*, is fusible and lighter than the pig iron formed. The slag floats on top of the molten iron and this renders the separation of iron from slag easy.

The Blast Furnace.—The reduction of iron ore is carried out in a tall vertical stack lined with firebrick known as a *blast furnace*. Fig. 25 is a diagram of a blast furnace of dimensions common in American practice. The names of the principal parts are shown in Fig. 25 and the approximate dimensions can be determined from the scale at the left of the figure. Fig. 26 is from a photograph of a blast-furnace plant and shows the general arrangement, with the storage piles of ore and limestone.

The ore, the fuel, and the flux for the blast furnace are carried to the top by means of the inclined hoist or "skip" (see Figs. 25 and 26) and there are fed in alternate layers of fuel, ore, and flux into the furnace through the double bell and hopper arrangement which is so designed that at no time is the interior of the blast furnace in direct communication with the outside air. The ore, fuel, and flux are fed to the furnace in the approximate proportion for the whole charge of one-sixth flux, a little less than one-third fuel, and a little more than one-half ore. The combustion of the fuel takes place principally at the bottom of the furnace in a blast of air forced through nozzles or tuyeres under a pressure of about 15 lb. per square inch, and the

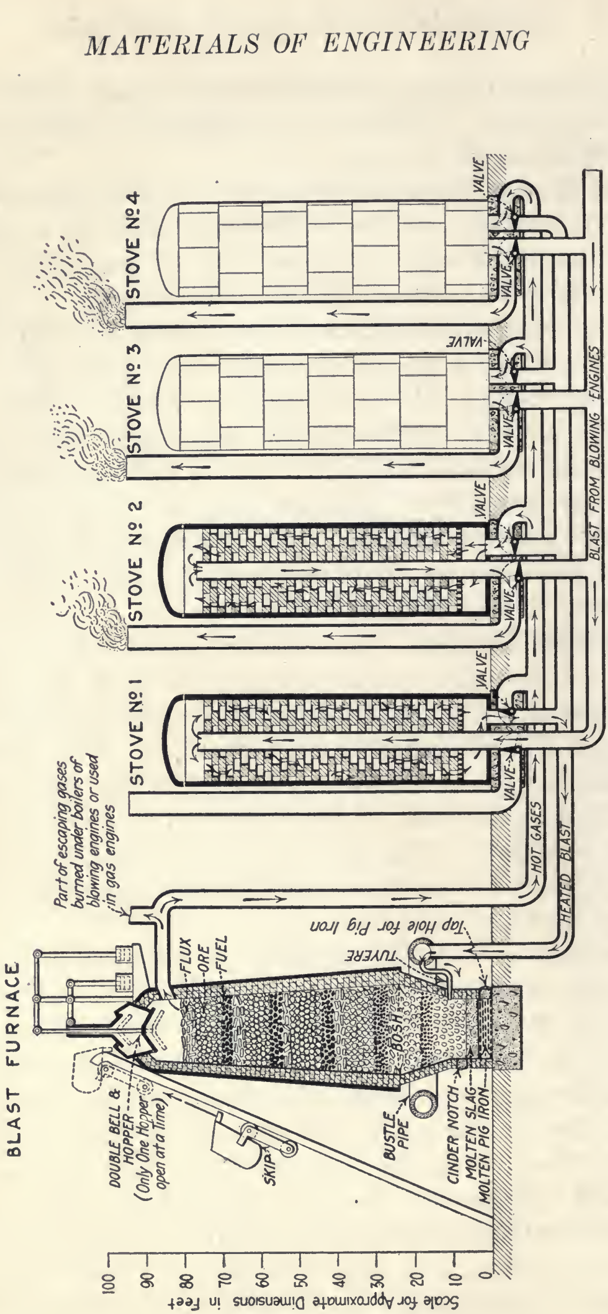
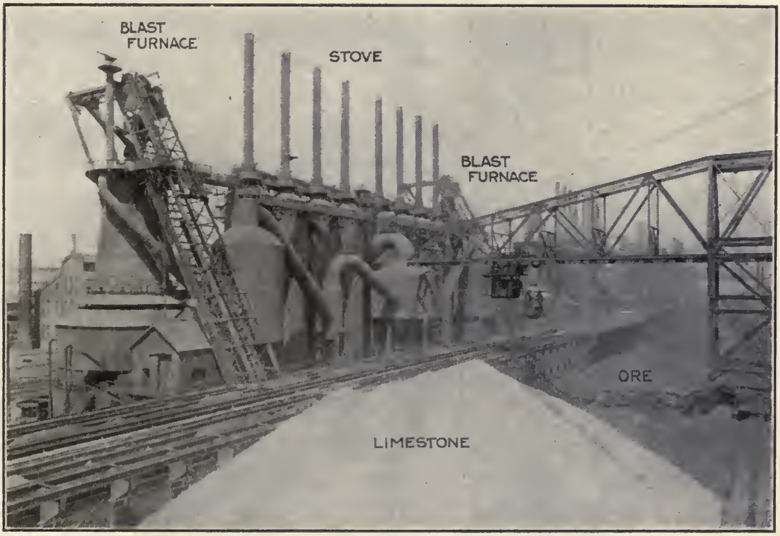


FIG. 25.—Diagram of a blast furnace.

carbon (coke) is changed to carbon monoxide. This carbon monoxide coming into contact with the hot ore reduces the ore to molten metallic iron which drips down to the hearth at the bottom of the furnace. The earthy impurities of the ore unite with the limestone and form a molten slag, which floats on top of the molten iron. At intervals the slag is drawn off by means of unplugging the cinder notch and the iron is drawn off through the tap hole in the hearth. The molten iron reduced from the ore as it drips



Courtesy of Illinois Steel Co.
FIG. 26.—General view of blast-furnace plant U. S. Steel Co., Gary, Indiana.

through layers of partially burned coke becomes saturated with carbon. Some of the carbon absorbed is chemically combined with the iron, and some is merely mechanically mixed with the iron in the form of crystals of graphite. The principal chemical changes and the temperatures attained are shown in Fig. 27. The chemical changes given above represent in a general way what happens in a blast furnace. The actual reactions are very complicated.

Preheating the Blast, Hot Stoves.—The blast of air blown through the tuyeres is furnished by means of large blowing engines. A great increase of economy of operation of the furnace is brought about if heated air is blown into the furnace. For heating the incoming air the heat of the exhaust gases of the blast furnace is utilized by means of a "hot-blast stove," shown in diagram in Fig. 25, and the utilization of heat which would otherwise be wasted is a

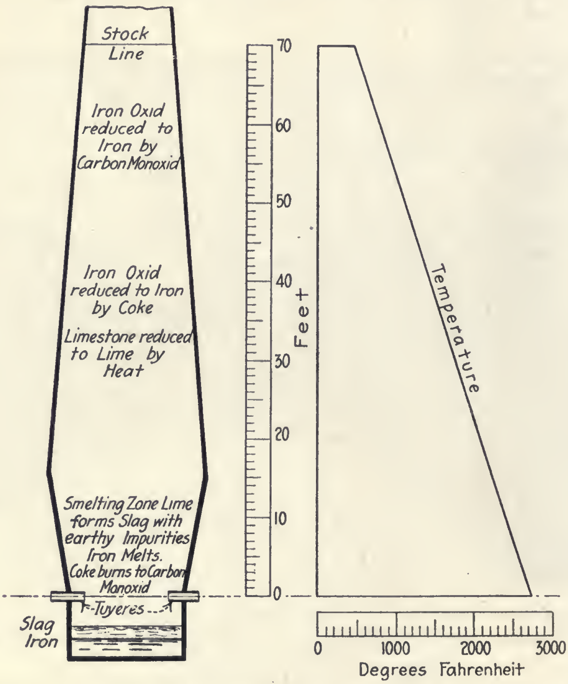


Fig. 27.—Principal reactions and temperatures in blast furnace.

source of great economy in the blast furnace, or, for that matter, in most metallurgical processes. Each stove is a steel shell lined with firebrick and filled with a checker-work of firebrick through which the hot gases from the blast furnace or cold air from outside may be passed. Four of these stoves are usually used with a single blast furnace. The hot gases from the furnace pass through three of these stoves (stoves 2, 3 and 4). The waste gases contain carbon monoxide, an inflammable gas, and this gas is burned as it passes through the stoves, and the brickwork inside the stove is heated to a high temperature. Meanwhile the outside air for the blast is being forced through the fourth stove (stove 1, Fig. 25) which has been previously heated by the escaping gases from the blast furnace, and this air is heated to a temperature of about 1,000°F. before being blown through the tuyeres. At intervals of about 20 min. the current of air is switched from one stove to another. The stoves are thus alternately heated for an hour by the blast-furnace gases and then used for 20 min. to heat the incoming air. The general method of utilizing the heat of exhaust gases to preheat the air for a furnace is called the "regenerative" process and is widely used in the production of metals. Usually there is more heat energy in the carbon monoxide of the blast furnace gases than is necessary to heat the blast, and the excess is used as fuel under the boilers for the blowing engines where these engines are steam engines, or is used directly in the blowing engines where these engines are gas engines, and in some cases there is still an excess of carbon monoxide which is utilized in driving gas engines which furnish power for general consumption.

In a blast furnace installation the escaping gases are led through dust catchers before being carried through the stoves or to gas engines. These dust catchers remove the solid particles carried along by the waste gas.

Production of Pig Iron.—The operation of a blast furnace is continuous. A blast furnace of the size shown in Fig. 25 is capable of producing about 500 tons of pig iron per day of 24 hr. To produce this amount of pig iron there must be fed into the furnace about 1,000 tons of ore, 500 tons of coke, and 300 tons of limestone. About 2,000 tons of air are blown through the furnace. Molten pig iron is drawn off about every 6 hr.

If the pig iron is to be used in steel-making, it is usually conveyed from the blast furnace in a molten condition to the steel plant. Special ladle cars are used for this purpose. If the pig iron is to be shipped to a steel plant at a distance or is to be used for making cast iron, it is cast into small pieces about 2 ft. long weighing about 100 lb. each. These are called "pigs." Two methods of casting pigs are used. The older method uses open molds in a sand bed directly in front of the blast furnace. The molten pig is led directly through the sand channels to the pig molds. This method is simple, but the heat produced on the casting floor makes the work of manipulation very exhausting, and considerable time elapses after a melt of iron is poured into the molds before it cools sufficiently to allow the removal of the pigs, and the preparation of the casting bed for another melt. Sand casting beds for pig iron are not much used today.

A more recent method of producing pigs of iron is to use casting machines. These consist of cast-iron molds lined with fireclay and arranged as buckets on an endless chain. These buckets are passed right side up in front of the blast furnace, and are filled with molten pig iron. The chain of molds is long enough so that when a mold reaches the end pulley over which the chain turns, the pig iron in that mold has solidified, and as the molds are turned upside down the pig is dumped into a car.

Utilization of Blast-furnace Slag.—The slag from the blast furnace is run off into slag cars or granulated by contact with a stream of water. Blast-furnace slag is sometimes utilized in making Portland cement, and in making mineral wool (a substance used for heat insulation or "lagging"). It is also sometimes used as an ingredient in paint or as ballast material for railway tracks.

In the blast furnace iron absorbs other impurities besides carbon. Sulphur and phosphorus are often absorbed from the fuel or from the flux, and these ingredients are very undesirable in iron and steel because they cause brittleness. (In iron castings in which brittleness is not objectionable, such as stove castings, phosphorus makes the molten cast iron very fluid and the castings produced very sharp and true to the form of the mold.) Pig iron is not used directly as a structural material. When remelted in a foundry cupola with scrap iron and cast into molds it is known as cast iron. The greatest use of pig iron is as the raw material for making steel.

Selected References for Further Study

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CHAPTER VI

THE MANUFACTURE OF WROUGHT IRON

Importance of Wrought Iron.—The methods in use for the refining of pig iron all include the removal of carbon from the pig iron by means of oxidation. The oldest method of refining pig iron is the puddling process which produces wrought iron.

Up to the latter part of the nineteenth century wrought iron was the most important of the iron and steel products, but the development of the Bessemer and of the open-hearth processes for refining pig iron into steel made wrought iron of secondary importance as a structural material. Wrought iron is, however, still used extensively for general blacksmithing work, on account of the ease of welding wrought iron as compared with steel; and for water and gas pipes on account of the judgment of many users that wrought iron rusts less easily than does steel (upon this question there exist sharp differences of opinion among metallurgists, see page 149). Wrought iron is also used for bolts and rods subjected to severe shock on account of the belief held by some engineers that wrought iron, on account of its "fibrous" nature, offers better resistance to shock than does steel (see page 38).

Definition of Wrought Iron.—Whether wrought iron shall be distinguished from steel by its low carbon content or by its method of manufacture is a much-debated question. The following definition as given by the American metallurgist Bradley Stoughton has been adopted for this book:

"Wrought iron is almost the same as the very low-carbon steels except that it is never produced by melting and casting in a mold but is always forged to the desired size and form. It usually contains less than 0.12 per cent. of carbon. Its chief distinction from the low-carbon steels is that it is made by a process which finishes it in a pasty, instead of a liquid form and leaves about 1 to 2 per cent. of slag mechanically disseminated through it."

The Puddling Process.—Wrought iron is produced by the removal of impurities from pig iron in a furnace known as a puddling furnace. A special pig iron known as forge pig is used. Forge pig contains a high percentage of silicon which aids in forming a layer of molten slag protecting the molten pig iron from oxidation by the air. A sectional diagram of a puddling furnace is shown in Fig. 28. The fuel usually used is soft coal (occasionally gas is used) and

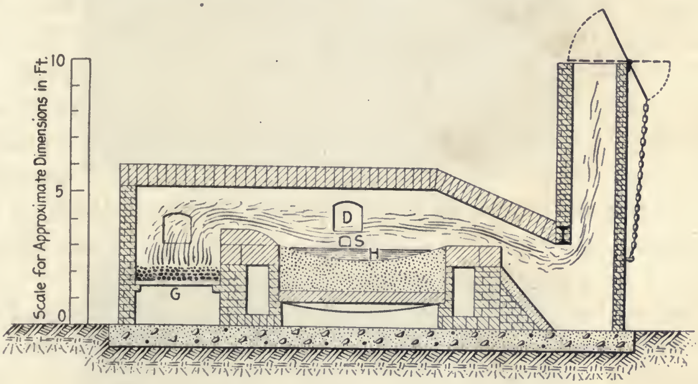

Fig. 28.—Diagram of puddling furnace.

the fire is built on the grate *G*; the flame passes over the fire bridge and is reflected by the roof of the furnace to the hearth, which is bedded or "fettled" with rich iron oxide which has a basic reaction, offsetting the acid properties of the silicon in the forge pig. A charge of about 500 lb. of forge pig is placed on the hearth and the draft to the chimney is opened wide so that the fire burns vigorously. In about half an hour the pig iron is melted. During this melting stage nearly all the silicon, manganese, and a considerable part of the sulphur and phosphorus present have been taken from the pig by uniting with the basic iron oxide to form a slag. It is necessary that the slag should be basic, else the phosphorus will return to the iron.

After the melting stage is complete the damper in the stack is closed and the temperature of the furnace reduced. There ensues a combination of the carbon of the pig with the oxygen of the iron oxide and carbon monoxide (CO) is formed. This stage of the puddling process is called the "boil," on account of the frothing and increase of volume of the molten charge in the furnace as the carbon monoxide bubbles through it. The charge rises in the furnace much as boiling molasses rises in a kettle, and this rising permits the removal of about half the slag, by allowing it to "boil over" the sill of the slag door *S* into a ladle called a "slag buggy" placed just outside the slag door. During the boil particles of pasty iron begin to separate from the boiling mixture of molten slag and molten pig iron, and by opening the chimney damper the temperature is gradually raised to preserve a proper degree of fluidity of the charge. The furnace operator, known as the "puddler," prevents these particles of iron from sticking to the bottom of the furnace by vigorously stirring ("rabbling") the charge with a long iron hoe through the door *D*.

After the boil has been in progress for about half an hour all the iron has separated in pasty masses from the surrounding slag and is said to "come to nature." The temperature of the furnace is reduced by closing the damper in the chimney, and the puddler and his assistant by means of a long rod gather the pasty particles of iron into "muck" balls weighing about 100 lb. apiece, and these balls (four or five for each heat) are removed one by one from the furnace (see Fig. 29). These balls contain a large amount of slag mixed with the iron. They are removed to a squeezer or a hammer where most of the liquid slag is squeezed out of the ball, much as water is squeezed out of a sponge. After squeezing, the balls are rolled into bars known as "muck bars;" these muck bars are cut and piled in crosswise layers, heated to a welding heat and rolled into "merchant" bars,—flats, rounds, squares, plate, or other shapes. This "merchant bar" is the wrought iron of commerce.

Characteristics of Wrought Iron.—The distinguishing characteristic of wrought iron is the presence of fibers of slag extending through the iron in the direction of rolling. Slag is never completely removed by the squeezing process.

Charging the puddling furnace.

Courtesy of Interstate Iron and Steel Co.

Preparing to draw the ball.

Fig. 29.—View in puddling-furnace plant. Interstate Iron and Steel Co., Chicago, Ill.

The characteristic slag fibers can usually be detected by etching a polished surface with acid. If the material is wrought iron the slag fibers cause the surface to turn black.

These slag fibers can be detected with certainty under the microscope (see Fig. 30). Small bars of wrought iron may sometimes be distinguished from bars of soft steel by allowing both to fall on a stone or on a concrete floor; the steel "rings" while the iron gives a dull thud. Another test is the "nick bend" test. A bar of the material is nicked with a sharp chisel and broken by bending. Wrought iron shows a fibrous fracture for such a test. A careful examination for the presence of slag is, however, the only certain means of distinguishing wrought iron from steel.

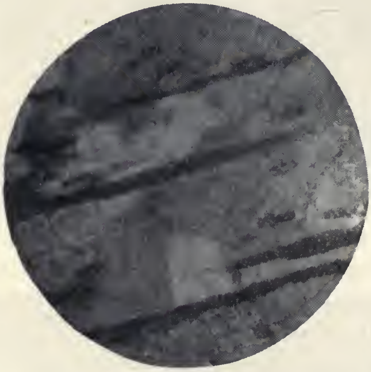

FIG. 30.—Longitudinal section of wrought iron showing slag "fiber." *Photomicrograph by E. O. Dixon and Jos. Simons.* Magnification 350 times.

Wrought iron is more costly than low-carbon Bessemer or open-hearth steel, and this leads to the occasional adulteration of wrought iron with a cheap grade of scrap steel. A mixture of bars of wrought iron and of scrap steel is piled together, heated to a welding temperature, rolled into "merchant bars" and sold as wrought iron. Of course, this mixture is not wrought iron, and it exhibits many of the properties of soft steel. This adulterated wrought iron should be distinguished from the "knobbled" wrought iron described in a succeeding paragraph.

Chemical Composition of Wrought Iron.—The chemical composition of different grades of wrought iron commonly found on the market is given, approximately, by the following table, the values being expressed in per cent.

	Carbon	Phosphorus	Sulphur	Silicon	Manganese	Slag
Common wrought iron..	0.08	0.25	0.05	0.21	0.10	3.00
"Best" wrought iron....	0.06	0.15	0.03	0.20	0.06	2.80
Swedish wrought iron...	0.05	0.055	0.007	0.015	0.006	0.61

Charcoal Iron.—While a mixture of steel scrap and wrought iron merely welded together is a very inferior product, an excellent grade of wrought iron is made from steel scrap by melting or "sinking" in a small puddling or "knobbling" furnace in which charcoal is used as a fuel. A highly basic slag is used as in a large puddling furnace, and the entire charge of steel scrap is transformed into true wrought iron. The removal of impurities is very nearly complete. Charcoal iron is used for some electrical apparatus, and for boiler tubes where a high degree of purity seems to give to the iron a power of resistance to corrosion.

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For references on the relative durability of wrought iron and steel see list at the end of Chap. XIII.

CHAPTER VII

THE MANUFACTURE OF OPEN-HEARTH STEEL

General Features.—In the refining of pig iron into *steel* complete fusion takes place. The steel is drawn off from the refining furnace in a molten state instead of being removed in pasty balls as is the case with wrought iron. The process most extensively used in making steel is the *open-hearth process,* sometimes called the Siemens-Martin process. In this process pig iron, steel scrap, and iron ore are placed on a shallow hearth, and are subjected to intense heat from a flame of gas or liquid fuel. The pig iron, steel scrap, and iron ore constitute the *charge,* and under the intense heat the charge melts, and a slag is formed which floats on top of the melted charge. This slag contains the iron ore (iron oxide), and the carbon and other impurities of the pig iron are oxidized and go into the slag. Direct contact of air with the molten pig iron would oxidize not only the impurities, but a considerable amount of iron as well. The oxygen in the slag is in the form of iron oxide, which will not attack iron, but will oxidize the impurities in the pig iron. Air, which is fed to the furnace with the fuel, oxidizes the slag, and the slag not only oxidizes the impurities in the pig iron, but also serves as a protective blanket against direct action of the air on the molten pig iron. The iron oxide in the slag serves as a carrier of oxygen from the air to the impurities in the pig iron.

Basic and Acid-steel Processes.—In most iron ores phosphorus is present in small quantities. Phosphorus is a very undesirable ingredient in steel, because it makes steel brittle, and if ores containing considerable phosphorus are to be used—and the supply of low-phosphorus ores is rapidly diminishing—this phosphorus must be removed in the process for refining pig iron into steel. Phosphorus oxidizes readily under the action of the slag in the open-hearth process, but if the slag is *acid,* the phosphorus is found combined with the steel again as the steel is drawn out of the furnace. If, however, the slag is *basic,* the phosphorus combines with the slag, and the steel is freed from its objectionable presence.

In the steel-making process in widest use in the United States calcined limestone is added to the charge fed into the furnace. This renders the reaction of the molten charge *basic,* and the phosphorus in the pig iron and in the ore of the charge is removed from the steel and carried into the slag, where it remains. In the *acid* process, which is less used, no limestone is added to the charge, the reaction of the molten charge is acid, and the phosphorus of the pig remains in the steel. The addition of the limestone and the removal of phosphorus renders the basic open-hearth process somewhat more laborious and somewhat longer than is the acid process, but the cost of the extra labor is more than compensated by the ability to make use of the cheaper ores of iron, which, in this country are too high in phosphorus for the acid process.

The Open-hearth Furnace.—Figs. 31, 32 and 33 show diagrams and a general view of the type of open-hearth furnaces common in the United States. A shallow hearth *H* lined with refractory brick contains the charge, and above this hearth is a roof lined with firebrick. Gas is the fuel commonly used. Gas and air, preheated, are admitted through ports, *P*. A chimney provides draft. The ingredients of the charge (pig iron, steel scrap, iron ore, and, for the basic process calcined limestone) are fed through a charging door *D*, and after the process is complete the melted steel is tapped off through a tap hole *T*.

The air is preheated by passing it through passages *C* which are filled with a checkerwork of brick which has been preheated by the exhaust gases from the furnace. The regenerative principle is the same as that utilized in the "stoves" of the blast furnace. At least four heating chambers are used with each open-hearth furnace. As shown in Fig. 31 they are located under the furnace, and the currents of incoming air and gas and outgoing hot gas are

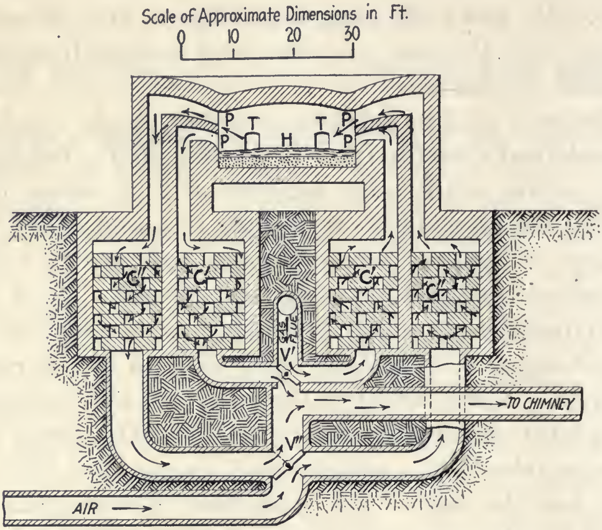


FIG. 31.—Diagram of open-hearth steel furnace.

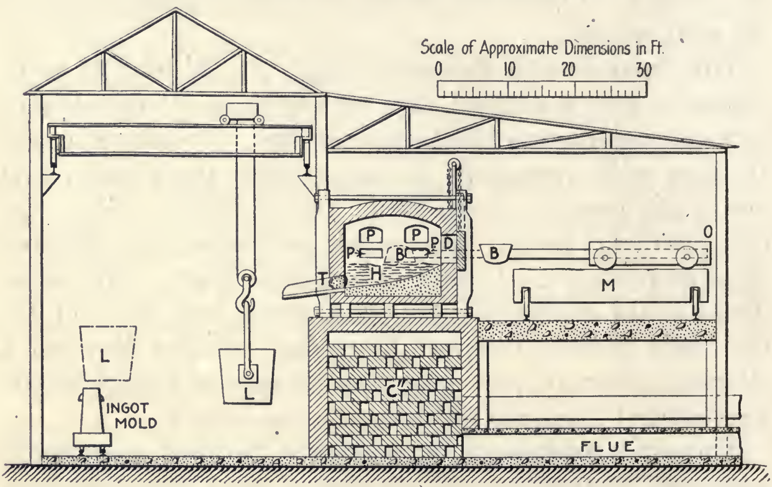


FIG. 32.—Diagram of open-hearth steel plant. Section of furnace is at right angles to the section shown in Fig. 31.

switched from one chamber to another at intervals of about 20 min.

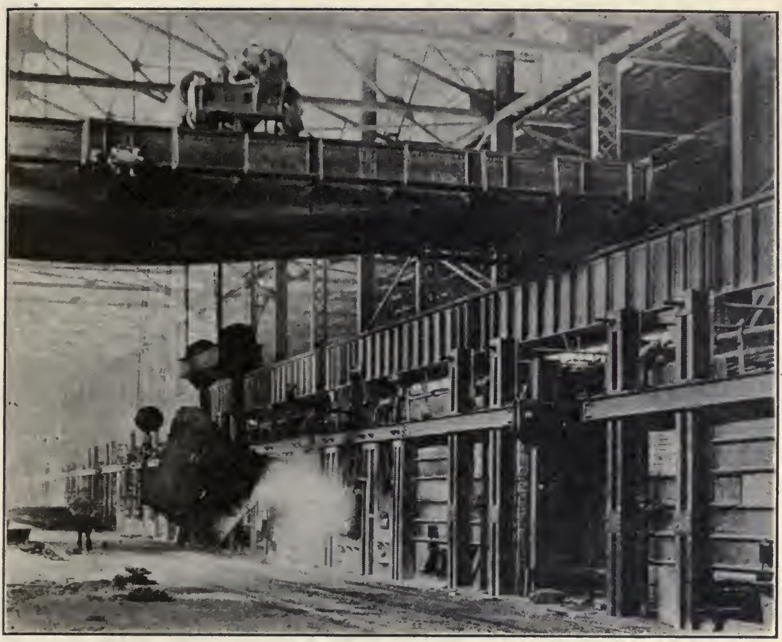
The general appearance of acid open-hearth furnaces and basic open-hearth furnaces is the same. Fig. 33 is from photographs of an open-hearth plant. An acid open-hearth furnace is lined with some form of silica brick, and a basic furnace with some form of dolomitic limestone, or with calcined magnesite. The silica brick has an acid reaction, and resists corroding action by the charge fed to the furnace in the acid process; the dolomitic limestone has a basic reaction, and resists corroding action by the charge fed to the furnace in the basic process. The lining of an openhearth furnace takes no active part in the refining of the charge into steel.

Charging the Open-hearth Furnace.—The charge of pig iron, steel scrap, iron ore and, for basic open-hearth furnaces, limestone is sometimes fed to the furnace by hand, but more often by a charging machine. A common type of charging machine is shown at *M* in Fig. 32. The operator seated at the rear end of the machine *O*, a safe distance away from the heat of the furnace, can control the motor-driven mechanism which picks up the bucket *B* containing the charge, which shoves the bucket with its charge into the furnace (broken lines in Fig. 32), which dumps the charge, and which backs the empty bucket out of the furnace. The pig iron of the charge is fed to the furnace, sometimes in a solid state, but usually molten. Fig. 33*a* shows molten pig iron being fed into the furnace.

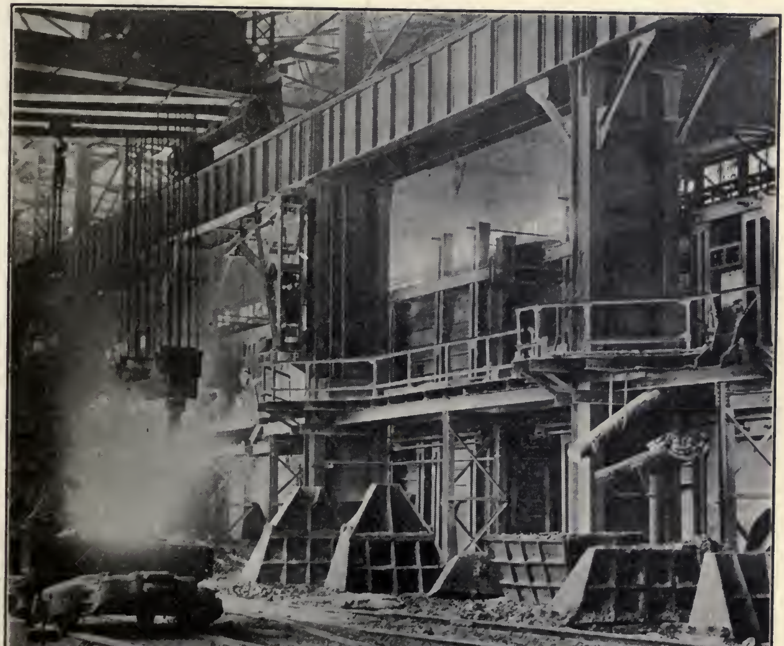
The Control of the Open-hearth Process.—The open-hearth furnace shown in Figs. 31 and 32 has a capacity of about 60 tons per charge, which is about the average size for open-hearth furnaces. About 8 hr. are required to refine a charge. The process may be watched through peep holes in the furnace doors, and at intervals small samples of the molten contents of the furnace are dipped out, run into molds, cooled and broken. Whether the refining process has progressed far enough may be told by the appearance of the fracture of these test pieces, of from a quick chemical analysis. If from the condition of a test sample it is found necessary to oxidize out more impurities, iron ore may be added to the charge in the furnace. The open-hearth process is under excellent control.

Recarburization of Steel.—Usually in the open-hearth process, especially in the basic open-hearth process, in order to insure the thorough removal of impurities the refining process is carried so far that the product is lower in carbon than is desired. This is remedied by adding carbon in some form, usually in the form of ferromanganese, a pig iron rich in manganese and carbon; sometimes the addition of carbon is made in the form of powdered coke or charcoal. This addition of carbon to the refined charge is called *recarburization.* Recarburization for acid open-hearth steel is sometimes carried out in the furnace before tapping the charge, but for basic steel recarburization is carried out in the ladle into which the charge is tapped and from which the slag has been removed. The manganese of the ferromanganese used as a recarburizer is a valuable ingredient to add to steel on account of its powerful affinity for oxygen and sulphur. Its addition tends to cause any oxygen present to combine with the manganese rather than with the iron and also serves to neutralize the bad effects of any sulphur present by causing a combination of sulphur and manganese in place of a combination of sulphur and iron. Sulphur is an undesirable element in steel, making it brittle when hot, and therefore very difficult to forge or roll into shape. Recently the open-hearth process has been successfully used to produce a product very low in carbon and manganese—chemically, almost pure iron. This product is claimed to offer great resistance to corrosion.

Other Types of the Open-hearth Furnace.—The type of the open-hearth furnace shown in Fig. 33, called the stationary type, is the one most commonly used. The tapping of the furnace is accomplished by piecing a clay plug in the tap hole; this is inconvenient, and sometimes at a critical stage of the process delay is caused in doing this. Another form of open-hearth furnace is the tilting furnace. In this form of furnace the steel is discharged by tipping the whole furnace, which is mounted on rockers, until the tap



a. Charging floor.



Courtesy of Illinois Steel Co. *b.* Pouring side.

Fig. 33.—General view in open-hearth steel plant U. S. Steel Co., Gary, Indiana.

hole comes below the level of the molten charge. The tilting furnace is very satisfactory in operation but its first cost and the cost of repairs, power for tilting, and general upkeep are higher than for the stationary furnace.

Fuel for the Open-hearth Furnace.—The fuel in common use in open-hearth steel furnaces is producer gas. Producer gas is generated in an apparatus called a producer by passing air mixed with steam through incandescent coal. Producer gas is a very cheap gas of low heating power. Other fuels used in open-hearth furnaces are natural gas (where available) and oil in the form of spray. Powdered coal and tar have each been used to a limited extent, and gives promise of usefulness as fuels for open-hearth furnaces.

Arrangement of Open-hearth Steel Plants.—In an open-hearth steel plant a number of open-hearth furnaces are placed end to end, and this row of furnaces is served from a charging floor in front of the furnace by one or more charging machines. The steel is tapped from the rear of the furnaces on a casting floor situated at a lower level than the charging floor. Fig 32 indicates the arrangement of a plant in diagram, and Fig. 33 shows views of the charging floor and of the casting floor of an open-hearth steel plant. On the casting floor the steel is tapped into a ladle *L* which carries it to molds. If steel castings are to be made, these molds are shaped so as to produce the forms desired; if rolled-steel rods, plates, or shapes are to be the product the molds are called ingot molds and the steel is produced in large blocks or ingots which are rolled into the shapes desired. The production of steel castings is treated in Chap. X and the production of rolled steel in Chap. XI.

Uses and Limitations of Open-hearth Steel.—The product of the open-hearth furnace varies in chemical composition from almost pure iron up to steel with 1 per cent. of carbon. Open-hearth steel is used for making steel castings, and for making rails, rods, plates, structural shapes, and spring steel. Owing to the greater purity of the pig iron which must be used in the acid open-hearth process, acid open-hearth steel is more costly than basic open-hearth steel, and by some users is considered to be of higher quality.

The refining action of the open-hearth process is limited by the fact that air is blown through the furnace with the fuel, and that if the removal of impurities is carried to the extreme, the steel itself becomes seriously oxidized. At the present time for the very highest grades of steel it is necessary to use processes which refine steel without direct contact of air with the charge in the steel furnace, such as the crucible process and the electric furnace process. However, for all but the highest grades of steel, the open-hearth process gives very satisfactory results.

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CHAPTER VIII

THE MANUFACTURE OF STEEL BY THE BESSEMER PROCESS

General Features.—Next to the open-hearth process the most widely used process for refining pig iron is the *Bessemer* process, so named from its inventor, Sir Henry Bessemer. Until recently this was the most important process for making steel. In the Bessemer process molten pig iron is poured into a pear-shaped vessel, called a converter, cold air is blown through the molten pig iron, and the oxygen of the air burns out practically all the impurities of the pig iron, including carbon; there is left very nearly pure iron. To this molten iron carbon is added in the proportions desired in the finished product. In this process no outside fuel is used, the impurities in the pig iron furnish fuel for the process.

The Bessemer Converter.—The purification of pig iron is carried on, in the Bessemer process, in a pear-shaped vessel called the converter. Fig. 34 shows in diagram a section of a converter, and Fig. 35 is from a photograph of a battery of converters in action. The usual capacity of a Bessemer converter is from 10 to 20 tons of molten metal per charge.

The converter is lined with bricks of refractory material, and the bottom is pierced with holes or tuyéres. Through these holes air is forced under a pressure of about 20 lb. per square inch, the necessary air pressure being supplied by means of blowing engines. As shown in Figs. 34 and 35, the converter is mounted on trunnions; one of the trunnions is hollow and serves as the entrance pipe for the air blast.

Pig Iron for the Bessemer Process.—The molten pig ron which serves as raw material for the Bessemer process is the product of several blast furnaces. It is carried molten in ladle cars to a large receiving vessel called a mixer. From this mixer the pig, still molten, is carried to the Bessemer converter. The object of the mixer is to secure pig iron with the proper composition, and of a higher degree of uniformity than could be secured from one blast furnace

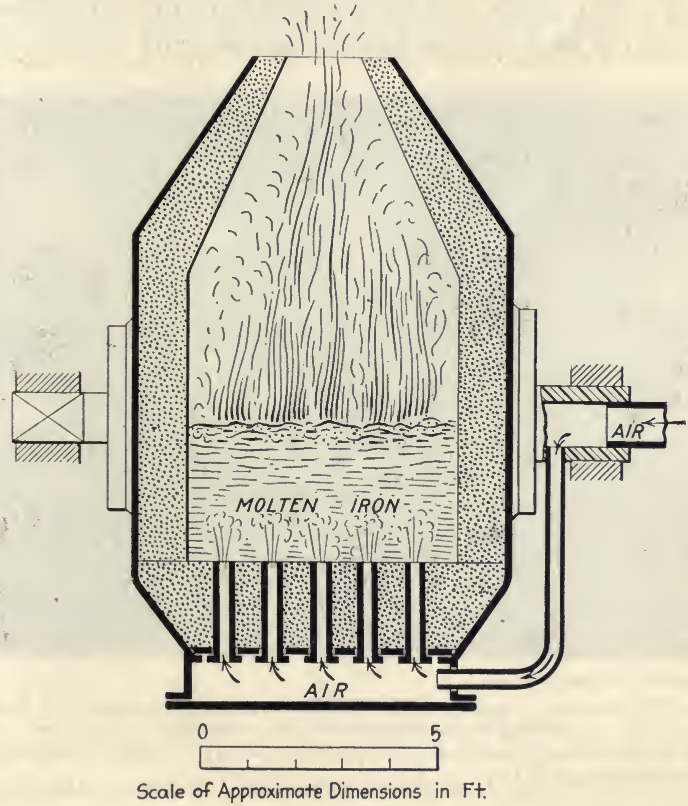

FIG. 34.—Diagram of Bessemer converter.

alone. Bessemer pig is the name given to pig iron suitable for conversion to Bessemer steel. It contains about 3 to 4 per cent. of carbon, 1 to 1.5 per cent. of silicon, less than 0.1 per cent. of phosphorus, and only small quantities of sulphur and manganese.

The Operation of the Bessemer Converter.—The general arrangement of a Bessemer steel plant is shown, in diagram, by Fig. 36. To receive the charge of molten pig iron the converter is tipped down to the position shown in the solid lines and the molten pig is poured in. The air blast is then turned on and the converter turned to an upright position (dotted lines Fig. 36). The "blow" is then said to be in progress. Under the heat of the molten iron the impurities in it ignite and burn in the current of air forced through the molten mass, and the temperature is increased.

Courtesy of Illinois Steel Co.

Fig. 35.—Battery of Bessemer converters in action, Illinois Steel Co., South Chicago, Ill. Converter A and converter C are "blowing." Steel from converter B is being poured into ladle of hydraulic crane at D. Steel is being poured into ingot molds at E.

Silicon and manganese are the first ingredients to burn out; they burn with a yellow flame. After about 4 min. carbon begins to burn out with an intense white flame. After the carbon is burned out, which occurs after about 10 min. of "blow," the flame drops and the contents of the converter have become, chemically, nearly pure iron containing, however some iron oxide and absorbed gases. Attempts to use this iron from the Bessemer converter have shown it to be weak and brittle on account of the presence of absorbed gases and of iron oxide, and it has been found necessary to add manganese to combine with the oxygen of the iron oxide removing it from the metal.

When the flame of the converter "drops" the converter is tipped into pouring position (dot and dash lines, Fig. 36), the blast of air is shut off, and the mass of molten iron is poured into a ladle. At the same time there is poured into the ladle a small quantity of molten pig iron high in carbon

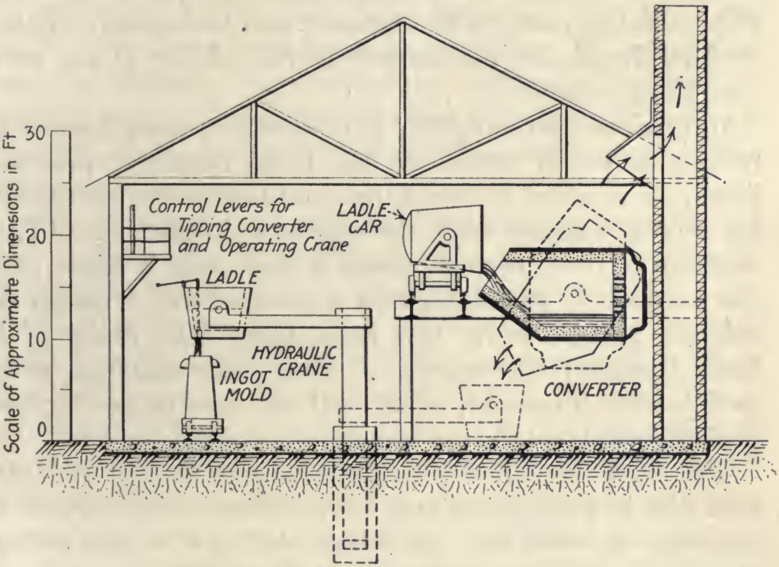

Fig. 36.—Diagram of Bessemer-steel plant.

and manganese. If the final product of the Bessemer process is to be low-carbon steel, this recarburizing pig iron is usually *ferromanganese,* if the product is to be high-carbon steel a pig iron known as *spiegeleisen* is generally used. The ferromanganese or the spiegeleisen is melted in a separate cupola, and is brought in a molten state to the Bessemer plant. The manganese in the recarburizer acts very effectively to absorb any oxygen present in the iron and thus to prevent this oxygen uniting with the iron. Manganese also unites with sulphur, forming manganese sulphide, which is less injurious to the steel than is iron sulphide. The carbon of the recarburizer unites with the iron, and steel is the resulting product.

After the recarburizing process is complete, the ladle of molten steel is lifted by a hydraulic crane over a row of ingot molds, which are successively filled with the molten steel, as shown in Figs. 35 and 36.

Basic Bessemer Process.—The Bessener process as outlined above is that common in the Bessemer plants of the United States. No elimination of phosphorus or sulphur takes place in the process, and the quality of the steel produced depends largely on the quality of pig iron used as raw material.

In England and especially in Germany, a basic Bessemer process is widely used. In the basic Bessemer process, limestone is added to the charge, and the blow is continued for several minutes after the carbon is burned out. The addition of the limestone causes a basic slag to form, and the phosphorus of the pig iron is oxidized and retained as calcium phosphate by this basic slag. The lining of a basic Bessemer converter is of some basic material, such as dolomitic limestone, which will not be attacked by the basic charge.

The basic Bessemer process is successful only with pig iron *high* in phosphorus and low in silicon. Low silicon is necessary in order that the charge shall not be acid rather than basic, and if the silicon is low, there will not be enough fuel (furnished by the other impurities of the pig) unless phosphorus is high. There are practically no American ores which produce pig iron high enough in phosphorus for the basic Bessemer process.[1] American pig iron too high in phosphorus for the acid Bessemer process, as the ordinary American Bessemer process is sometimes called, is made into steel by the basic open-hearth process.

General Quality and Use of Bessemer Steel.—The Bessemer process of steel making is not so well under control as is the open-hearth process, but is much more rapid, and

[1] The Basic Bessemer process is used in at least one Canadian steel plant.

owing to the fuel requirements of the open-hearth process the Bessemer process is cheaper. However, to make pig iron suitable for the acid Bessemer process, a special grade of ore, low in phosphorus, is necessary and the known supplies of this ore in America are becoming exhausted. The general opinion of metals users rates acid open-hearth steel as the best steel produced for general structural purposes (special steels of very high price may, of course be of higher quality, but their use in general structural work is very limited), basic open-hearth steel is usually ranked second to acid open-hearth steel, and Bessemer steel is ranked third. Bessemer steel seems to be inferior to open-hearth steel in reliability and uniformity. There is, however, no certain way to distinguish whether a given lot of steel was made by the open-hearth or by the Bessemer process unless its history is known.

The Bessemer process is used extensively in producing the lower grades of structural steel and was formerly the principal process used in producing railroad rails. The production at frequent intervals of a few tons of steel, which is characteristic of the Bessemer process, feeds to the rail-forming rolls a steadier supply of steel than is furnished by the production twice a day of a large quantity of steel, the latter manner of production being characteristic of the open-hearth process. By the use of a battery of open-hearth furnaces, the tapping of different furnaces can be timed to supply steel at frequent intervals, and owing to the increasing scarcity of ores of iron low in phosphorus the Bessemer process is less used in rail-producing steel plants, than the basic open-hearth process.

Duplex Processes of Steel-making.—Combinations of the Bessemer process and the open-hearth process are in use at some steel plants, whereby the process is started in a Bessemer converter, and the final purification, including the removal of phosphorus, is carried out in a basic open-hearth furnace. This duplex process has become one of great importance in the leading American steel plants.

In another process partial refinement of pig iron is accomplished in a Bessemer converter or an open-hearth furnace, or by a combination of the two, and final refinement takes place in an electrically heated refining furnace. The advantages and limitations of the electrically heated steel furnace are discussed briefly in Chap. IX.

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CHAPTER IX

CEMENTATION STEEL, CRUCIBLE STEEL, AND ELECTRIC-FURNACE STEEL

The Cementation Process.—The oldest process of steel-making is called the cementation process. This process, still in use in England for making fine grades of cultery steel, uses as raw material small bars of wrought iron (see Chap. VI). These are packed in cast-iron boxes and each bar is surrounded with powdered charcoal. The boxes, sealed tight, are then heated in a tall conical furnace up to a temperature of 1,200°F., and this heat is continued for several days. At this temperature carbon is readily soluble in iron and for every 24 hr. of heating the wrought iron is carbonized to a depth of about ⅛ in. This carburizing period may extend over a week or more, and is followed by a slow cooling period. The bars, when removed from the cast-iron boxes, are covered with gas blisters, and the steel is called *blister steel.* These bars of blister steel are worked or drawn under a hammer, piled together, heated to a welding heat and redrawn under a hammer, producing *shear steel.*

Cementation Steel, Case-carbonized Steel.—Cementation steel is very expensive, but of a very high quality. The cementation process has never been used to any great extent in the United States for making steel, but a similar process, the *case-carbonizing* or *case-hardening* process, is in common use for giving wrought iron or soft steel a hard "skin" of high-carbon steel. In this process small articles of wrought iron or soft steel are packed in some carbonizing agent, such as charcoal, leather scraps, bone dust, or potassium ferrocyanide, or are exposed to a hydrocarbon gas and heated for a short period of time. The case-carbonizing process is the same in principle as the cementation process. The hardness given by case hardening is, however, only a surface hardness, and the strength of a case hardened part is increased very slightly by the process.

The Crucible Process.—A process which is in wide use for producing high-grade steel is the crucible process. Like the cementation process, it depends on the solubility of carbon in hot iron, but in the crucible process the iron is

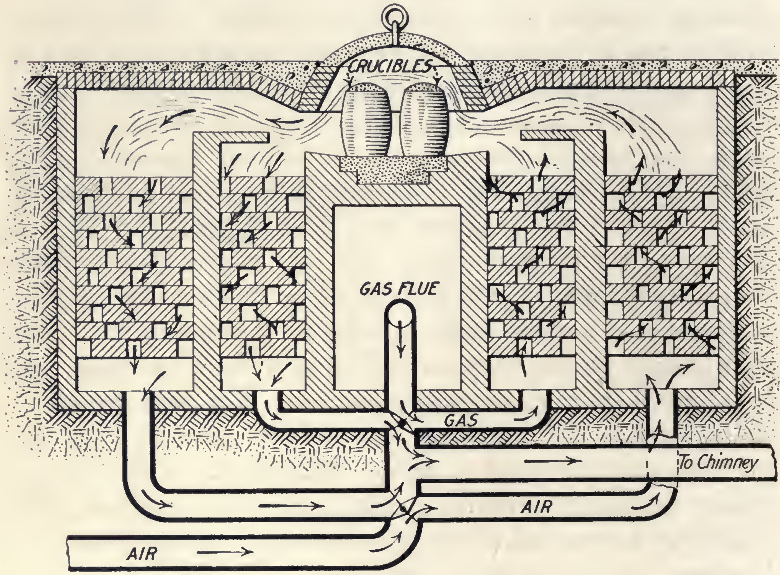


FIG. 37.—Diagram of crucible-steel furnace.

actually melted, and the carbonization takes place much more rapidly than in making cementation steel.

In the crucible process, the charge consists of powdered charcoal and bars of wrought iron and other ingredients containing elements desired in the finished steel, such as manganese, tungsten, etc. The charge is placed in clay or graphite crucibles. The crucibles are covered to keep out air and placed in a furnace (Fig. 37). The temperature is so high that the wrought iron is actually melted, and in 4 or 5 hr. it has combined with the carbon and with other elements present in the substance placed in the crucible.

The crucible is allowed to stand quietly in the furnace for half an hour after the carbonization is complete; this allows any gas bubbles in the molten mass to escape, and after this quiet half hour, or "killing" as it is called, the crucible is lifted out of the furnace, and the steel poured into ingot molds. The ingots formed in the molds are afterward rolled or hammered into rods and bars for commercial purposes. Fig. 37 gives a diagram of a gas-fired crucible furnace. Fig. 38 gives a view in a crucible-steel plant.

Courtesy of the Columbia Steel Co.

Fig. 38.—View in crucible-steel plant. Columbia Steel Co., Chicago Heights, Ill.

In the United States crucible furnaces are usually regenerative furnaces using gas as fuel; in England coke-fired furnaces are in use. Each crucible contains about 75 lb. of metal and is handled by one man. The labor of handling the hot crucible is severe. Only the best quality of wrought iron or very high grade steel scrap should be used. The heat required to melt the wrought iron is very great. All of these causes combine to make the cost of crucible steel five to twenty times that of open-hearth steel or of Bessemer steel, and limits its use to small parts, such as tools, small shafts and axles, etc., which must be very hard or very strong. Crucible steel is, however, less expensive than cementation steel.

The superiority of cementation steel and of crucible steel over Bessemer steel and open-hearth steel is due in large measure to the fact that crucible steel and cementation steel during their process of making are heated in closed vessels out of contact with air. If in the open-hearth process or in the Bessemer process it is attempted to carry the removal of impurities so far as to give steel of the quality of crucible steel, the iron itself becomes oxidized from the air present. To produce the highest grades of steel the heating must be done out of contact with air.

The Electric Furnace for Refining Steel.—If the heat necessary to refine steel is produced by an electric current, the heat can be produced in direct contact with the charge of a steel furnace, but without the presence of air. Direct contact with the charge of a furnace means a more economical utilization of heat than is possible where the heat must be supplied through the walls of a crucible, and freedom from contact with air makes possible the highest refinement of steel without danger of oxidation. For producing low temperatures, electrically produced heat is very expensive as compared with heat produced by burning gas or coke; however, for high temperatures the relative cost of electrically produced heat is less. With fuel-produced heat more air must be used to produce high temperatures, and this air must be heated as well as the charge of the furnace. With fuel-produced heat the higher the temperature the greater the waste of heat in heating the air required to produce combustion and the higher the relative cost of the heat. With electrically produced heat the cost is nearly proportional to the temperature. For some limiting temperature, then , the cost of electrically produced heat will be equal to that of fuel-produced heat, while for still higher temperatures the cost of electrically produced heat will be actually less than that of fuel-produced heat. The temperatures used in refining steel approach this limiting temperature under the conditions prevalent at most steel plants, and it becomes feasible to use the electric furnace for the final refining processes of steel-making.

Duplex and Triplex Processes of Steel Making, using the Electric Furnace.—The non-oxidizing nature of electrically produced heat, and the relatively diminished cost of such heat at high temperatures are utilized in composite processes of steel making which use the open-hearth furnace, the Bessemer converter, or both for preliminary refining of pig iron, and the electric furnace for the final refining. In the *triplex* process pig iron from blast furnaces is first fed to "mixers" (see p. 95) and then to Bessemer converters where silicon, manganese and carbon are nearly all removed; the steel, still molten, is then transferred to basic open-hearth furnaces, where phosphorus is removed by the basic oxidizing slag, and the steel is recarburized; the steel is then removed to an electric furnace where it is deoxidized and desulphurized by the action of the slag "blanket" in the electric furnace. Usually only a part of the product of the basic open-hearth furnace is thus treated in the electric furnace, the larger part is poured into ingot molds after the open-hearth furnace treatment and is thus duplex-process steel. The composite processes of steel making, involving final refining in the electric furnace, give promise of great importance in the steel industry.

Types of Electric Steel Furnaces.—Electric furnaces for refining of steel are, in general, of two types: the arc furnace, and the induction furnace. In the arc furnace the heat is produced by means of an electric arc between carbon electrodes or between a carbon electrode and the furnace charge. Fig. 39 shows a diagram and Fig. 40 a general view of a typical arc-type electric furnace. The electrodes project through the roof of the furnace. The charge rests on the hearth and is purified by the action of a slag formed on top of it which contains decarbonizing, dephosphorizing, and desulphurizing ingredients, as may be needed.

Fig. 41 shows in diagram an induction type of electric furnace. The charge *cc* when melted forms the short-

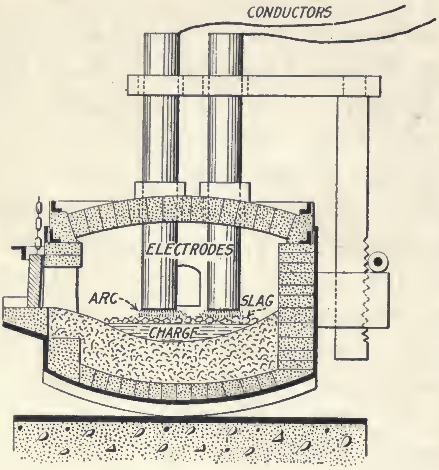
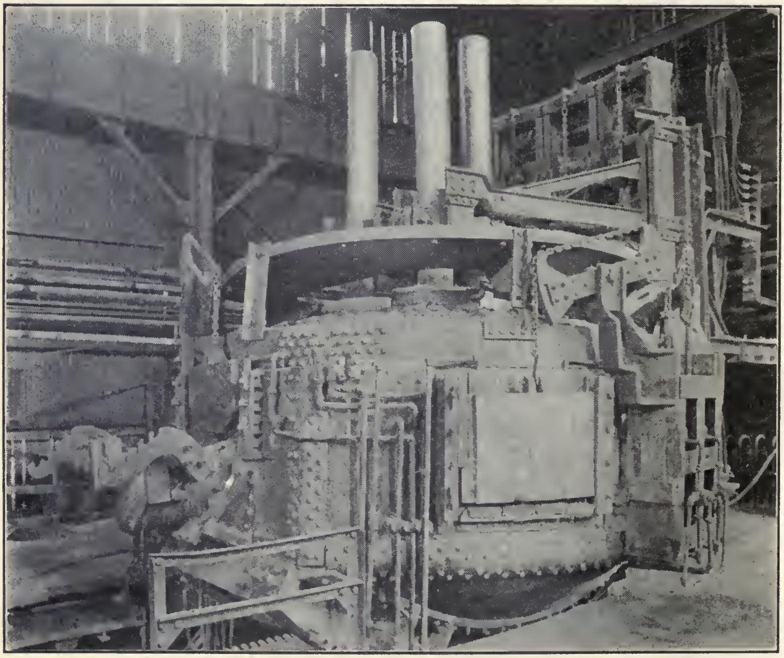


Fig. 39.—Diagram of arc-type electric steel furnace.



Courtesy of Illinois Steel Co.

Fig. 40.—Arc-type electric steel furnace, Illinois Steel Co., So. Chicago, Ill. The furnace shown has three electrodes and uses three-phase current.

circuited secondary winding of a transformer of which the primary winding is shown at *a*. To start such a furnace it is necessary that a ring of metal be placed in the grooves *c* or that the charge be supplied molten. In general, induction furnaces are used to produce small quantities of steel.

The electric process of steel-refining is very recent, but is claimed to produce steel of as high grade as the crucible process. Rail steel refined by the electric process is in use to a limited extent and seems to be of excellent quality. The electric refining process is of special promise for producing steel free from phosphorus, sulphur, oxide, and gas bubbles.

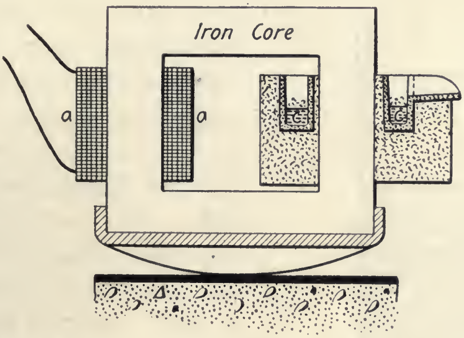


FIG. 41.—Diagram showing principle of induction electric furnace for refining steel.

Electric Reducing of Iron Ore.—In certain localities, notably in Sweden and Norway, where abundant water power makes electricity inexpensive, iron ore is reduced directly in electrically heated furnaces. This produces a very pure grade of iron, but, except in locations where electric power can be produced very cheaply, the direct reduction of ore in electrically heated furnaces is far too expensive to be practicable.

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CHAPTER X

IRON AND STEEL CASTINGS

Cast Iron; the Cupola.—When pig iron is to be used for the direct production of parts of structures or machines, it is remelted and cast into molds. This remelting is necessary because the product of any one blast furnace is usually quite variable in quality, and because a mixture of different varieties of pig iron usually produces a better grade of castings than does any one grade of pig iron; also because by different mixtures different qualities of casting can be produced for special purposes. Pig iron remelted and cast into molds is called *cast iron*. The remelting is usually done in a *cupola* which is somewhat like a small blast furnace. Fig. 42 shows a diagram of a cupola. A blast of air under light pressure is blown through tuyères at the bottom of the stack, which is charged from the top with alternate layers of coke (fuel) and pig iron mixed with scrap. The pig and the scrap melt and trickle down through the fuel to the bottom of the cupola, and a slag forms which floats on top of the melted iron. As in a blast furnace the slag is drawn off through a slag hole and the iron through a tap hole. The principal differences between the action of a blast furnace and that of a cupola

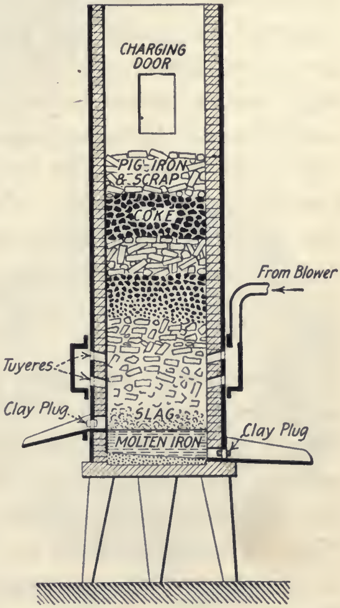


FIG. 42.—Diagram of foundry cupola for cast iron.

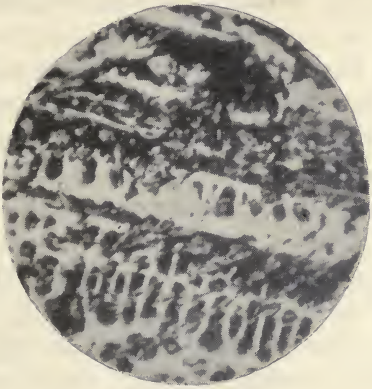
are that in the cupola there is no marked chemical change in the raw material as the process progresses, and that the proportion of fuel to iron in a cupola is only about 20 per cent.

Castings of cast iron are made in molds of loam or of sand. Ordinary cast iron contains from 2.5 to 6 per cent. of carbon, which may be present as combined carbon, graphite flakes, or finely divided graphite.

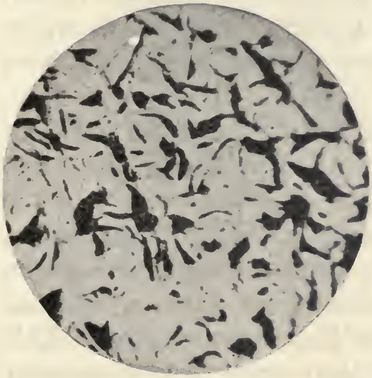
Air-furnace Iron.—A limited amount of cast iron of superior quality is produced by remelting in the *air furnace* rather than in the cupola. An air furnace is not dissimilar in general appearance to a puddling furnace. The iron is melted on a hearth, while the fuel, usually soft coal, is burned on a grate. Iron melted in an air furnace is usually superior to cupola iron because it is less contaminated by the impurities (especially sulphur) in the fuel. The melting is under better control in an air furnace than in a cupola, and in an air furnace some purification of the pig iron usually takes place. The intimate mixture of the charge and the fuel in the cupola, while it tends to contamination of the charge, does, however, cause high economy of fuel. Air-furnace iron requires about twice as much fuel as cupola iron and hence is more expensive than is cupola iron.

Open-hearth Furnaces for Cast Iron.—Open-hearth furnaces such as are used in steel-making are used to a limited extent for producing cast iron. The advantages of their use are greater economy of fuel than the air furnace, and less contamination of charge by fuel than in the cupola. The open-hearth to be at all economical must be operated continuously day and night, and this can be done only in foundries with a very large floor space for setting up molds, as the preparation of molds cannot be well done by artificial light.

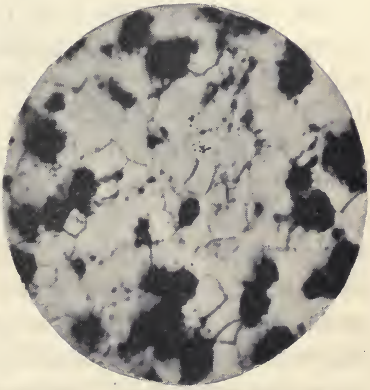
Semi-Steel.—Semi-steel is the rather misleading name given to a product of the air furnace or of the cupola which is made by melting a mixture of 20 to 50 per cent. of steel scrap with pig iron. The product is a cast iron of high strength and low carbon content; it is not steel. Semi-steel is used to make iron castings in which strength is important. Punch and shear frames, parts of hydraulic presses and other machines subjected to severe stresses are frequently made of semi-steel.



a. White cast iron.
Photomicrograph by F. E. Rowland. Magnification 100 times.



b. Gray cast iron.
Photomicrograph by H. T. Manuel.
Magnification 45 times.



c. Malleable cast iron.
Photomicrograph by F. E. Rowland.
Magnification 100 times.

Fig. 43.—Crystalline structure of cast iron.

Gray Cast Iron, White Cast Iron, Chilled Cast Iron.—If cast iron is allowed to cool slowly, a large part of the carbon in the cast iron will be found in the form of crystals of graphite (see Fig. 43*b*). Such cast iron is known as gray cast iron. The crystals of graphite make gray cast iron very brittle as compared with steel or wrought iron. Gray cast iron is soft and easily machined. Its tensile strength is about one-third that of soft steel, and its compressive strength fully equal to that of soft or medium steel. Ordinary cast iron for machine frames, stoves, etc., is gray cast iron.

If cast iron is very rapidly cooled in the mold, the carbon will not have time to be precipitated as graphite, but will remain chemically combined with the iron, giving what is known as white cast iron (see Fig. 43*a*). White cast iron is stronger than gray, but is much harder, so hard that it can not be machined, and is extremely brittle.

If a part of a casting is suddenly cooled while other parts are allowed to cool slowly, the resulting casting will be white cast iron where sudden cooling occurs, and gray cast iron where slow cooling occurs. Local sudden cooling (chill) can be produced by lining a part of the mold with metal, which rapidly conducts the heat away from that part of the casting. The rims of cast-iron wheels are chilled to resist wear while the center is of gray iron, which can be bored for the axle, and which resists shock better than does the very brittle chilled iron.

Malleable Cast Iron.—Malleable cast iron is produced from white cast iron by an annealing process. The white cast iron is cast directly into the desired shapes, and the annealing process does not materially change these shapes. The castings of white iron are packed in pulverized iron oxide (sometimes lime or even sand is used) and are heated to a temperature of about 1,300°F. for several days. This annealing process (a reverse of the cementation process for making steel) changes the combined carbon of the white cast iron to graphite, which, however, occurs in finely divided particles called temper carbon rather than in flakes (see Fig. 43*c*). Malleable cast iron has rather more than twice the tensile strength of gray cast iron, and has very much higher ductility than gray cast iron; the ductility of malleable cast iron is about a quarter of the ductility of structural steel. Malleable cast iron is used for small castings for which forged steel is too expensive, and in which the material should have considerable ductility; for example, hubs of wagon wheels, small fittings for railway rolling stock, parts for agricultural machinery, pipe fittings, door hinges, etc.

Malleable cast iron is not so strong as cast steel, but can be poured at a lower temperature, and gives castings truer to pattern than are steel castings.

Steel Castings.—In recent years there has been a great development in the production of steel parts for machines and structures by direct casting. This has been especially

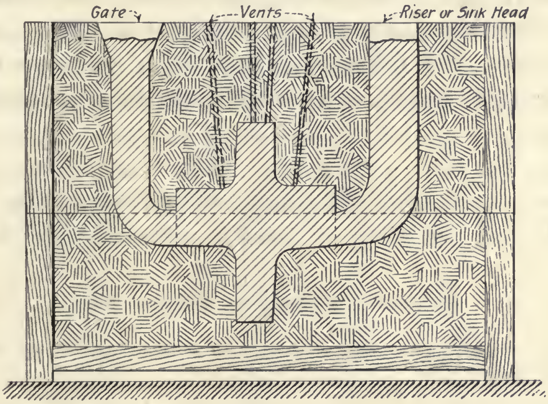


FIG. 44.—Mold for steel casting.

noticeable in the production of railway equipment, such as locomotive frames, car couplers, draft rigging, etc. Steel castings may be made either of open-hearth steel or of Bessemer steel; but open-hearth steel castings are much more common. The molten steel from the furnace or converter is poured directly into molds. Steel castings may be made of almost any desired carbon content. There are a large number of complex foundry problems involved in producing steel castings. To insure soundness of steel in castings and freedom from cavities formed during cooling it is usually necessary to pour the castings with large masses of steel, called sink heads, so placed in the mold that molten steel may flow from them to any part of the casting where there is a tendency toward the formation of cavities due to quick cooling (see Fig. 44).

The material of steel castings is not so strong nor so tough as is forged steel of the same chemical composition. As they come from molds steel castings usually have severe internal stresses set up in them by uneven cooling. These internal stresses may be greatly relieved, and the quality of the material in various parts of the casting made more nearly uniform, by annealing the finished casting, and this is very frequently done.

For many purposes today steel castings are becoming available in place of steel forgings on account of the greater ease of making castings of complicated shape, and steel castings are also displacing gray iron castings for many machine parts in which strength and toughness are prime requisites.

Values for the strength of gray cast iron, malleable cast iron, and steel castings are given in the table of strength and ductility of ferrous metals (Table 5, p. 150).

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CHAPTER XI

THE MECHANICAL TREATMENT OF STEEL ROLLING, FORGING AND PRESSING

Uses of Rolled Steel.—Among the materials used by engineers for structures and machines, rolled steel occupies a place of importance second to none. Bolts, nuts, rivets, screws, nails, structural shapes (such as *I*-beams, channels, and angles), steel plates for metal stacks, tanks, and boiler shells, shafts and axles, railway rails, wire, chain, thin sheet metal for roofing, siding and tubing, gas and water pipe—these are some common articles made from rolled steel.

Steel Ingots.—When steel which comes from the furnace or the converter is to be rolled or forged, it is poured

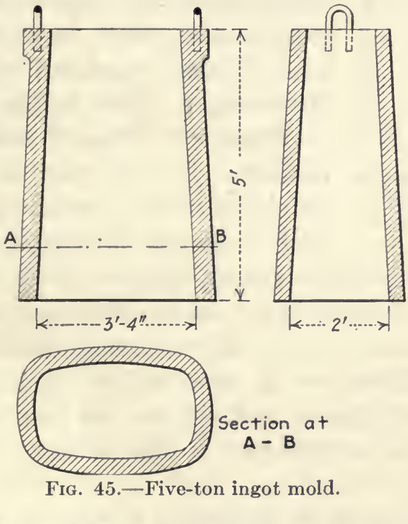


FIG. 45.—Five-ton ingot mold.

into large ingot molds mounted on cars. Each mold contains from 3 to 10 tons of steel (see Fig. 45). These ingot molds after filling are transferred on ingot cars to a yard under a crane which strips the ingot molds from the steel after solidification has taken place. The ingot, solid but still hot is then transferred to a "soaking" furnace where it is kept at red heat until it can be carried to the rolls or to the steam hammer for final shaping.

Defects in Steel Ingots.—As the steel solidifies in the ingot mold there are three actions which tend to make the ingot vary in quality in various parts: (1) the steel in contact with the surface of the mold solidifies first, and, contracting, tends to draw the remaining steel away from the center of the mold, the result being a cavity or "pipe" in the upper part of the ingot (see Fig. 46); (2) the carbon, the sulphur, and the phosphorus instead of remaining uniformly distributed throughout the ingot tend to gather together or "segregate" in spots, especially in the upper part of the ingot; (3) gases escaping as the steel is on the point of solidification may leave minute blowholes "honey-combing" the upper part of the ingot. (See *h*, Fig. 46.)

Fig. 46.—Longitudinal section of steel ingot.

Effects of "Pipes" and Their Prevention.—If that part of the ingot in which there is a pipe is passed through rolls or under a forging hammer at a temperature as high as the welding temperature of steel the walls of the cavity will be welded together; however, this welding action is not at all sure under usual rolling or forging conditions, and a pipe in the ingot, if rolled into rails, plates, or shapes is liable to produce a longitudinal seam in the finished product. This is especially dangerous in rails.

As piping occurs in the upper portion of the ingot, its evil effect may be prevented by cutting off or "cropping" the top of the ingot. This cropped portion is then used as scrap for the open-hearth furnace. It is usually necessary to crop from 20 to 30 per cent. of the ingot in order to insure freedom from piping in the finished steel. The reheating of the cropped portion of the ingot is expensive, and many attempts have been made to prevent the formation of pipes, or to lesses their extent and consequently to lessen the amount of cropping of ingot required. One method of minimizing piping which is in successful use especially in British steel works consists in compressing the ingot in a powerful hydraulic press while the interior is still in a pasty state. Another method recently proposed consists in heating the top of the ingot in the ingot mold so that its solidification shall be retarded and the solidification of the whole ingot made more nearly uniform. Slow pouring of the steel into the ingot mold lessens piping by allowing the metal of the mold to become heated gradually, and the temperature changes in the ingot to take place more gradually.

Effects of Segregation and its Prevention.—The evil effects of segregation are due to the variation of quality in steel which it causes in various parts of the finished piece. The segregation of carbon causes some parts of the rolled product to be too hard, and some to be too weak. If, for example, the carbon of a steel rail is segregated so that there is higher carbon content in the base than in the head, there results a rail with a head so soft that it soon wears out, and with a base so hard that it is unduly brittle. The segregation of phosphorus may cause cold shortness in spots, that is, there will be very brittle spots in a piece of steel in which, as a whole, the phosphorus is not dangerously high. The segregation of sulphur may cause trouble in rolling the steel on account of red shortness, that is, brittleness when hot. Segreation is minimized by quick cooling of the ingot. The contradictory requirements of slow colling to minimize piping, and quick cooling to minimize segregation render the handling of any lot of steel a matter of carful study in order that the best quality may be secured.

Effects of Honeycombing and Its Prevention.—The minute blow-holes in "honeycombed" steel render its strength uncertain, especially under repeated stress, which causes cracks to spread from the minute blow-holes. The steel seems "rotten." Honeycombing is minimized by allowing the steel to remain quietly in the ladle before pouring into the ingot mold until the entrained gases have had an opportunity to escape. This process is known as "killing" the steel, and steel from which gases are freely bubbling is known as "wild" steel. A small quantity of aluminium thrown into the ladle hastens the "killing" process. The use of titanium is said to produce the same result. The superior quality of electric-furnace steel is due, in part, to the freedom from contact of boiling steel with air and gas during the process of manufacture, with the consequent absorption of gas by the steel.

The Rolling Mill.—In cooling the temperature of the surface of the ingot is lowered below that required for suc-

FIG. 47.—Different cross-sections during the process of rolling a steel rail.

cessful rolling, and the ingot is reheated in a "soaking pit," usually fired by waste gas from a blast furnace or an open-hearth furnace. From the soaking pit the ingot is passed through a series of ten or a dozen rolls which reduce its cross-section and increase its length until the desired shape is reached. Fig. 47 shows the shapes given the steel by

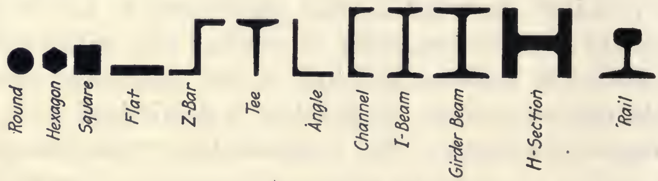


FIG. 48.—Common rolled sections.

successive rolls as an ingot is rolled into a railroad rail. For producing plates rods, rails, structural shapes, etc., the steel ingots are pased through rolls which gradually reduce the cross-section of the ingot to that of the desired product. Fig. 48 shows some common rolled sections.

The rolls to which the ingot is first sent are known as "cogging" rolls, or as a "blooming mill." The rolls are usually two in number for such a mill, which is known as a "two-high" mill, and after the ingot is passed through the rolls they are brought closer together, the direction of rotation reversed, and the ingot passed back through them. Later as the section of the metal approaches its final form "three-high" rolls are used. Figs. 49 and 50 show a two-high, and Fig. 51 shows a three high rolling mill. It will be evident that it is not necessary to reverse the three-high mill in order to send the ingot back through it. Figs. 50 and 51 also show the rollers and the table which feed the steel to the rolls; in a three-high mill this table can be raised and lowered so that the steel may be fed either between the upper and the middle or between the middle and the lower rolls. The actual mechanism for raising and lowering the table involves a somewhat complicated lever system. Fig. 52 shows the principle of a "universal" rolling mill. The distinguishing feature of this mill is the use of a pair of vertical rolls to finish the edge as well as the surface of the steel passed through it.

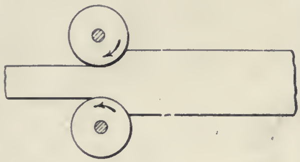
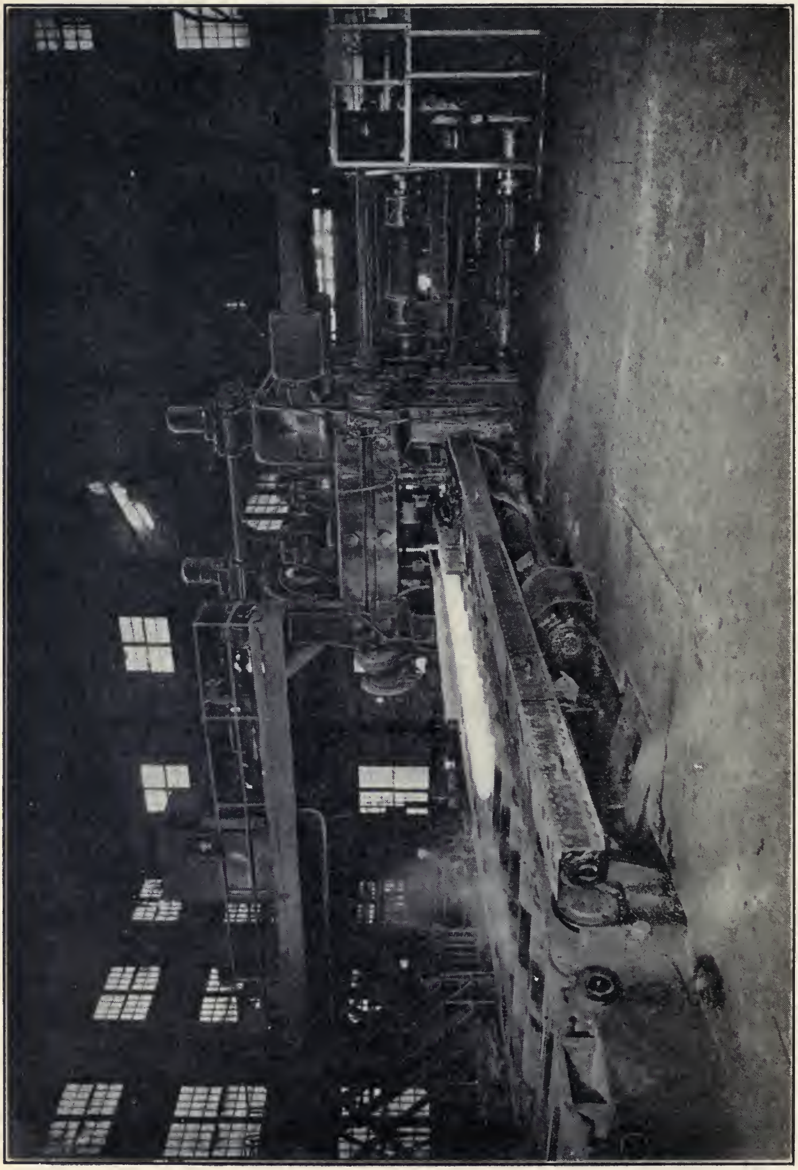


FIG. 49.—Two-high rolls.

Cold-rolled and Cold-drawn Steel.—Rolling steel if done at a proper temperature improves its quality. Small cavities are closed up, and all the particles are packed closely together. Ordinary steel is rolled at a red heat, and the strength and the ductility of the steel are raised by rolling. If steel is brought to its final size by rolling at temperatures below red heat, it is known as cold-rolled steel. The cold-rolling of steel increases its static strength above that of hot-rolled steel, but diminishes it ductility. The same effect may be produced in rods and wire by drawing the steel through hardened steel dies. Cold-drawn and cold-rolled steel are used extensively for shafting. The process leaves the steel with a very smooth surface, and the cold-drawn or cold-rolled steel may be produced so true to shape



Courtesy of Illinois Steel Co.

Fig. 50.—Two-high rolling mill for slabs.

and size that it is not necessary to machine it before using it as shafting. One drawback to the use of cold-rolled or cold-drawn shafting is its liability to "kink" if keyways or holes are cut in the steel. The cold-rolling process sets up very high stresses in the metal, and in cutting a keyway

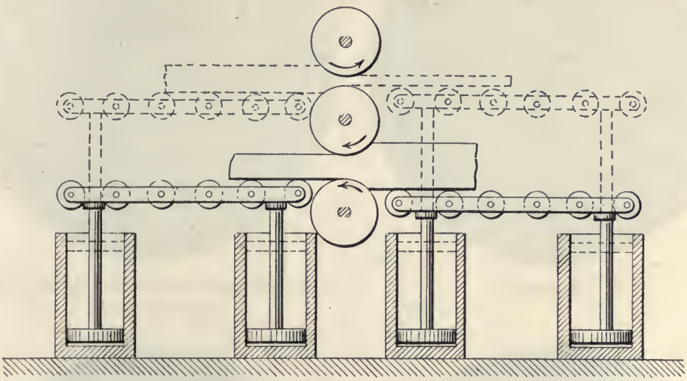


FIG. 51.—Diagram showing principle of three-high rolling mill.

or hole some of the internal stress is relieved, and to preserve internal equilibrium of stress a redistribution of the remaining internal stress takes place, with a consequent distortion of the shaft. Test results seem to show that cold-rolled or cold-drawn steel develops no greater resistance to fatigue under repeated stresses than does hot-rolled steel with the same chemical composition.

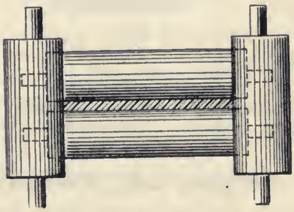
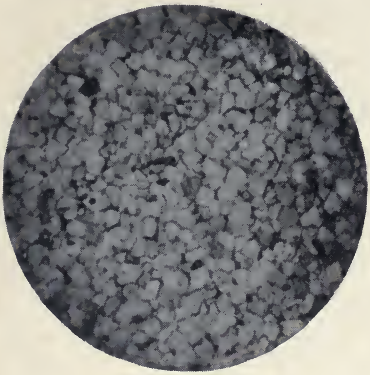
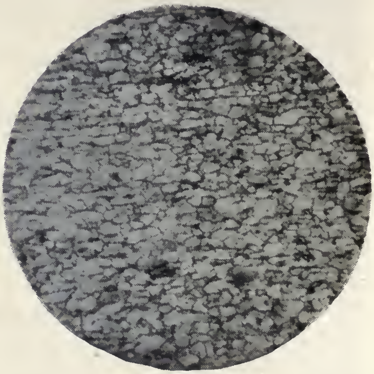


FIG. 52.—Diagram showing principle of universal rolling mill.

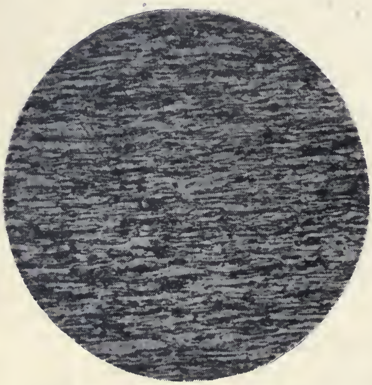
Cold-drawing steel through hardened steel dies produces much the same effect as does cold-rolling. Cold-rolling or cold-drawing distorts the crystalline structure of steel, drawing out the crystals in the direction of rolling. The effects of rolling may be largely removed by annealing at proper temperatures. Fig. 53 gives photomicrographs showing the effect of cold-working on the crystalline structure of steel. Cold-drawn or cold-rolled shafts and rods may be obtained up to 3 in. in diameter. Nearly all steel wire is cold-drawn.



a. Annealed.

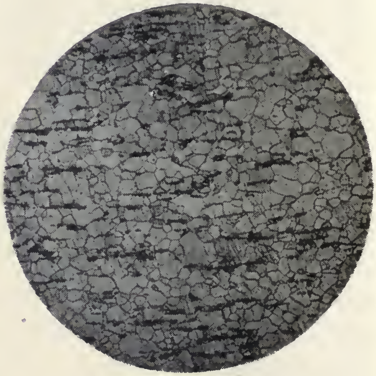


b. 15 per cent. reduction from original cross-section.



Courtesy of Iron Age.

c. 60 per cent. reduction from original cross-section.



d. Annealed after cold-drawing.

Fig. 53.—Effect of cold-drawing and annealing on steel wire with 0.08 per cent. carbon. *Photomicrographs by John F. Tinsley.* Magnification 80 times.

Forging and Pressing Processes.—Large steel objects such as heavy shafts, cannon, thick plate, etc., are shaped by forging hot under a hydraulic press or a steam hammer. In general, pressing and hammering both inprove the quality of the steel, and pressing affects the steel to a greater depth than does hammering. Hammering because it acts by means of a large number of blows applied to all parts of the surface of the object, gives greater uniformity throughout all parts of thin forgings than does pressing. Small objects made of high-grade crucible steel, such as high-carbon steel rods, stock for cutlery, tools, etc., are usually hammered to shape. If a large number of objects of the same size is to be produced, and if a better quality of material is desired than is obtainable in steel castings, these articles are frequently shaped by hammering steel hot between hardened steel dies. This process is called drop forging.

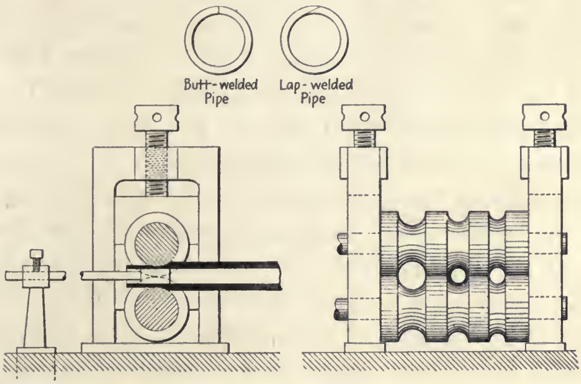


Fig. 54.—Diagram of pipe-welding rolls.

Steel plate is pressed into shape for tanks, boxes, hollow cylinders, boiler heads, etc., in "flanging" presses. In these presses the steel is shaped by means of steel dies. Seamless steel tubing is formed by rolling hot steel over a long mandrel. Ordinary steel and iron pipe is made from plates, known as "skelp" which are rolled into tube shape, after which the "skelp" is heated to welding temperature and passed through rolls and over a mandrel as shown in Fig. 54.

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CHAPTER XII

THE CRYSTALLINE STRUCTURE OF IRON AND STEEL AND ITS SIGNIFICANCE; THE HEAT-TREATMENT OF STEEL; WELDING

The Importance of the Crystalline Structure of Metals. The strength and toughness of metals depend not only on their chemical composition, but also on the shape and size of the crystals which make up the substance of the metal. These crystals in strong, tough iron and steel are so small that they can be detected only under a powerful microscope. In recent years the microscope has come to be recognized as an instrument of great usefulness in the study of the structure of metals. The effect of various kinds of heat-treatment on the crystalline structure of iron and steel, and the relation between crystalline structure and strength and toughness can be studied only with the aid of the microscope. Since the use of the microscope has become general in testing laboratories, great improvements have been made in the strength and toughness of iron and steel by means of suitable heat-treatment: for example, the crystalline "grain" of steel castings has been made finer, and the quality of steel in castings has been greatly improved by the development of annealing processes; the elastic strength of springs and automobile parts has been greatly raised by proper tempering; the wearing properties of the teeth of steel gears have been improved by heat-treatment; a study of the effect of heat-treatment on the crystalline structure and properties of inexpensive grades of steel has made it possible to use them for some machine parts in place of more expensive grades.

Crystallization of Pure Iron.—Iron like all solid metals has a crystalline structure. This is shown by Fig. 55 which is from a photomicrograph of very nearly pure iron which has been produced by electrolysis.[1] The metal is seen to be made up of imperfectly formed crystals, or rather crystalline grains. Only one kind of crystals can be seen. The structure is homogeneous. Nearly all pure metals show a structure similar to that shown in Fig. 55.

The commercial grades of iron and steel are not pure metal, but contain various ingredients besides iron, notably carbon. Commercial iron and steel are produced from a molten state, and to get some idea of the genesis of their

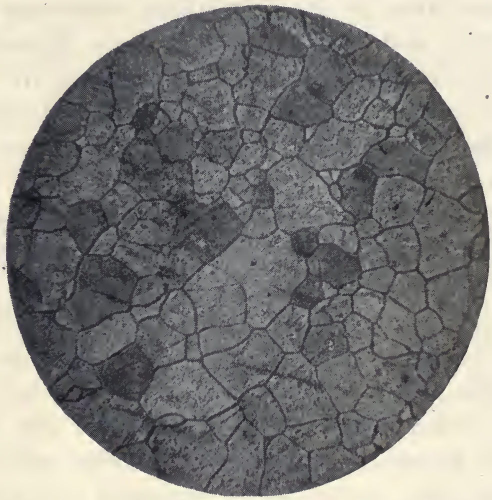


FIG. 55.—Crystalline structure of electrolytic iron. *Photomicrograph by D. F. McFarland.* Magnification 55 times.

structure it will be convenient to consider briefly the behavior of liquid mixtures as they cool and solidify.

Solutions, Solid Solutions.—When a substance is dissolved in a liquid (without chemical combination taking place) the resulting solution differs from a chemical compound in that the proportions of ingredients are not fixed, and it differs from a mechanical mixture in the intimacy of the union of the solvent and the substance dissolved. For

[1] Photomicrographs are obtained by polishing the surface of a small specimen of the metal to be examined, then etching the polished surface with acid to bring out the crystalline structure, and finally photographing a portion of the etched surface through a microscope. The process involves high degree of skill in manipulation if good results are obtained.

example, in a salt solution the intimacy of union between salt and water is much greater than in a mixture of sugar and salt. If a liquid solution is cooled until solidification takes place, the ingredients may act in one of three ways:

1. They may remain so intimately mixed that even after solidifying the substance shows a uniform structure throughout, even when examined under a microscope. The resulting solid is called a *solid solution,* and like a liquid solution it differs from a chemical compound in the indefiniteness of proportions of its ingredients, and from a mechanical mixture in the intimacy of mixture of the ingredients.

2. The ingredients of the substance separate as the solution solidifies and the resulting solid is a mechanical mixture of the ingredients, a very intimate mixture it may be, requiring the use of the microscope to detect the two ingredients. In this second case the ingredients form a liquid solution, but not a solid solution.

3. The ingredients may form a chemical compound. This case is not of much importance for iron and steel.

Illustrations of the Action of Solutions, Eutectics.—Two illustrations of the action of metal solutions, as stated above, will be given. First, a solution of silver in gold will be considered. Silver will dissolve in molten gold in any proportion, forming a liquid solution, and if the molten mass is cooled a solid solution is formed. The structure of the solid, if examined under a microscope, shows only one kind of crystal, appearing something like the crystalline structure of pure iron, Fig. 55. No separation of gold from silver can be detected.

Second, a solution of tin in molten lead will be considered. Tin will dissolve in molten lead forming a liquid solution. If this solution is cooled to solidification, separation of the constituent metals occurs, and an examination under the microscope shows a conglomerate composed of fine crystalline grains of lead and of tin. If there is more than 69 per cent. of tin in the liquid, the excess of tin above this content separates out as a solid before the whole mass solidifies;

if there is more than 31 per cent. of lead in the liquid, the excess of lead above this content separates out as a solid before the whole mass solidifies. Whatever the proportions of tin and lead in the liquid solution, just before solidification of the entire mass is complete the part remaining liquid has the composition, tin 69 per cent., lead 31 per cent., and the final solidification of this particular mixture takes place so rapidly that there is no time for the formation of large crystalline grains, and as a consequence the crystalline grains of lead and tin in this 69-31 mixture are small and very intimately mixed. This particular mixture which remains melted longest and which solidifies in an intimate mechanical mixture of fine grains is called the *eutectic* of tin and lead. A solid tin-lead alloy contains comparatively large crystalline grains of either tin or lead mixed with tin-lead eutectic.

A eutectic is like a chemical compound in that its ingredients exist in definite proportions, but under the microscope its structure is seen to be a mechanical mixture of fine crystalline grains of the ingredients.

The Cooling of Iron-carbon Alloys.— All commercial grades of iron and steel are alloys of iron and carbon. Iron-carbon alloys in cooling to solidification combine both the actions described in the previous paragraphs. A solid solution of carbon in iron is formed[1] and this solid solution acts as one ingredient, while carbon, if present in excess of about 2 per cent., acts as a second ingredient, and these two ingredients solidify in a manner similar to that described for lead-tin alloys forming a eutectic. Carbon will form a solid solution in iron only up to about 2 per cent. carbon content; if the iron-carbon alloy has less than 2 per cent. of carbon, all the carbon is taken up in the iron-carbon solid solution; if the iron-carbon alloy has more than 2 per cent. carbon the excess of carbon will separate out, normally in the form of graphite. Iron-carbon alloys containing less than 2 per cent. of carbon are usually classed

[1] Some authorities claim that the solid solution consists of iron carbide (Fe_3C) dissolved in iron.

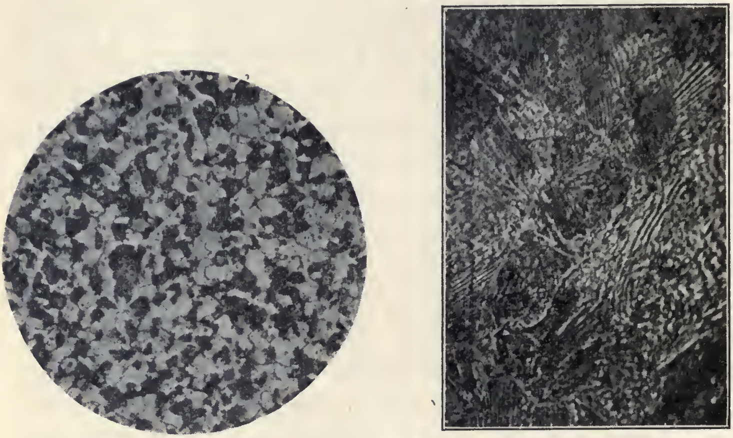
as *steel*, and iron-carbon alloys containing more than 2 per cent. of carbon are usually classes as *cast iron*.[1]

The Solidification of Cast Iron.—The eutectic for an iron-carbon alloy containing more than about 2 per cent. of free carbon has for its ingredients 4.3 per cent. of free carbon, normally in the form of graphite, and 95.7 per cent. of a solid solution of carbon in iron. If the alloy as a whole contains more than 2 per cent. of carbon and less than 4.3 per cent. of free carbon the excess of "iron-carbon solid solution" solidifies first, until the carbon content of the *remaining liquid* reaches 4.3 per cent., when the eutectic solidifies. The resulting solid consists of crystalline grains of a solid solution of iron mixed with crystalline grains of the iron-carbon eutectic. If the alloy contains more than 4.3 per cent. of free carbon, the excess ingredient is carbon, which solidifies from the liquid in the form of graphite. The resulting solid consists normally of flakes of graphite and crystalline grains of the iron-carbon eutectic. In the above it has been stated that *normally* carbon separates from the solution in the form of graphite. This is true if the cooling takes place slowly. If the cooling takes place rapidly there is not time enough for the graphite flakes to form, and the carbon is present in the form of "combined carbon" (iron carbide, Fe_3C), which makes the resulting solid hard and brittle. White cast iron has its carbon in the form of combined carbon rather than in the form of graphite (see Fig. 43, page 111).

The Cooling of Steel to Solidification and after Solidification.—As steel is an iron-carbon alloy containing less than 2 per cent. of carbon it solidifies as a solid solution of carbon in iron. The remarkable thing about steel is that the changes in its crystalline structure do not cease when solidification occurs, but continue to take place as the solid steel cools until the temperature is about 690°C. (1,274°F.) far below the temperature of solidification of molten steel.

[1] The line of demarcation between steel and cast iron is given different values by different authorities, ranging from 1.7 to 2.2 per cent.

At the temperature of solidification steel is a solid solution of carbon in iron, but as cooling goes on this solid solution normally breaks up into two ingredients, carbide of iron called *cementite*, and pure iron called *ferrite*. If the carbon content of the steel is greater than 0.90 per cent., cementite will separate out before the steel takes its final crystalline form; if the carbon content is less than 0.90 per cent. ferrite will separate out. In either case the last part of the steel to reach its final crystalline form has a carbon content of 0.90 per cent. This is called the *eutec-*



(*Courtesy of the Wyman-Gordon Co. and the Aluminum Castings Co.*)

a. Steel with 0.32 per cent. carbon content. *Photomicrograph by J. H. Nelson.* Magnification 75 times.

b. Pearlite. *Photomicrograph by R. S. Archer.* Magnification 650 times.

FIG. 56.—Crystalline structure of ferrite-pearlite steel (hypoeutectoid steel).

toid of steel. The properties of the eutectoid are like those of a eutectic, but the eutectoic is formed from a solid not from a liquid. The eutectoid of steel is called *pearlite* and consists of very fine intimately mixed grains of ferrite and cementite. (See Fig. 56*b*.)

Steel with a carbon content of less than 0.90 per cent., commonly called hypoeutectoid steel, is normally made up of crystalline grains of ferrite and crystalline grains of pearlite. Fig. 56 is from a photomicrograph of such steel; the light portions are ferrite, and the dark portions are pearlite. Under a very high magnification the structure of pearlite would be seen to be made up of an intimate mixture of very fine grains of ferrite and of cementite. (See Fig. 56*b*.)

Steel with a carbon content of more than 0.90 per cent., commonly called hypereutectoid steel, if allowed to cool slowly is made up of crystalline grains of cementite and crystalline grains of pearlite. Fig. 57 is from a photomicrograph of such steel. The light portions are cementite, and the dark portions are pearlite.

FIG. 57.—Crystalline structure of annealed cementite-pearlite steel (hypereutectoid steel). *Photomicrograph by H. T. Manuel.* Magnification 265 times.

In slowly cooled steel the principal ingredients are ferrite and pearlite, or cementite and pearlite. Under the microscope other ingredients can be detected by the trained observer. Among them are slag, which is always present in wrought iron (see Fig. 30, page 84) and is sometimes present in small quantities in steel; manganese sulphide, globules of which are sometimes mixed in the structure of the steel; and iron oxide, due to the direct oxidation of the iron during the removal of impurities.

The Critical Temperature of Steel, the Recalescence Point.—As steel is heated or cooled the change in its temperature does not proceed regularly but shows sudden variations at certain stages. The most important stage is that at which the eutectoid (pearlite) forms, which occurs at a temperature of about 690°C. (1,274°F.). When this temperature is reached in cooling steel, there is a sudden giving off of heat, the cooling process is momentarily checked, and if the steel is in a dark room it suddenly is seen to glow more vigorously. This temperature is called a *critical temperature* or the steel is said to be at the *recalescence point.* The structure of the steel has not reached a stable condition until this point is reached, and normally is in a stable condition after the recalescence point is passed.

The changes taking place at the recalescence point require some time for their completion, and if the cooling is rapid the normal structure of the steel may not be developed. In the case of low-carbon steels the principal ingredient is ferrite and very little variation from the normal can be brought about by sudden cooling. In the case of steel with a carbon content greater than about 0.25 per cent., sudden cooling from above the recalescence point does not give time for complete formation of the eutectoid (pearlite) and some of the solid solution of carbon in iron seems suddenly frozen—or it may be that the iron itself exists in a different (allotropic) form. The structure developed in steel as it cools depends on the rapidity of cooling. If the cooling of high carbon steel is carried on with extreme rapidity—e.g. by cooling in brine at 0° Fahr.—a considerable portion of the steel is left in the form of a solid solution of carbon (or iron carbide) in iron. This solid solution is known as *austenite.* Austenite is very rarely an ingredient in commercial steels, except a very few special alloy steels in which some alloying ingredient (e.g. manganese) acts to retard very markedly the structural transformation of steel as it cools.

If the cooling of high-carbon steel takes place at a somewhat slower rate than is the case for cooling in cold brine, e.g. by cooling in water at room temperature—a structure of needle-like crystals is developed, known as *martensite.* Fig. 58 shows this structure. Steel in the form of martensite is very hard and very brittle. Such steel is suitable for very sharp-edged cutting tools, such as razor blades, but is not suitable for stress-carrying members of machines or structures on account of its brittleness.

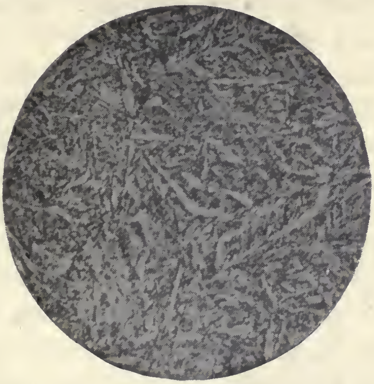
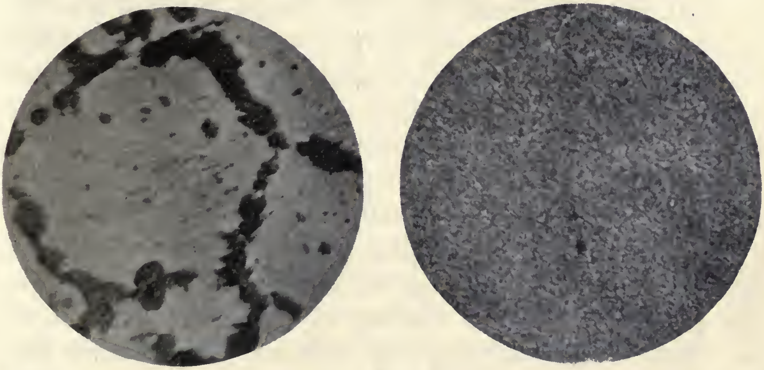


Fig. 58.—Martensite, characteristic crystalline structure of very suddenly cooled hypereutectoid steel. *Photomicrograph by H. T. Manuel, Univ. of Illinois.* Magnification 265 times.

With still slower cooling the characteristic structure developed is known as *troostite,* shown in Fig. 59*a*. Troostite can be identified by the fact that in the process of etching it assumes a very dark color. Troostite is slightly



a. Troostite. *Photomicrograph by J. W. Harsch.* Magnification 350 times. *b.* Sorbite. *Photomicrograph by R. S. Archer.* Magnification 75 times.

Fig. 59.—Crystalline structure of steel with varying rates of cooling (*Courtesy of Univ. of Ill. Metallographic Lab. and the Aluminum Castings Co.*)

Fig. 57, Fig. 58, and Fig. 59 all give photomicrographs of hypereutectoid steel. As the suddenness of cooling increases the structure obtained is successively cementite-pearlite (Fig. 57), sorbite (Fig. 59*b*), troostite (Fig. 59*a*), and martensite (Fig. 58). The sorbitic structure with its extremely fine grain is supposed to give the toughest steel, and to give maximum resistance to repeated stress.

softer, slightly weaker, and slightly more ductile than martensite. The structure of hardened steel used in cutting tools and machine parts is usually made up of martensite, troostite, or a mixture of the two.

With still slower cooling—e.g., cooling in an oil bath at a temperature somewhat above room temperature—steel assumes the structure known as *sorbite,* which is shown in Fig. 59*b*. Sorbite seems to be an intermediate structure between hardened steel (troostite) and annealed steel (pearlite). The sorbite structure seems to yield steel of very high strength and a fair degree of ductility,—a tough steel. Sorbite is generally regarded as the ideal structure for medium and high-carbon steel to be used for stress-carrying parts of machines.

With very slow cooling (annealing) the structure of steel consists of pearlite and ferrite for hypoeutectoid steels (see Fig. 56) and of pearlite and cementite for hypereutectoid steels (see Fig. 57). For steel with a carbon content less than about 0.25 per cent. the changes of structure during cooling take place so rapidly that even with water-cooled steel the structure found is practically always ferrite and pearlite. Carbon in steel acts as a brake to slow up the changes from one stage to another.

Tempering Steel.—If steel is suddenly cooled, leaving its structure martensite, troostite, or sorbite the structure is a state of unstable equilibrium, and will start to change to pearlite if heated to temperatures somewhat below the recalescence point. By heating to temperatures more or less closely approaching the critical temperature the degree of transformation can be regulated, and with it the hardness, strength and ductility of the steel. Martensitic steel can be tempered to troostitic steel producing a steel somewhat less brittle, or to sorbitic steel, producing a steel combining a high degree of strength and ductility.

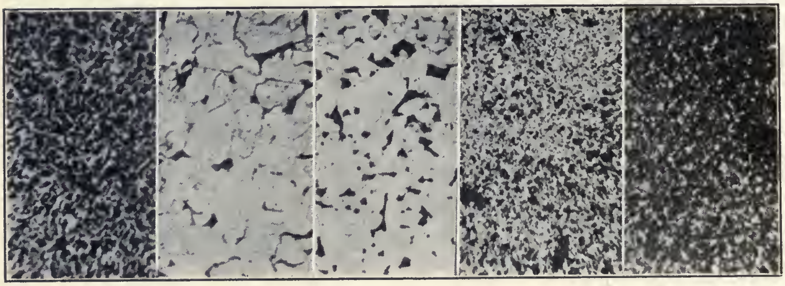
The object of tempering or "heat treating" steel may be either to produce a desired degree of hardness, as in cutting tools, or to produce a desired combination of strength and ductility, as in the case of axles and crank-pins for automobiles.

The technique of heat-treating steel to produce a desired quality is very complex, and can not be treated in this book. It may be noted, however, that a study of the effect of heat-treatment on crystalline structure and resulting strength, hardness, and ductility has in many cases made possible the use of a heat-treated inexpensive grade of steel in place of an expensive grade.

The effectiveness of certain ingredients in steel, notably manganese, in making it hard even when cooled in air is due mainly to their power to retard the formation of the eutectoid as steel cools, so that even if the cooling proceeds slowly in air the steel is still hard when it reaches atmospheric temperature.

Grain Size of Iron and Steel.—If iron or steel is cooled very slowly and quietly past the recalescence point, there is given time for the formation of a coarse crystalline structure, and owing to the large planes of cleavage between grains the steel tends to be brittle. If the steel is cooled rapidly or is hammered while being cooled the resulting structure will be fine-grained, and the material will be improved in ductility. If coarse-grained steel is heated slightly above the recalescence point the eutectoid structure will be broken up and the carbon will go into solid solution in iron. If the metal is then cooled, the recalescence point will soon be reached, before there has been time for the formation of large grains, and the resulting steel will be fine-grained. This process has been called the refining of steel by heat-treatment. Fig. 60 shows changes in grain size of steel caused by cooling in different ways. The change in grain size may be brought about in any grade of steel, though high-carbon steels are more sensitive to change of grain size by heat-treatment than are low-carbon steels. The change of grain size by proper heat-treatment is widely utilized by steel makers and steel users. Steel castings are, of necessity, slowly cooled in their molds from the temperature of melted steel to a temperature but little above atmosphere. The resulting grain structure is coarse, and the steel is brittle; great improvement in the quality of steel castings can be brought about by annealing. If two pieces of iron or steel are welded together, it is necessary first to heat the ends to be welded to a temperature almost that of fusion. This high heating causes coarse crystalline structure in the material near the weld. A welded joint can usually be made tougher by annealing after the weld is made.

Steel heated to very high temperatures in the presence of air is sometimes actually "burned," and under the microscope is seen to contain iron oxide in appreciable quantity.



a *b* *c* *d* *e*

a. Steel as rolled.
b Heated to 1200 degrees C. for 2 hours, cooled in furnace.
c. Heated to 1000 degrees C. for 6 hours, cooled in furnace.
d. Heated to 900 degrees C., cooled in air.
e. Heated to 725 degrees C., quenched in water, reheated to 650 degrees C., cooled in air; sorbitic structure.

Fig. 60.—Crystalline structure of 0.40 per cent. carbon steel with various heat treatments. *Photomicrographs by Henry Daubet, Univ. of Ill.* Magnification 55 times.

Annealing will not restore the quality of such steel; it can be restored only by remelting under a deoxidizing slag.

The grain size of steel may be kept small by hammering or rolling the steel as cooling occurs. Quiet and slow cooling are necessary for the formation of large crystals, and as large crystals are undesirable in structural metals, hammering or rolling the metal as it cools improves the quality. This improvement in quality is well illustrated by the increased toughness given to welded joints by hammering them as they cool, also by the superior toughness of rolled steel as compared with steel castings.

Annealing Steel to Remove the Effects of Overstress.—In service machine parts are occasionally overstressed, and if made of ductile metal are "cold-worked" by this overstressing with the result that their resistance to subsequent impact and to repeated stress is diminished. Heating the metal slightly above the critical temperature removes the effects of such overstress. Iron and steel chains are frequently subjected to overstress when the links "kink" or a sudden impact load comes on a chain, and some large users of chain anneal their chains at regular intervals. Such annealing should be done in a furnace where the temperature can be controlled and kept uniform. Merely heating a chain in a forge fire usually results in overheating some links and underheating others, with damage rather than improvement to the quality of the chain as a whole. The same difficulty would be met in annealing any machine part in an open fire.

Whether annealing can be counted on to weld up the microscopic cracks caused by fatigue of steel under repeated stress is an unsolved question.

The Welding of Steel; Types of Welds.—Welds in steel, and in other metals, may be divided into two classes: (1) welds made at a plastic heat, and (2) welds made by actual fusion of the adjacent metal in the parts joined. Plastic welding is accomplished by bringing the edges to be joined up to a temperature a little below fusion and then pressing or hammering them together. Wrought iron can be readily welded by plastic welding, soft steel can be welded without much difficulty and high carbon steel can be thus welded only by a skilled workman. Cast iron pieces cannot be joined by plastic welding.

Plastic welding is sometimes done in a forge fire, as is the usual case for the welding of rods or of chain links, or the heat may be supplied by means of an electric current passing through the parts to be welded. Special welding machines using electric current are used for welding rods, chain links, and other machine parts; these are to be distinguished from the machines for making electric welds by fusion of the metal, which are noted a little later. Spot welding is a special method of plastic welding by the use of electric current, and its operation is shown in principle in Fig. 61. Alternating current is supplied at low voltage by a transformer *T* and passes through electrodes *CD* and the pieces *EF* to be joined. Pressure is applied to the electrodes, and sufficient heat is generated in the metal to bring a small spot to a plastic welding heat, and thus to "tack" the pieces together. Spot welding is used

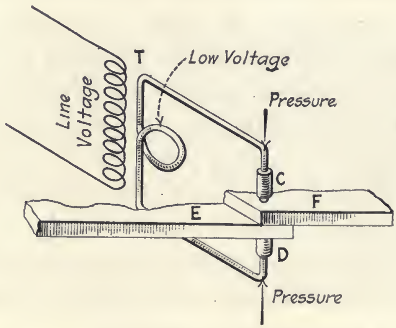


FIG. 61.—Diagram of spot-welding apparatus.

for fastening together pieces which do not have to transmit heavy stress, or for "tacking" together pieces which are to be more thoroughly welded by a fusion process of welding as described in the next paragraph.

Fusion Welding.—If the edges of two adjacent pieces of metal are heated to a temperature of fusion, and then allowed to cool the process is known as *fusion* or *autogenous* welding. The high localized temperatures required may be produced by (1) the heat of a flame of gas, usually acetylene, burning in a stream of pure oxygen, (2) the ignition of a mixture of iron oxide and aluminum (the thermit process), and (3) the use of the electric arc.

In welding with an oxyacetylene torch the oxygen and the acetylene are fed through a blow pipe and ignited at its tip. The flame has a temperature of approximately

5000°F. and a narrow strip of metal at the junction of the parts is fused, uniting the parts. Usually additional metal is added to the joint by melting in a small steel or iron rod. Wrought iron, steel, cast iron, copper, brass, aluminum, and numerous alloys of those metals are welded by the oxyacetylene process. Hydrogen and other fuel gases are sometimes used for welding, but acetylene is by far the most common gas used for that purpose. If an excess of oxygen is supplied to the torch it becomes a very effective cutting tool, or, more correctly a burning tool, for wrought iron or steel. In the presence of excess of pure oxygen heated iron or steel burns, and an oxyacetylene cutting torch burns a narrow gash when applied to a piece of steel or iron. The oxyacetylene cutting torch is widely used to cut up steel scrap.

In the thermit process of welding a specially prepared mixture of aluminum and iron oxide is placed in a crucible and ignited. The heat of the resulting combustion raises the temperature of the mass to about 4800°F., and there is produced superheated melted iron which is poured round the joint to be welded, and which forms a solid casting at the joint.

In the electric arc process of welding an arc is drawn between the metal to be welded and an electrode (usually a steel or iron rod) held in the hand of the operator. The heat of the arc melts the end of the electrode and also melts metal at the surfaces to be joined. The electric current supplied may be either direct or alternating.

Applications of Different Types of Welds.—Forge welding is used for general blacksmith work, for chain making, and for repair work. Forge-made welds are hammered as they cool, and if the heating has been properly done the resulting joint has a fine crystalline structure and is as strong as the original metal. However, the difficulty of judging and controlling temperatures under ordinary shop conditions is so great that forge welds, in general, can not be counted on for more than 50 per cent. of the strength of the material welded.

Plastic welding with an electric current to supply heat is used in special manufacturing operations, such as welding valve stems to valve seats, chain manufacture, etc. This process permits close control of temperature and in some cases pressure or hammering as the weld cools, with the result of producing a fine crystalline structure throughout the joint.

Oxyacetylene welding is especially applicable to thin plates of metal. The joint produced is a casting and has the rather coarse crystalline structure characteristic of castings, and has corresponding physical properties. Annealing somewhat improves this structure. The commonest weakness in oxyacetylene welded joints arises from failure to fuse thoroughly the metals at the joint, leaving a zone of unwelded metal at the middle of the thickness of the plates. Oxyacetylene welding is widely used for repair work, and as it is a fusion process cast metals can be welded as well as rolled metals. The very high temperature applied to a narrow area often produces heavy shrinkage strains in the cooled parts, and in welding complicated shapes it is frequently necessary to preheat the pieces to minimize such strains. The material in carefully made oxyacetylene welds has about 80 per cent. of the strength of the material welded. There is, however, always danger of overheating the metal adjacent to the weld, and under ordinary repair shop conditions it would hardly be safe to count on an efficiency of an oxyacetylene weld greater than 50 per cent.

The thermit process is especially adaptable to repair work on heavy sections and to heavy welds in the field. Welding electric railway rails, repairing broken punch frames, cracked locomotive frames, etc. are examples of the use of the thermit process. The thermit process produces cast metal at the welded joint. The process is patented.

Electric arc welding requires an installation of transformers or motor-generators to produce current, and necessitates an available source of electric power. It is usually used under manufacturing plant conditions rather than under repair shop conditions. The joint produced is a casting and is similar in its characteristics to an oxyacetylene welded joint. It is a disputed question whether electric arc welds or oxyacetylene welds are the better. The electric arc process is somewhat quicker than the oxyacetylene and, where a large amount of welding is to be done, somewhat cheaper. For manufacturing the electric arc process is used for somewhat heavier work than the oxyacetylene, though on account of the portability of the outfit the oxyacetylene process is used for heavy repair work.

Strength of Steel and Other Metals under High Temperatures.—It is a matter of general knowledge that iron and

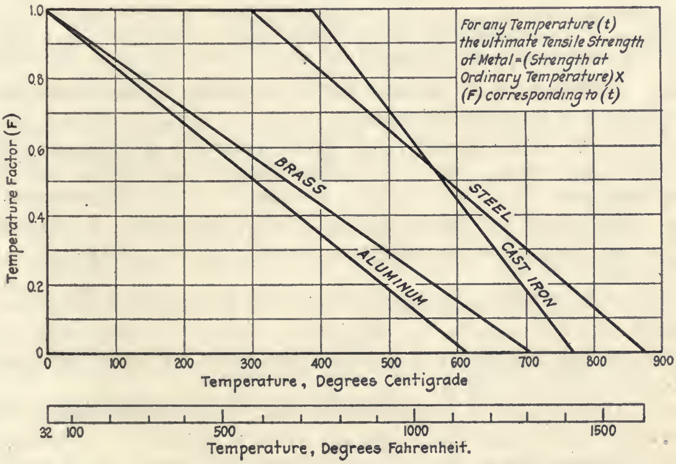


FIG. 62.—Effect of temperature on the strength of steel and of other metals.

steel lose nearly all their stiffness and strength at red heat. A summary of experiments on the strength of various grades of steel shows that the ultimate increases very slightly up to about 500°F. (260°C.) above which the ultimate diminishes approximately in proportion to the temperature. The material loses practically all its strength at about 1,600°F. (870°C.). The change of value of proportional limit under increase in temperature has not been so thoroughly studied, but such test data as are available indicate a regular diminution of proportional limit from atmospheric temperatures to a temperature of about 1,600°F., where the proportional limit becomes zero.

Fig. 62, which is based on test data given by Howard of the U. S. Interstate Commerce Commission, by Ludwik of the Royal Technical High School of Vienna, by Rudeloff and by Bach shows graphically the reduction of ultimate strength of various metals which should be allowed for different temperatures.

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CHAPTER XIII

THE EFFECT OF VARIOUS INGREDIENTS ON THE PROPERTIES OF IRON AND STEEL; CORROSION

The Importance of Chemical Composition of Iron and Steel.—In Chaps. X, XI and XII the effects of heat-treatment and mechanical treatment of iron and steel were discussed. Of equal if not of greater importance is the effect on the strength, hardness, ductility, and toughness of iron and steel produced by the presence of various ingredients. So many ingredients are present in the various grades of commercial iron and steel that anything like a systematic tabulation of their effects is impossible. This chapter will discuss in a general way the effects of the more common ingredients found in steel.

Commercial Pure Iron.—Swedish wrought iron and very low-carbon open-hearth steel are the commercial products which are nearest to pure iron. Experimentally, iron of still higher purity has been produced by electrolysis. Pure iron has a tensile strength of about 40,000 lb. per square inch, is very ductile, and as compared with the commercial grades of steel is very soft.

Carbon.—Carbon up to about 1.25 per cent. increases the strength of iron, and the increase is approximately proportional to the carbon content. Carbon in chemical combination with iron in the form of cementite increases the hardness and lowers the ductility. An alloy of iron and carbon containing less than about 2 per cent. of carbon is called steel (except the product of the puddling process which is wrought iron); an alloy of iron and carbon containing more than about 2 per cent. of carbon is called cast iron. The reason for this distinction is discussed in Chap. XII.

The carbon contents of the common varieties of steel are:

	Per cent.
Soft steel	0.05–0.15
Structural steel	0.15–0.25
Medium steel for forgings	0.20–0.40
Rail steel	0.35–0.55
Spring steel	0.80–1.10
Carbon steel for cutting tools	0.60–1.50

In cast iron the carbon may be present either as combined carbon or as graphite. In general, slow cooling of the iron from a molten state causes a precipitation of the carbon as flakes of graphite and "gray" iron is the product: quick cooling tends to cause the retention in combination of a high percentage of carbon, and the product is "white" iron. Up to about 1.25 per cent., combined carbon increases the strength of cast iron, while graphite lowers the strength but makes cast iron soft and readily machined. The flakes of graphite as they are precipitated from the molten iron take up space between the crystals of iron, causing a tendency for the iron to expand in the mold and diminishing the final shrinkage of the iron which takes place as the iron cools, and which for gray cast iron amounts to about ⅛ in. per foot.

Silicon.—Ordinary steels contain less than 0.20 per cent. of silicon, and this amount has no appreciable effect on the strength or the ductility. Special silicon steel contains much larger percentages of silicon, usually from 1.0 to 4.0 per cent. A silicon steel containing low carbon content and about 1.9 per cent. of silicon has recently been used as a structural steel of high strength. A silicon steel with about 0.50 per cent. carbon, 2.0 per cent. silicon, and 0.70 per cent. manganese has been used for leaf springs for automobiles and carriages. This last-named alloy is sometimes called silico-manganese steel. Steel with about 4 per cent. silicon and a very low carbon content is used for transformer cores on account of its very high magnetic permeability. Silicon tends to give a bath of molten steel an acid reaction and hence steel made in a basic furnace always has a low silicon content.

Phosphorus.—Phosphorus is known as "the steel maker's bane." Small amounts increase the strength of steel, but increase its brittleness especially under cold weather temperatures (see Fig. 63). Steel which is brittle when cold is called "cold short." Phosphorus is especially dangerous in railroad rails which are exposed to severe shocks in service, and which, in winter, are exposed to low temperatures. For most purposes not more than 0.05 per cent. of phosphorus is allowable in steel, except for thin rolled plates in which experience has shown that the presence of phosphorus makes hot-rolling easier.

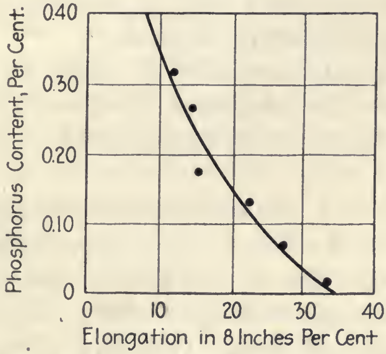

FIG. 63.—Effect of phosphorus on the ductility of steel.

In cast iron phosphorus lengthens the period of solidification of the cast iron in the mold, and makes the iron more fluid. With a high phosphorus content (say 1.0 per cent.) very sharp clean-cut castings are produced, but they are very brittle. Such cast iron is useful for castings in which brittleness is not a drawback, and where sharpness of form is of great importance, *e.g.*, in castings for stoves and kitchen ranges, decorative work, street signs, etc.

Sulphur.—If sulphur combines directly with iron as ferrous sulphide, it diminishes the strength and the ductility of iron. If manganese is present the sulphur combines with it rather than with the iron forming manganese sulphide. This has little effect on the strength or the ductility of the iron, but by many metallurgists it is claimed to render the iron liable to rapid corrosion. Sulphur tends to make iron brittle when red hot—"red short" is the term used. Sulphur is not a very dangerous ingredient in rolled steel which on inspection is seen to be free from cracks, because the presence of a dangerous amount of sulphur would have rendered the steel so "red short" that it would have been impossible to roll it. Sulphur is an ingredient more troublesome to the steel producer than to the steel user, while phosphorus is more troublesome to the user than to the producer.

The maximum allowable sulphur content for most steels is fixed by specification at 0.05 per cent. though some metallurgists claim that a sulphur content of 0.10 per cent. is not necessarily injurious to steel.

In cast iron, sulphur tends to cause the carbon of the iron to assume the combined form rather than that of graphite, and hence tends to make the cast iron hard and brittle.

Manganese.—In small quantities manganese does not have a great direct effect on the properties of iron and steel, but is of great value in combining with any sulphur or oxygen present, and thus preventing the combination of these elements with iron. Ordinary steels contain from 0.30 to 0.70 per cent. manganese. A manganese content greater than about 7 per cent. makes steel very strong and tough, but so hard as to be practically unworkable. *Manganese steel* usually contains about 12 per cent. of manganese, and while by the exercise of great care it may be forged or rolled, it is usually cast directly into the desired shape of the finished product. It is used for the jaws of rock crushers, for special rails, frogs, and crossings for railroad work, for burglar-proof safes, and, in general, where extreme hardness or resistance to wear is of prime importance.

Nickel.—A nickel content of about 3.5 per cent. makes steel stronger and more resistant to shocks. Nickel steel is somewhat more expensive than ordinary carbon steel, but is widely used where high strength is necessary, *e.g.*, for armor plate, automobile axles, gas-engine valves, special rails, long-span steel bridges. Nickel strengthens steel without reducing its ductility to any great extent, hence nickel steel is tough.

Steel alloyed with about 36 per cent. of nickel has a very low coefficient of expansion (about one-sixth that of ordinary iron)—lower than for any known metal. This steel alloy is known as "invar" steel and is used in making measuring tapes and steel scales, and in measuring instruments in which expansion affects the accuracy of the instrument. Invar steel is very expensive and is very brittle, hence invar steel measuring tapes can not stand severe field service.

Chromium.—Chromium makes possible a steel of great hardness and strength. Chromium is usually used in connection with nickel or vanadium in making special grades of steel. Chrome-nickel steel is used for armor plate, projectiles, safes, automobile axles, etc. Chrome-nickel steel gears are in extensive use, and have excellent wearing qualities.

An iron ore mined at Mayari, Cuba contains considerable quantities of nickel and of chromium, and steel made from this ore is a natural chrome-nickel steel of high strength. Mayari steel is used especially for making rails and track bolts.

Vanadium.—Vanadium in the form of ferrovanadium adds great strength to steel, and seems to be especially valuable in adding resisting power against repeated applications of stress, and in giving steel free from flaws and seams. Possibly these two characteristics are inter-related. Vanadium steel is used for springs, axles, locomotive frames, and other parts of railway equipment; it is also used in automobile construction. Vanadium seems to benefit cast iron, probably on account of its tendency to remove oxygen from the iron.

Tungsten, Molybdenum and Cobalt.—The presence of tungsten and molybdenum in steel so affects the critical temperature, at which steel changes from a very hard material to a much softer material, that with proper heat-treatment tungsten and molybdenum steels retain their hardness at a red heat. The various "high-speed" tool steels used for machine-tool cutters depend for their peculiar properties on the presence of tungsten or molybdenum.

Recently cobalt has given promise of usefulness as an alloying element for high-speed steel. In this connection may be noted the high-speed cutting metal *Stellite*, which is an alloy composed mainly of cobalt, chromium, and molybdenum.

Copper.—A small amount of copper, not more than 1 per cent., has no marked effect on the strength or the ductility of steel, but is claimed by some metallurgists to diminish the tendency to corrosion.

Titanium.—In making pig iron the presence of titanium in the ore is objectionable as it tends to make the pig iron "sticky" as it flows from the blast furnace. Recently titanium had been used as an alloying ingredient for steel, and is claimed to render the steel more uniform in quality throughout. Titanium has been used in making rail steel.

The Corrosion of Iron and Steel.—The surface of iron or steel as it is machined is a silvery white. After exposure to the air the surface becomes covered with a thin layer of oxide. With prolonged exposure to moist air this film of oxide becomes somewhat deeper and the surface of the iron assumes a reddish-brown color. The mere formation of an evenly distributed coat of rust (oxide) does very little structural injury to the metal, the coat of oxide soon protects the iron from further general rusting. There is, however, a corrosive action known as "pitting" which sometimes attacks steel and iron in small spots, eating deep holes into the metal. This pitting action seems to spread, once such a hole is started, and may continue until the member attacked is fatally weakened.

The phenomena of corrosion involve very complicated chemical and electrolytic actions: it is now generally accepted that destructive corrosion, or pitting, is the result of electrolytic action between the pure iron and the impurities mixed with it in steel, and manganese sulphide is suspected of being an active corroding agent. It is claimed by the makers of wrought iron that the presence of slag in wrought iron tends to inhibit corrosion, or at least to check its spread throughout the metal. The question of the relative resisting power to corrosion of wrought iron and of steel is a much-disputed one. Many examples are given of structures of both materials which have failed by corrosion, and many structures of both materials have given good service for many years. Care in the manufacture of the material seems to be of about as much importance in producing a rust-resisting material as does the nature of the process used.

Since the general acceptance of the electrolytic theory of corrosion the efforts of steel manufacturers to produce a rust-resisting steel have been directed along three lines: (1) to produce a material of a very high degree of purity so that they will be present very few foreign ingredients to set up electrolytic action with iron; (2) to put into the steel some ingredient which will act to inhibit electrolysis of the iron; and (3) to produce a specially fine-grained surface to the steel by working it in special rolls, and making it dense and mechanically resistant to corroding action. All these methods give promise of usefulness, but none has been in use for a sufficient period of time to demonstrate completely its value.

Strength and Ductility of Iron and Steel.—In Table 5 are given average values for the proportional limit, ultimate strength, and ductility of the common grades of iron and steel. The values in the table are general averages and considerable variation from them may be expected in individual lots of metal.

It will be noted in Table 5 that values of proportional limit for steel in compression are the same as for steel in tension. Recent tests by the U. S. Bureau of Standards indicate that for thick rolled steel the proportional limit and the yield point are not infrequently found to be lower for compression than for tension.

TABLE 5.—AVERAGE VALUES FOR STRENGTH STIFFNESS AND DUCTILITY OF IRON AND STEEL

The values given in this table are based on test data from various materials testing laboratories.

Material	Strength in tension, lb. per sq. in.		Strength in compression, lb. per sq. in.		Strength in shear, lb. per sq. in.		Modulus of elasticity, lb. per sq. in.		Elongation in 2 in., per cent.
	Proportional limit	Ultimate	Proportional limit	Ultimate	Proportional limit	Ultimate	Tension	Shear	
Gray cast iron	(a)	20,000	26,000	75,000	(b)	(b)	15,000,000	6,000,000	Slight
Malleable cast iron	15,000	45,000	15,000	(d)	10,000	(c)	23,000,000	10,500,000	7.5
Electrolytic iron	20,000	40,000	20,000	(d)	12,000	30,000	27,000,000	10,000,000	50.0
Commercial wrought iron	30,000	50,000	30,000	(d)	18,000	35,000	27,000,000	10,000,000	35.0
Steel, 0.10 per cent. carbon:									
Rolled metal	30,000	50,000	30,000	(d)	18,000	35,000	30,000,000	12,000,000	45.0
Steel, 0.20 per cent. carbon:									
Rolled metal	35,000	60,000	35,000	(d)	21,000	45,000	b30,000,000	12,000,000	35.0
Castings	30,000	60,000	30,000	(d)	18,000	45,000	30,000,000	12,000,000	30.0
Steel, 0.40 per cent. carbon:									
Rolled metal	50,000	90,000	50,000	(d)	30,000	65,000	30,000,000	12,000,000	20.0
Castings	40,000	80,000	40,000	(d)	24,000	60,000	30,000,000	12,000,000	15.0
Steel, 0.60 per cent. carbon:									
Rolled metal	60,000	115,000	60,000	(d)	36,000	85,000	30,000,000	12,000,000	14.0
Steel, 0.80 per cent. carbon:									
Rolled metal	70,000	135,000	70,000	(d)	42,000	100,000	30,000,000	12,000,000	10.0
Steel, 1.00 per cent. carbon:									
Annealed rolled metal	80,000	150,000	80,000	(d)	48,000	115,000	30,000,000	12,000,000	5.0
Heat-treated rolled metal	160,000	200,000	160,000	(d)	96,000	150,000	30,000,000	12,000,000	Slight
Cold-rolled steel, 0.20 carbon	60,000	80,000	60,000	(d)	36,000	60,000	30,000,000	12,000,000	18.0
Silico-manganese steel, 1.95 Si, 0.70 Mn:									
Annealed rolled metal	60,000	77,000	60,000	(d)	36,000	55,000	30,000,000	12,000,000	16.0
Heat-treated rolled metal	130,000	174,000	130,000	(d)	78,000	120,000	30,000,000	12,000,000	14.0
Structural nickel steel, 3.5 per cent. nickel	50,000	90,000	50,000	(d)	30,000	65,000	30,000,000	12,000,000	25.0
Nickel steel, 15 per cent. nickel	140,000	170,000	(c)	(c)	(c)	(c)	(c)	(c)	Slight
Chrome-nickel steel, 0.40 C, 1.5 Ni, 1.2 Cr:									
As rolled	75,000	95,000	75,000	(d)	45,000	70,000	30,000,000	12,000,000	25.0
Heat-treated	115,000	145,000	115,000	(d)	69,000	105,000	30,000,000	12,000,000	15.0
Vanadium steel, 0.40 C, 1.00 Cr, 0.17 V:									
As rolled	45,000	85,000	45,000	(d)	27,000	65,000	30,000,000	12,000,000	28.0
Heat-treated	180,000	220,000	(c)	(c)	(c)	(c)	30,000,000	(c	14.0
Wire (not annealed):(e)									
Iron or soft steel	70,000	85,000	(f)	(f)	(f)	(f)	30,000,000	(f)	(c)
High-carbon steel	150,000	200,000	(f)	(f)	(f)	(f)	30,000,000	(f)	(c)

(a) No well-defined proportional limit.
(b) Greater than tensile strength, under pure shear cast iron fails by tension on an oblique plane.
(c) Data lacking.
(d) For ductile metal the yield point which is only slightly higher than the proportional limit is the praetical ultimate in compression.
(e(For annealed wire the values would be about the same as for the corresponding grade of steel not drawn out into wire.
(f) Wire can offer resistance only in tension.

Fig. 18 (page 39) gives typical stress-strain diagrams up to the yield point for the common grades of iron and steel.

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CHAPTER XIV

THE NON-FERROUS METALS AND ALLOYS

Importance of Non-ferrous Metals.—While iron and steel are by far the most important of the metals used for structures and machines, other metals are by no means without importance. This chapter gives a very brief treatment of the occurrence and properties of some of the more important of the non-ferrous metals, and of some of the more important of their alloys.

Copper.—In the United States thare are extensive deposits of copper ore in the Lake Superior region and in the Rocky Mountain region. The Lake Superior ores contain native copper in a very pure form, while in the mines of Montana, Utah, and Arizona, the ore is in the form of copper sulphide and copper-iron sulphide.

Copper is obtained from sulphide ores by a complex process involving four stages: roasting, smelting, converting (or Bessemerizing) and electrolytic refining. Roasting of copper consists in partially burning out the sulphur of the sulphides of copper and iron present in the ores leaving oxides in place of sulphides. The roasting of copper ore is carried out in special roasting furnaces. The roasting stage is frequently combined with the smelting stage.

Smelting of the roasted ore takes place either in a blast furnace or in a "reverberatory" furnace. In the smelting process the chief change is the removal in slag of the earthy impurities, and the production of a mixture of metallic sulphides of iron and copper. This mass is known as *matte.*

The matte is further purified in a Bessemer converter. The converting process takes place in two stages. In the first stage the air blown through the molten matte sets up very complicated reactions, the result being the oxidation of the iron sulphide, and the passing of the iron oxide formed into slag, while there is left "white metal" which is nearly pure copper sulphide. In the second stage this copper sulphide is "blown" and after a complicated reaction crude copper, known as "blister" copper is produced.

In the electrolytic refining process anodes of blister copper are placed in a sulphuric acid bath. The sulphuric acid is obtained from the products of roasting the sulphide ores. A cathode of very pure copper is used and from the electrolytic bath very pure copper is produced. "Electrolytic" copper is the purest copper on the market, and is the only kind of copper used for electric conductors.

The native copper (found mainly in the Lake Superior region) is concentrated from its ores, though if copper for electrical conductors is to be produced the final process is that of electrolytic refining.

In recent years deposits of low-grade copper ores have been successfully worked by treating the ores with sulphuric acid, and then, by electrolysis of the solution, obtaining pure copper.

Uses of Copper.—Copper is widely used for electrical wires, on account of its high electric conductivity. Next to silver it is the best conductor known. It is also very extensively used as a constituent of alloys with tin, zinc and aluminium. These alloys are discussed in later paragraphs of this chapter. Copper is sometimes used for the tubes of condensers and other tubes in cases where the corrodibility of iron and steel render them unsuitable, also for small tubes which must withstand high pressure and yet be flexible. On account of its high resistance to atmospheric corrosion, copper, in the form of rolled plate, is used for roofing and sheathing.

Physical Properties of Copper.—Copper is a malleable and ductile metal with a characteristic reddish color. In Chap. XI was discussed the variation in the physical properties of steel due to mechanical working. Copper exhibits even greater variability in physical properties due to treatment. For cast copper the ultimate strength is about 25,000 lb. per square inch. It has no yield point. A poorly defined proportional limit is found at about 8,000 lb. per square inch. It has an elongation in 8 in. of about 7 per cent. When cold-rolled or cold-drawn (hard-drawn is a term frequently used), copper has an ultimate of from 40,000 to 60,000 lb. per square inch depending on the amount of reduction by drawing. It has a poorly defined proportional limit of about three-quarters the ultimate, and an elongation in 10 in. of about 3 per cent. Hard-drawn copper may be softened by annealing, and its physical properties are then about the same as those of cast copper. Data on the compressive strength and on the shearing strength of copper are very few. The ultimate in compression may be taken as 0.75 the ultimate in tension, and the ultimate in shear as 0.6 the ultimate in tension.

Aluminum.—Aluminum is a silvery white metal of considerable ductility and malleability and of extreme lightness. All clayey earths contain a high percentage of aluminum usually in the form of a silicate, but sometimes in the form of an oxide. At the present time the commercial ores of aluminum contain the oxide or the fluoride. The pure metal is produced by the electrolysis of molten aluminum oxide which is protected by a "slag" of aluminum fluoride. The process is carried on in an electric furnace and the electric current furnishes heat, and also causes the separation of the metal from its ore.

Uses of Aluminum.—Aluminum is used in metallurgical processes on account of its property of "quieting" molten metals which without its addition would boil vigorously under the action of escaping gas.

Aluminum is used alloyed with small amounts of tin and of zinc, and with larger amounts of copper to form several valuable alloys which are discussed later in the chapter. Aluminum either cast or rolled is used for the material of machine parts in which weight is objectionable and in which great strength is not necessary; for example, for the crank and gear cases of motor cars. It is also used for electrical conductors on account of its high conductivity (about 60 per cent. that of copper), light weight, and (in the form of hard-drawn wire) fairly high strength. The burden put on the supporting towers and poles of an electrical power transmission line by the dead weight of wire is about half as much if the conductors are of aluminum as when they are of copper. On account of its high resistance to corrosion aluminum is extensively used for cooking utensils.

Properties of Aluminum.—The salient property of aluminum is its extreme lightness. It weighs about 0.093 lb. per cubic inch as compared with 0.280 lb. per cubic inch for steel. Cast aluminum has an ultimate strength of about 13,000 lb. per square inch with a poorly defined proportional limit of about 9000 lb. per square inch. Hard-drawn aluminum wire has an ultimate of about 30,000 lb. per square inch and a poorly defined proportional limit of about 20,000 lb. per square inch. The ultimate in compression may be taken as 0.75 the ultimate in tension, and the ultimate in shear as 0.6 the ultimate in tension. Aluminum resists very strongly the corroding influence of the atmosphere, but is readily attacked by strong alkalies or organic acids.

Zinc.—Zinc is a bluish-white metal found in nature mainly in the form of the carbonate or the sulphide. In the United States there are extensive deposits of zinc ore in New Jersey, in southwest Missouri, and in southwest Wisconsin. Zinc ore is first roasted to transform the sulphide or the carbonate to zinc oxide. The oxide is then heated with charcoal or some other cheap form of carbon. The carbon combines with the oxygen of the oxide; pure zinc is separated from the ore, is volatilized, and the metal vapor is conducted to cooling chambers where it is condensed to liquid form and poured into small ingots. Zinc thus produced is commonly known as spelter. Spelter is remelted and rolled into sheets. The rolling is done at a temperature of about 250°F., and it is important that the temperature be maintained very closely during rolling, as zinc is much less ductile at temperatures either higher or lower.

Properties of Zinc.—Zinc weighs about 0.27 lb. per cubic inch. Cast zinc has an ultimate strength of about 9,000 lb. per square inch, but no well-defined proportional limit. Rolled zinc has an ultimate of about 24,000 lb. per square inch and a poorly defined proportional limit of about 5,000 lb. per square inch. Zinc resists atmospheric corrosion strongly, but is readily attacked by acids. Of all the commercial metals zinc is the most electronegative. Zinc properly rolled is highly ductile.

Uses of Zinc.—The electronegative action of zinc makes it useful in electric batteries, it is the negative element in practically all primary batteries. Zinc is widely used as a protective coating against corrosion on iron and steel plates. Plates so protected are known as galvanized iron, when the coating is applied by dipping the plate in molten zinc, or by plating the zinc on the iron by electrolysis; and are known as sherardized iron when the coating is formed by the condensation of volatilized zinc dust on the iron. To a limited extent zinc plates are used for roofing and spouting for houses on account of the corrosion-resisting powers of zinc. Zinc is rarely used as a stress-carrying member of a machine or structure; in some cases zinc strips have been used to support electric cables which are exposed to the corroding action of the atmosphere. Zinc is an important ingredient in various alloys, and its use as an alloy material is discussed in succeeding paragraphs.

Non-ferrous Alloys.—A large variety of useful metals are produced by melting together various combinations of the commercial non-ferrous metals. The study of the nature of the alloys thus produced is an interesting chemical problem. In some cases the resulting alloy seems to be merely a mixture of the elementary metals which may be present in almost any proportion; in other cases the alloying of certain definite proportions of metals seem to produce definite chemical compounds. In many cases the properties of the alloy differ widely from those of the constituent metals. The properties of an alloy depend not merely on its chemical composition, but also on the methods used in producing it, and on the mechanical treatment it receives.

Copper-zinc Alloys; Brasses.—Copper and zinc alloyed produce brass, one of the commonest of alloys. Copper and zinc can be alloyed in any proportion. The average physical properties of brass with varying percentages of copper and zinc are shown in Fig. 64, which is self-explana-

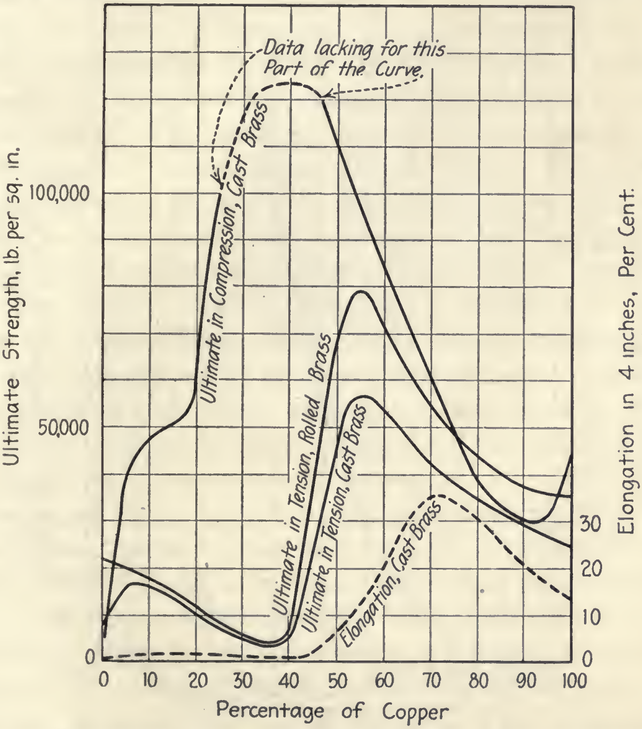

FIG. 64.—Properties of copper-zinc alloys (brasses). The modulus of elasticity for brass varies from 9,000,000 to 14,000,000 lb. per sq. in., averaging about 13,000,000 lb. per sq. in.

tory. Brass can be cast directly into shape, and can be rolled or drawn into sheets, tubes, rod, and wire. It corrodes less easily than iron or steel, and finds a wide use for hydraulic fittings, pump linings, and in places where prolonged exposure to moisture is necessary. Brass costs seven or eight times as much as iron or steel. Brass is a useful metal for bearings. If it is attempted to run a steel shaft in a steel bearing, the rubbing surfaces cut and tear each other. If, however, a softer metal, such as brass, is used as a bearing metal against steel, a smooth surface is worn, and cutting is not so likely to take place.

Copper-tin Alloys; Bronzes.—Copper and tin like copper and zinc can be alloyed in any proportion. The properties of bronze, as the alloy of copper and tin is called, for

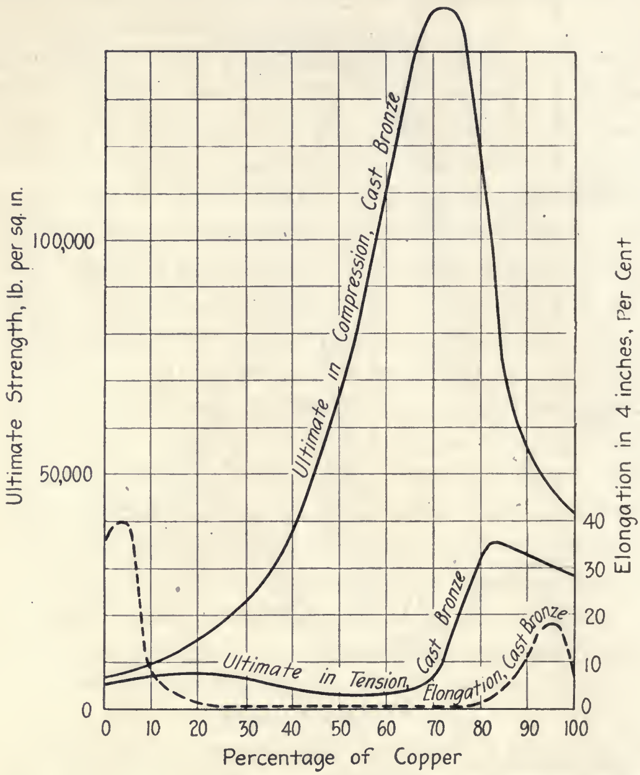

FIG. 65.—Properties of copper-tin alloys (bronzes). The modulus of elasticity for bronze varies from 9,000,000 to 17,000,000 lb. per sq. in., averaging about 15,500,000 lb. per sq. in.

varying proportions of the ingredients are shown in Fig. 65, which is self-explanatory. Bronze can be cast into shape or rolled into wire, rods, and sheets. Its resists corrosion even better than brass, it is more expensive than brass, and its uses are, in general, the same. The terms "brass" and "bronze" are somewhat loosely used in practice, either term being frequently used to denote any yellow metal containing copper in large proportion.

"Season" and Corrosion Cracking of Brass and Bronze.—Brass and bronze rods, tubes, and sheets which are apparently made of perfectly sound metal occasionally develop cracks under light service, or while in storage under no external load. This phenomenon is rather inaccurately known as "season" cracking. It is accelerated by the presence of moisture or moist air, which tends to corrode the metal. Hence the phenomenon is also known as corrosion cracking. This cracking may also be caused by sudden changes of temperature. Brass with a composition varying between 20 per cent. zinc and 45 per cent. zinc seems the metal most liable to season cracking, but other brasses and bronzes, and other copper alloys also suffer from this defect. Season cracking is confined to brass which has been cold-worked, and is caused primarily by the initial stresses set up by that cold-working. Corrosion by roughening the surface sets up localized stresses at the root of the minute pits and corrugations formed, and thus is a contributary cause toward cracking.

Season cracking may be prevented by removing the initial stress, this can sometimes be done by annealing, but in many cases annealing leaves the brass too weak, especially in the case of brass for springs. Very careful heat treatment may reduce the initial stresses to a low value without reducing the strength greatly, but the manipulation is rather too delicate for shop conditions. The introduction of neutralizing stresses by "springing" the metal in the proper direction is used with some success. Keeping the surface of brass parts polished prevents localized stress at the root of scratches and minute corrosion pits, and tends to inhibit season cracking.

Three-metal Alloys.—Alloys with very high strength and ductility can be produced by the proper mixture of copper, zinc, and tin. Table 6 gives the approximate composition and the physical properties of a number of common

TABLE 6.—AVERAGE VALUES FOR STRENGTH AND DUCTILITY OF VARIOUS METALS AND ALLOYS

Values for the strength and ductility of brass (copper-zinc alloys) and bronze (copper-tin alloys) given in Fig. 63 and Fig. 64. Values given are based on test data from various materials testing laboratories. Values for the strength of pure copper, aluminum, and zinc are given in the text of Chap. XIV.

Metal or alloy	Approximate composition, per cent.	Weight, lb. per cu. in.	Strength in tension,[a] lb. per sq. in.		Elongation in 2 in., per cent.
			Proportional limit	Ultimate tensile strength	
Aluminum bronze:					
Cast	Copper 90, aluminum 10	0.27	25,000	60,000	25
Rolled			30,000	70,000	30
Cold-drawn			80,000	90,000	10
Delta metal:					
Cast	Copper 65, zinc 30, iron 5	....	......	45,000	10
Rolled			......	65,000	17
Tobin bronze:					
Cast	Copper 58, zinc 40, tin 2	0.29	25,000	60,000	
Rolled			54,000	79,000	35
Yellow brass:					
Cast	Copper 60, zinc 35, lead 5	0.31	......	35,000	28
Rolled			......	60,000	30
Red brass:					
Cast	Copper 83, tin 4, lead 6, zinc 7	0.31	16,000	30,000[b]	17
Soft gear bronze:					
Cast	Copper 88, tin 10, lead 2	0.32	18,000	32,000	7
Manganese bronze:					
Cast	Copper 60, zinc 39, traces of iron and of manganese	0.30	30,000	70,000[c]	25
Rolled			45,000	75,000	25
Phosphor bronze:					
Cast	Copper 95, tin 4.9, phosphorus, trace	0.32	16,000	32,000	7
Rolled			40,000	65,000	30
Hard-drawn spring wire			......	105,000	5
Admiralty gun metal:					
Cast	Copper 88, tin 10, zinc 2	0.31	10,000	35,000	17
Monel metal					
Cast	Nickel 67, copper 28, iron + carbon + manganese + silicon, 5	0.32	37,000	72,000[d]	34
Rolled			50,000	85,000	42
Lead:					
Cast	Lead 100	0.41	......	1,700[e]	....
Rolled			......	3,300[f]	....
Tin:					
Cast	Tin 100	0.26	1,600	4,000[g]	35
Rolled			......	5,300[h]	....
Antimony-lead:					
Cast	Lead 90, antimony 10	....	4,000	6,900	....

three-metal alloys. It should be remembered that the properties of an alloy depend largely on the proper foundry treatment of the ingredients while the alloy is being melted, such as temperature of pouring, and on the mechanical treatment after melting, such as rolling or drawing out, as well as on the chemical composition. The properties given in Table 6 would be found only in alloys manufactured under good foundry conditions.

The effect of cold-rolling and cold-drawing on the properties of alloys is similar to the effect on iron and steel, namely a raising of the elastic strength of the material, and, especially in the case of the copper alloys, a raising of the ultimate also.

Alloys of Aluminum.—Aluminum is alloyed with copper, magnesium, zinc and other metals. Light aluminum alloys are composed mainly of aluminum, which gives lightness; the alloying metals give greater strength than that of pure aluminum. Like brasses and bronzes aluminum alloys are made stronger by cold-drawing.

Aluminum is used as an alloying element in alloys in which the principal metal is copper, zinc, tin, or a combination of two or more of these metals.

Table 6 gives values of the mechanical properties of a number of the alloys with small aluminum content. Table 7 gives values of the mechanical properties of a number of light aluminum alloys.

Special Alloys.—Space is lacking to enumerate all the alloys of metals in common use. A few alloys of special significance will be briefly noted; the mechanical properties of a somewhat larger number of alloys are given in Table 6.

NOTES TO TABLE 6

[a] If special values for compressive strength are not given the ultimate in compression may be safely taken as equal to the strength at the proportional limit in tension. Strength in shear may be taken as 0.6 of the strength in tension.

[b] Ultimate in compression, 77,000 lb. per sq. in.

[c] Modulus of elasticity in tension, 14,000,000, lb. per sq. in.

[d] Modulus of elasticity in tension, 22,000,000 lb. per sq. in.

[e] Modulus of elasticity in tension, 700,000 lb. per sq. in.

[f] Modulus of elasticity in tension, 1,000,000 lb. per sq. in.

[g] Ultimate in compression, 6400 lb. per sq. in.

[h] Modulus of elasticity in tension, 4,000,000 lb. per sq. in.

Table 7.—Average Values for Strength and Ductility of Aluminum and Aluminum Alloys

The values given in this table are based on data from various testing laboratories.

Metal	Weight lb. per cu. in.	Tensile strength,[a] lb. per sq. in.		Elongation in 2 in. per cent.
		Proportional limit	Ultimate	
Commercial aluminum, 99 per cent. pure:				
Cast	0.093	9,000	13,000	20
Rolled and annealed	0.097	8,500	13,500	23
Hard rolled	0.097	20,000	30,000	4
Wire, hard drawn	0.097	30,000	40,000	6
Aluminum 96 per cent., copper 4 per cent.:				
Cast	0.104	11,500	19.500	12
Hard rolled	0.104	35,000	41,000	5
Aluminum 92 per cent., copper 8 per cent.:				
Cast	0.104	13,000	19,000	2
"Duralumin," aluminum 96 per cent., magnesium 1.5 per cent., copper 2.5 per cent., iron and silicon, trace:				
Rolled and annealed	0.102	......	35,000	22
Cold-rolled	0.102	......	56,000	2
Annealed, then heat-treated	0.102	......	55,000	15
Aluminum 96 per cent., copper 2 per cent., manganese 2 per cent.:				
Cast	0.102	14,300	20,300	5
Rolled	0.102	27,100	38,200	16
"Magnalium," aluminum 95 per cent., magnesium 5 per cent.:				
Cast	0.091	8,000	22,000	7
Aluminum 95 per cent., nickel 5 per cent.:				
Cast	0.093	9,000	21,000	9
Rolled	0.093	13,500	22,300	22
Cold-drawn	0.093	22,900	27,900	8
Aluminum 81 per cent., copper 3 per cent., zinc 16 per cent.:				
Cast	0.106	14,000	35,000	2

[a] The compressive strength of the metals in this table may safely be taken at values equal to the corresponding proportional limit in tension. The shearing strength may safely be taken at 0.6 of the tensile strength.

Aluminum bronze is an alloy of aluminum with copper. The aluminum gives the alloy lightness, while the addition of copper to pure aluminum increases its strength.

Manganese bronze is an alloy of copper with manganese and a little iron. The manganese by its strong affinity for oxygen "cleanses" the metal of any small particles of oxide. Manganese bronze has a very high strength, about equal to that of strucural steel. Manganese bronze resists corrosion by either salt or fresh water remarkably well and is used for propeller wheels and other parts of ships.

Phosphor bronze is prepared by the addition of a little phosphorus to a copper-tin alloy. The phosphorus itself has but little effect on the physical properties of the bronze but it unites with any oxide present, and "cleanses" the alloy from the injurious effects of the oxide.

Monel metal is an alloy of about 67 per cent. nickel, 28 per cent. copper, and the remaining 5 per cent. comprising iron, manganese, silicon, and carbon. It has a strength equal of that of mild steel, and a high degree of ductility. It resists corrosion to remarkable degree, and also resists the action of dilute acids, saline solutions, and many alkaline liquids, unless conditions bring about electrolytic action. Monel metal retains its strength at high temperatures to a greater degree than any other commercial metal with the possible exception of cold-drawn steel. It has been used for steamship propellers, roofing for large railway terminals, steam turbine blades, and valves subjected to high temperature, pump rods and pistons for pumps designed to handle corrosive liquids.

Bearing Metals.—In choosing metals for bearing surfaces where shafts turn in bearings or members slide on one another it is of prime importance that the bearing metals should have sufficient compressive strength to carry the bearing pressure, should wear to smooth surfaces as they rub together, and should develop a minimum of friction when they actually come in contact, as, for example, when a shaft is starting or stopping. All satisfactory bearing metals have a characteristic crystalline structure made up of hard crystals alternating with relatively soft crystals. The hard crystals support the load and resist wear; the softer crystals suffer some plastic deformation and permit the hard crystals to adjust themselves to the surface requirements of the rotating shaft or the sliding member. Moreover, the softer crystals wear slightly below the surface of the harder crystals and thus form minute depressions on the surface which retain lubricant. This retained lubricant is sufficient to keep the bearing from undue friction and heating when starting or stopping. Around a properly lubricated shaft in motion is a film of lubricant, so that the nature of the bearing metal is not of much consequence once the shaft is up to speed, but the lubricant-retaining nature of good bearing metal is of great consequence during starting and stopping. Usually it is found advisable to make the shaft or other moving part of hard metal and the bearing face of soft metal. Steel on cast iron, steel on brass or bronze, and steel on various special soft "bearing metals" are examples of good wearing surfaces. The faces of bearings are frequently made of special "bearing metals" which are soft and which melt at a low temperature. Bearing facings made of such metals can be cast directly in place, and usually require no machining.

The best known of such bearing metals is "Babbitt metal," which has the approximate composition tin 89 parts, copper 4 parts, antimony 7 parts. Another bearing metal has the approximate composition, lead 80 per cent., antimony 20 per cent. Lead alone is too soft for a bearing metal, and the addition of antimony is necessary to give the requisite hardness. A large number of special bearing metals are on the market, most of them alloys of lead, tin, and antimony.

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CHAPTER XV

TIMBER

Uses in Engineering Construction.—Timber has been used as a structural material since the earliest times. It is less costly than iron, steel, concrete, or brick; it is light and handled with ease, and it can be readily sawed and cut to almost any desired shape. On the other hand it is easily destroyed by fire and is subject to decay and these facts greatly diminish its value for permanent construction. In general, at the present day timber is used for cheap or for temporary construction, for structural members (notably railway ties) which must possess a high degree of resilience under shock, and for small members for which lightness is especially important.

Principal Varieties of Structural Timber.—The commercial varieties of wood are divided into two general classes, soft wood and hard wood. The distinction between hard wood and soft wood is not entirely logical. Some of the harder and stronger of the "soft" woods (*e.g.*, yellow pine) surpass in hardness and strength the softer species of "hard" wood (*e.g.*, poplar). The term soft wood is applied to wood from any one of the numerous cone-bearing trees of which the pines, the spruces, the hemlock, the fir the tamarack, the cedar, the cypress aud the redwood are the principal species. Nearly all cone-bearing trees are "evergreens." The term hard wood is applied to wood from the "broad-leaved" trees some of the commonest of which are: the white oak, the red oak, the ash, the hickory, the poplar, the maple, the walnut, the chestnut, the breech, the catalpa, the eucalyptus, and the mahogany. For general structural purposes the soft woods are much more generally used than are the hard woods. The principal uses of the hard woods are for interior finish, furniture, cabinet work, and the like, though white oak and red oak are used for railroad ties, and hickory and ash are used for the wooden parts of vehicles and agricultural implements. Table 8 gives the characteristics and the uses of the more common kinds of wood.

TABLE 8.—CHARACTERISTICS AND USES OF WOOD

See Fig. 66 for location of regions in the United States producing different species of wood.

Species	Characteristics	Uses
Soft woods:		
Yellow pine	Heavy, hard, strong, tough, coarse grained, decays in contact with soil.	Heavy framing timbers, flooring.
White pine	Light, soft, straight grained, not very strong.	Pattern making, interior finish.
Norway (red) pine	Light, hard, corase grained.	All kinds of construction.
Western pine	Trade name for a number of kinds of wood, general characteristics like somewhat like Norway pine.	General construction work.
Douglas fir (Oregon fir)	Hard, strong, wide variations in quality, durable, rather difficult to work.	All kinds of construction.
Hemlock	Soft, light, brittle, splits easily, not durable.	Cheap framing timber, boxes and crates.
Tamarack (larch)	Hard, heavy, strong, durable.	Posts, poles, ship timbers, ties sills.
Spruce	Light, soft, close grained, straight grained, resists decay and marine boring insects.	Framing timbers, piles, underwater construction.
Cedar	Soft, light fine grained, very durable.	Water tanks, shingles, posts, fencing, boat building.
Redwood	Light, soft, weak, brittle, coarse grained, straight grained, easy to work, durable in contact with soil.	Ties, posts, poles, general construction work.
Cypress	Very durable, light, hard, close grained, easily worked, takes high polish.	House siding, shingles, poles, building lumber, interior finish.
Hard woods:		
White oak	Heavy, strong, tough, close grained, splits with difficulty, checks if not carefully seasoned, takes high polish.	Framed structures, interior finish, ties, vehicle and furniture making.
Red oak	Softer, weaker, and more porous than white oak.	Ties, furniture, interior finish.
Hickory	Heaviest, hardest and toughest of American woods. Attacked by boring insects.	Vehicles, handles, agricultural implement manufacture.
Maple	Heavy, hard, strong, coarse grained. Takes good polish.	Flooring, interior finish, furniture.
Ash	Heavy, hard, birttle, "springy."	Interior finish and cabinet work.
Elm	Heavy, hard, strong, tough, very close grained, difficult to split and shape, warps badly.	Vehicle and ship building, sills.

Production of Timber in the United States.—Fig. 66 is a map of the United States showing the location of the principal supplies of timber. The future supply of timber is a question of great importance to structural engineers. At the present time the annual consumption of timber in the United States is about four times the amount of the annual growth of timber. Already several regions formerly supplying great quantities of timber are practically deforested, and the price of timber shows a marked rise from decade to decade. It seems probable that in the future many structures now built of timber will be built of steel, concrete, or brick. Efforts to insure an adequate supply of timber give some promise of success along several lines among which are: the systematic growing of timber on land not suitable for food crops, economy in the use of wood through a careful study of the physical properties of various species and the utilization of species formerly thought unavailable, and such methods of lumbering as will minimize the danger of great forest fires, which in past years in this country have destroyed as much timber as has been used for all structural purposes.

The first step in the production of commercial lumber is "logging," that is the felling of trees in the forest, trimming off branches and vegetation, cutting the trunks and limbs to sizes which can be handled, and transporting the resulting logs to the saw mill. Methods of felling trees, and of transporting logs vary widely according to local conditions. Logging is usually carried on in the winter. During the late fall and winter wood is freer from sap and if cut in that condition decays less rapidly than if cut in the spring or early summer when the sap is more plentiful. At the saw mill the logs are sawed into commercial sizes of lumber, either by rotary saws or by band saws. Poles, posts, and most railway ties are usually hewed to shape rather than sawed.

Seasoning of Timber.—The high moisture content of green timber is reduced by exposure to atmospheric air, or by heating in kilns. The former process is called seasoning,

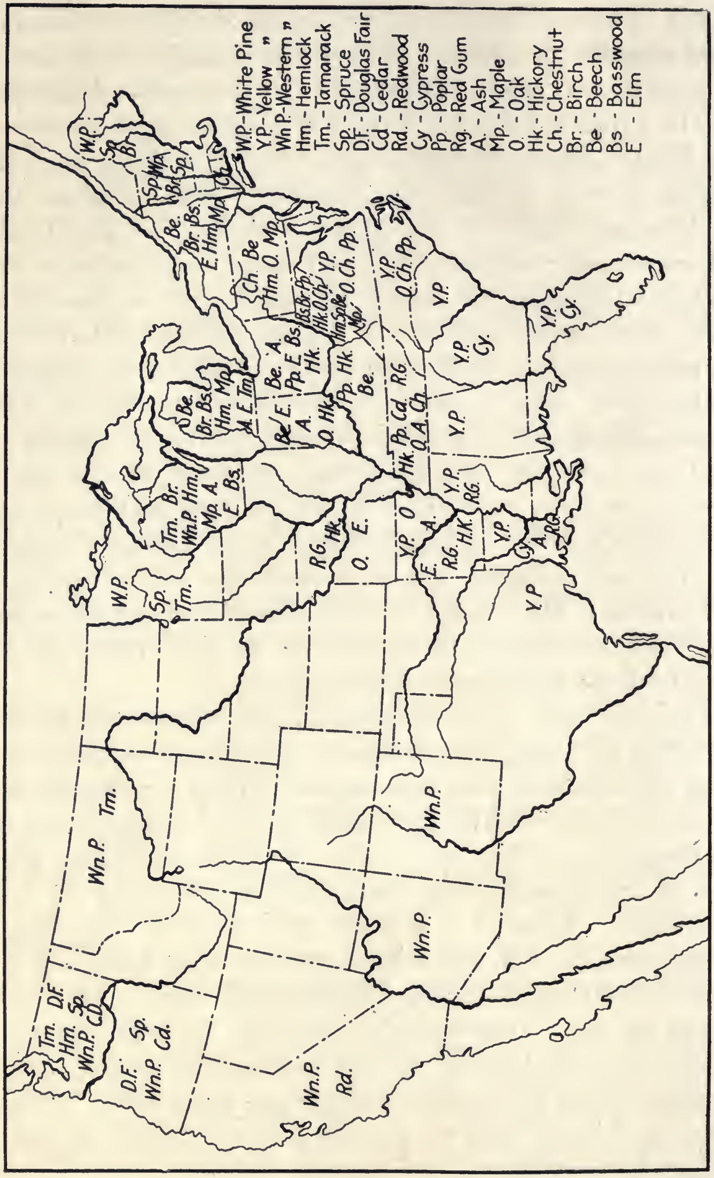

Fig. 66.—Location of timber supplies in the United States. Based on reports of the *U. S. Forest Service* for the production of lumber for 1915. This map shows sources of marketed timber rather than location of standing forests.

and reduces the moisture content from 30 or 35 per cent. to 12 or 15 per cent. During the period of seasoning, timber should be piled so that air has free access to each stick. The time required for proper seasoning varies greatly for different kinds of wood, and for different sized pieces, but is never less than several weeks. Hard wood is usually seasoned for several months before being kiln-dried. Kiln-drying of timber is carried on at a temperature of 158° to 180°F. Kiln-drying reduces the moisture content of timber to about 3.5 per cent. If the timber is allowed to get too hot, chemical changes take place in the wood structure which reduce the strength and the resilience of the wood.

Shrinkage of Timber during Seasoning.—During the seasoning of wood, shrinkage takes place, and the circum-

a. Cracks. *b.* Warping.

FIG. 67.—Defects in wood caused by too rapid seasoning or kiln-drying.

ferential shrinkage of a stick is relatively greater than the radial shrinkage. This is due partly to the resistance to radial shrinkage offered by the rays of the wood, and partly to the fact that in a radial direction the rings of summer wood are resisted in their tendency to shrink by the less shrinkable spring wood, while circumferentially the summer wood shrinks along the rings. The effect of this unequal shrinkage is to set up internal stresses which sometimes cause cracks or checks in timber as illustrated in Fig. 67*a*.

In sawing boards or beams from a log of wood if the log is sawed into parallel strips, as shown in Fig. 68*a*, the boards which are cut squarely across the annual rings are spoken of as "quarter-sawed," while the boards from the edges are spoken of as "slabs." The width of a slab is nearly tangential to the annual rings, and under the unequal shrinkage due to drying the slab is warped much more than the quarter-sawed board. This effect is shown in Fig. 67*b*. The method of sawing shown in Fig. 68*a* is the common method for sawing the ordinary grades of lumber. Fig. 68*b* and 68*c* show methods of cutting boards from a log so that slabs will be eliminated and at the same time waste minimized.

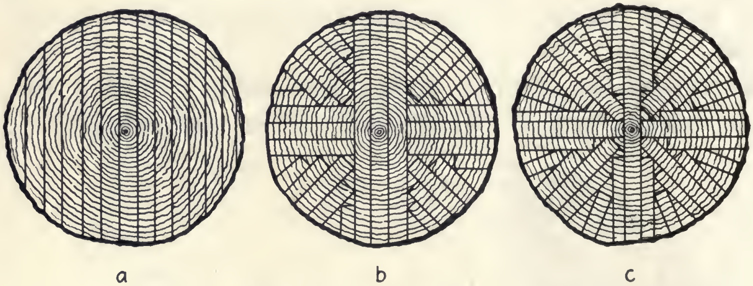

FIG. 68.—Methods of cutting boards from logs.

Classification of Lumber.—The term lumber includes all material sawn from logs, and used for structural or other commercial purposes. The large sizes of structural members, beams, joints, struts, etc., are called timbers. Lumber sawed on all four sides is known as "resawed" lumber, and if this resawed lumber is planed it is known as "dressed" lumber. The actual dimensions of commercial lumber are somewhat less than the nominal dimensions. Lumber sawed to size is not regarded as being "short" in dimension unless an actual dimension is ¼ inch or more under the nominal dimension. For dressed lumber an allowance of ¼ inch for each dressed face is made; a stick nominally 12 in. by 12 in., dressed on the four sides would actually measure about 11½ in. by 11½ in.

The standard lengths for commercial lumber are multiples of two feet, from 10 to 24 feet. The standard widths for lumber are multiple of one inch.

Flooring includes pieces 1, 1¼, and 1½ inches thick, by 3 to 6 inches wide, excluding 1½ by 6.

Boards include lumber less than 1½ inches thick and more than 6 inches wide.

The term plank applies to any piece of lumber from 1½ to (but not including) 6 inches thick by 6 inches or over in width.

Scantling includes all sizes over 1½ and under 6 inches in thickness and from 3 to 6 inches in width.

Dimension limber includes all sizes 6 inches or over in width by 6 inches or over in thickness.

Uses of Timber.—At the present time there are used annually in the United States about 52 billion board feet of lumber.[1] About 28 per cent. of this is used for general construction purposes, 26 per cent. for planing mill products,—sash, doors, and general mill work,—9 per cent. for boxes and crates, 9 per cent. for railroad ties, 5 per cent. for mine timbers, 4 per cent. for pulp for paper manufacture, 2.5 per cent. for car manufacture, 2.5 per cent. for shingles, and the remaining 14 per cent for a large variety of products including furniture, vehicles, lath, veneers, agricultural implements, chairs, poles, ship building, etc. In addition to the above uses of lumber there are used annually about 43 billion board feet of firewood and 6 billion board feet of wood for fence posts and rails.

Structure of Wood.—A tree grows by the annual addition of consecutive rings of wood fiber. The growth takes place on the outside rings. A cross-section of a tree shows a central core or "pith" of small diameter which assists the tree growth by storing up plant food during the first year or two. Outside this pith are concentric rings, usually well marked, which show the growth of the tree from year to year. The width of these rings varies widely in different species of trees, and in different trees of the same species grown under different conditions. The width of rings is a function of the rate of growth of the tree. The

[1] The commercial measure of quantity of lumber is the board foot, one square foot of wood, one inch thick.

outer rings of a mature tree serve as ducts for the passage of sap, which furnishes the plant food necessary for the growth of the tree, and the wood of the outer rings is called sap wood (Fig. 69). The inner rings have ceased to carry sap, and the wood from the inner rings is called heart wood. In general, unless decay has set in, the heart wood is stronger than the sap wood.

In the temperate zone the rate of growth of a tree varies greatly for different seasons of the year. The growth is most rapid in spring, less rapid in summer and early fall,

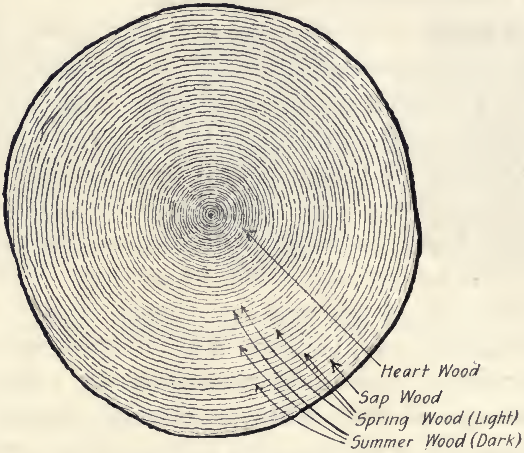

Fig. 69.—Cross-section of tree showing annual rings.

and practically zero for late fall and winter. The "spring wood" is usually lighter colored than the "summer wood" and the annual rings of a tree usually appear distinct on account of the juxtaposition of the dark-colored summer wood and the light-colored spring wood of the next year's growth.

The soft woods are made up for the most part of an aggregation of elongated tubular cells (tracheids) which extend in a direction parallel to the axis of the tree trunk. These cells are closed at the ends and absorb water through their porous walls. At right angles to these tubular cells are numerous groups of cells extending in a radial, direction and called rays. Through these rays plant food is distributed across the tree section. In some soft woods there are longitudinal tubes called resin ducts, in which resin is formed.

The hard woods have a much more complex structure than the soft woods. In hard woods the rays are much larger and more numerous than in soft woods. The elongated tubular cells (tracheids) are of minor importance, and the principal structural elements of the hard woods are longitudinal wood fibers, made up of elongated, sharp-pointed cells with very thick walls.

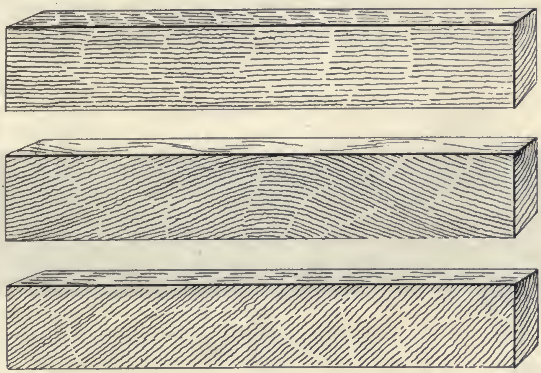

Fig. 70.—The "grain" of wood. Upper stick is straight-grained, lower two sticks show cross-grained or twisted-grained wood.

The general longitudinal direction of the tubular cells which make up the greater part of wood give a distinctive "grain" to its structure. If these cells extend parallel to the axis of tree trunk, the timber from the tree is straight-grained, if the fibers take a spiral course the grain is twisted, and if the "sense" of the spiral (right-handedness or left-handedness) is reversed as the tree grows, the timber is cross-grained. Fig. 70 shows examples of straight-grained, twisted-grained, and cross-grained timber.

When, during the growth of a tree, the trunk end of a branch becomes enclosed by successive annual rings, there is formed a knot in the wood. Knots sometimes constitute serious defects in timber. This will be discussed later.

Strength of Wood.—The strength of timber is affected by a great many factors, and for timber structures, the safe working stresses are very much lower than the ultimate as shown by laboratory tests of specimens; in other words, it is necessary to use a high "factor of safety" for timber. One of the factors which influence the strength is the "grain" of wood. The tensile strength and the compressive strength in a direction parallel to the grain (along the grain) are much higher than in a direction perpendicular to the grain (across the grain). The shearing strength along the grain is much lower than the shearing strength across the grain. The shearing strength of timber along

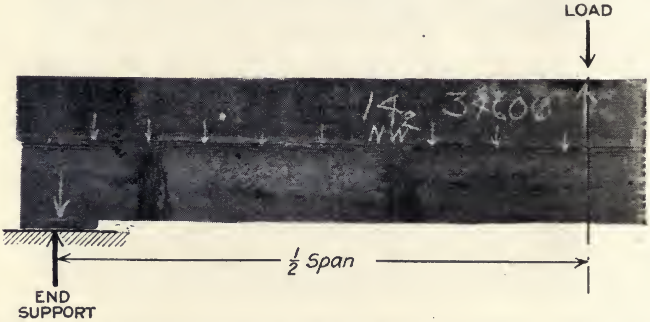

FIG. 71.—Failure of wood beam by horizontal shear. Shear crack can be seen extending along the beam at about mid-depth.

the grain is very much lower than the tensile or compressive strength along the grain, and this fact must be kept in mind when the strength of timber beams is being considered. For this reason the horizontal shear in timber beams is a much more important factor than it is in steel beams, and it must always be taken into account in designing such a beam. Fig. 71 shows a characteristic failure of a timber beam by horizontal shear. The low shearing strength along the grain makes it difficult to use wood for tension members of structures on account of the shearing stresses accompanying tension stresses. Fig. 72*a* shows a stick of timber in tension, held at the ends by bolts through the stick. For this stick there is danger of failure by shear along the line *ac* and *bd* rather than by tension on a cross-section of the stick. To develop the tensile strength of the cross-section it would be necessary to have very long ends. Fig. 72*b* shows a joint between two timbers. The danger of failure by shear along *mn* must be considered as well as the compressive stress on *nq*. The tensile strength of timber is of importance chiefly in the consideration of the tensile stresses in timber beams.

Timber makes good material for compression members, and it is frequently used for such members. In trusses for roofs and bridges it is not uncommon to make the tension members of steel and the compression members of timber. In this connection, however, it must be borne in mind that

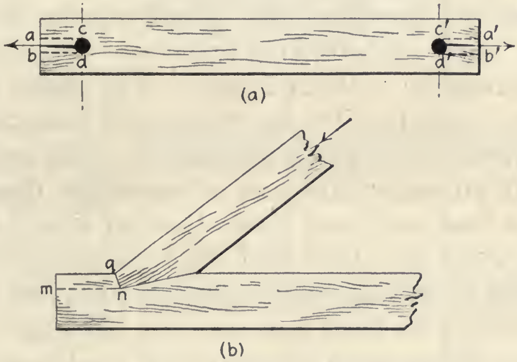

FIG. 72.—Wooden structural parts under stress.

timber has a low modulus of elasticity, that is, its stiffness is low, and its texture is non-uniform, and these facts make long timber columns or beams very sensitive to influences tending to produce sidewise buckling. For wooden columns there should be a large reduction in the average compressive unit stress to allow for the effect of length of column upon allowable compressive stress. Timber is very rarely used for shear members or for torsion members. Table 9 gives average values for the strength of various kinds of wood, as determined by laboratory tests.

Elastic Properties of Wood.—The elastic limit and the proportional limit of wood are less well defined than the corresponding limits for steel, and wood has no yield point.

The proportional limit furnishes the best criterion of static strength, and values of the proportional limit for varous kinds of timber are given in Table 9, which also gives values of the modulus of elasticity for timber. The ratio of strength to stiffness is much higher for timber than for iron or steel, and very much higher than for cast iron or concrete.

Wood is a good material for structural members and machine parts which must withstand shock, such as railway ties, fence posts, spokes and rims of wheels, hammer handles, etc. The reason for this is the fact that resistance to shock depends on two factors: (1) the stress which can be carried, and (2) the deformation (stretch, compression, or deflection) which can be withstood. Wood can not withstand a high unit stress without injury, but can withstand a very large deformation without injury. The *elastic* resistance to impact (resilience) for any material is measured by the area under the stress-strain diagram up to the proportional limit, and an examination of stress-strain diagrams for wood, cast iron, and steel shows that for elastic resistance to shock, wood has about half the capacity per cubic inch of steel, and a much higher capacity per cubic inch for elastic resistance to shock than does cast iron (see Fig. 15, page 31 for typical stress-strain diagrams for steel, cast iron and wood). Wooden parts for structures and machines have, in general, ten or twelve times the volume of steel or cast-iron parts, in order to resist the stresses set up, and as shock-resisting capacity of a member is proportional to the product of its volume and the shock-resisting capacity per cubic inch of the material, wooden structural members have a higher capacity for elastic resistance to shock than do steel members, and a very much higher capacity than do cast-iron members.

In resistance to complete rupture under shock wood ranks higher than does cast iron, but lower than structural steel. Resistance per cubic inch of material to complete rupture under shock is measured by the area under the entire stress-strain diagram. An examination of Fig. 14, page 30, gives

TABLE 9.—STRENGTH AND STIFFNESS OF WOOD

Average results from a large number of tests mainly by the U. S. Forest Service, the University of Illinois and the University of California. For small pieces of wood which can be very carefully selected (such as wood for airplane framework) higher strength values can be obtained.

Species of wood (a)	Weight (dry) lb. per cu. ft.	Strength and stiffness (all values in lb. per sq. in.)							
		Cross-bending			Compression parallel to grain			Compression across grain	Shear parallel to grain
		Modulus of elasticity	Unit stress at proportional limit	Modulus of rupture (computed unit stress at ultimate)	Modulus of elasticity	Unit stress at proportional limit	Unit stress at ultimate	Unit stress at proportional limit	Unit stress at ultimate
		1. Soft wood, full size structural timber with ordinary defects, green (b)							
Yellow pine	34	1,350,000	3,800	4,600	1,100,000	2,800	3,300	440	360
Douglas fir	28	1,550,000	3,900	4,300	1,170,000	2,500	4,400	430	310
Norway pine and white pine	24	1,400,000	2,800	4,100	1,370,000	2,000	2,800	350	190
Hemlock	28	1,700,000	2,900	4,300	2,000,000	3,200	3,900	320	200
Tamarack	31	1,300,000	2,500	3,700	1,300,000	2,200	2,900	300	200
Redwood	22	890,000	2,300	2,600	950,000	2,200	2,900	350	170
Spruce	24	1,500,000	2,500	3,600	1,000,000	2,300	3,000	430	190
Cedar	23	860,000	2,800	3,400	900,000	2,000	2,600	380	130
		2. Soft wood, small, clear test specimens, air-dry (12 per cent. moisture content) (c)							
Yellow pine	34	1,670,000	6,600	11,000	1,450,000	4,100	5,800	900	800
Douglas fir	28	1,700,000	6,700	10,400	1,080,000	3,800	5,000	800	500
Norway pine and white pine	24	1,390,000	6,400	7,900	1,370,000	3,800	5,400	700	400
Hemlock	28	1,670,000	6,300	10,400	1,920,000	4,600	5,400	600	400
Tamarack	31	1,620,000	7,600	13,100	1,350,000	3,700	4,800	700	400
Redwood	22	1,150,000	4,800	7,800	960,000	3,900	5,100	560	330
Spruce	39	1,640,000	8,400	10,000	1,000,000	5,700	7,300	700	800
Cedar	23	910,000	5,800	6,300	900,000	4,000	5,200	700	400
Cypress	29	1,290,000	6,600	7,900	....	.....	6,000	800	500
		3. Hard wood, small, clear test specimens, air dry (12 per cent. moisture content) (c)							
White oak	50	2,090,000	9,600	13,100	....	5,000	8,500	2,200	1,000
Red oak	45	1,970,000	9,200	11,400	....	4,500	7,200	2,300	1,100
Hickory	50	2,400,000	11,500	16,000	....	5,500	10,000	2,700	1,150
Ash	39	1,640,000	7,900	10,800	....	4,000	6,000	1,900	1,100
Elm	34	1,540,000	7,300	10,300	....	5,500	6,500	1,200	800
Maple	43	1,300,000	5,000	7,000	....	5,500	8,000	1,300	500

(a) The wood marketed as Western pine includes several species. It has about the same average strength values as white pine.

(b) For all large structural timber except pieces very carefully dried and protected from reabsorption of moisture test values for green timber should be used. For the rare cases where air-dry timber is used, and can be kept in an air-dry condition the strength values will be increased about 50 per cent. above those given.

(c) For most small pieces of timber it is possible to use air-dry wood and to keep it in that condition. For small pieces which are liable to reabsorb moisture the values given will be diminished by about 33⅓ per cent. For the rare cases where kiln-dry wood can be used and protected from reabsorption of water the values given will be increased by about 33⅓ per cent.

some idea of the relative capacities of wood, steel and cast iron for resistance to complete rupture under shock.

Strength of Large Pieces of Timber.—In using the values of ultimate strength given in Table 9 as the basis from which to determine allowable working stresses for full-sized wooden structural members the effect of size of member must be considered. If the structural member is small, *e.g.*, a rod for the frame of an aeroplane, and a selected piece of clear, straight-grained timber can be used, the values for ultimate strength given in Table 9 for small, clear test specimens could be developed. For a large structural member of the same kind of wood, *e.g.*, for a bridge stringer, the probability of knots, cross-grained wood, and other defects would be high, and the ultimate fiber stress would be that given for full sized structural timbers. Tests of large timber beams and columns always give lower results for ultimate stress than do tests of small selected specimens of the same kind of wood. Table 4 gives working stresses for various kinds of timber, which have come to be considered safe by engineers.

Effect of Moisture on the Strength of Timber.—Structural timber as ordinarily placed on the market contains about 12 per cent. of water. If the timber has been kiln-dried, the moisture content is reduced to about 3.5 per cent. Green timber may contain as high a moisture content as 35 per cent. Up to a moisture content of about 25 per cent. the fibers of the wood absorb water and are softened and weakened by it, especially in compression. Above this saturated condition, which is called the "fiber saturation point" water no longer affects the strength and stiffness of wood. The general effect of moisture content on the strength and the stiffness of soft wood is shown by Fig. 73, the basis of which is found in the results of tests by the U. S. Forest Service, made principally by Mr. H. D. Tiemann. As an illustration of the use of Fig. 73 consider the flexural strength of wood which, when in a green or saturated condition has a moisture content of 25 per cent. If such wood is air-dried until its moisture content is reduced to 12 per cent. it is then $^{12}/_{25}$ or 48 per cent. saturated, and its flexural strength will be increased to about $^{60}/_{39}$ or 154 per cent. of its strength green. If it is kiln-dried until its moisture content is reduced to 3 per cent. it will be $^{3}/_{25}$ or 12 per cent. saturated and its flexural strength will be increased to about $^{90}/_{39}$ or 231 per cent. of its strength green.

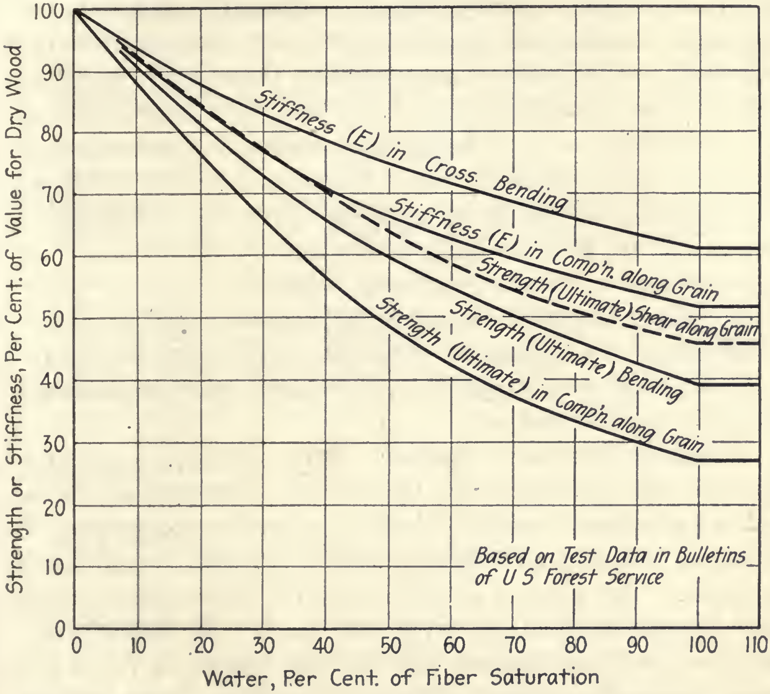

FIG. 73.—Effect of moisture on strength and stiffness of soft wood. For soft wood fiber saturation occurs at a moisture content averaging about 25 per cent.

Time Element in the Strength of Timber.—Under long-continued static loads timber will fail with fiber stresses much lower than the ultimate stresses found by laboratory tests, in which the loading extends over a few minutes. This time effect extends over several months, if not over longer periods of time, for large pieces of timber. Under long-time loading, test pieces of timber have been broken under stresses a little greater than 50 per cent. of the utilmate strength as given by short-time tests. This very pronounced time effect is one of the reasons why working stresses for timber are so low as compared with the utilmate strength as determined by tests in a testing machine.

Relation of Strength and Shrinkage of Timber to Density.—An examination of a large number of test results, made by Newlin and Wilson of the U. S. Forest service have established fairly definite relations between the strength and the shrinkage properties of wood and its specific gravity. In their investigation they determined the specific gravity as the ratio of the weight of a specimen of wood *oven-dry* to the weight of a volume of water equal to the volume of the specimen *at the time of testing.* Calling this ratio G the following equations give the shrinkage in per cent from green condition to oven-dry condition.

Shrinkage in volume, per cent $= 28\ G$
Shrinkage in radial dimensions, per cent $= 9.5\ G$
Shrinkage in tangential dimensions, per cent $= 17.0\ G$

Table 10 gives the relations of strength values established by the study of test data.

Common Defects in Timber.—Some of the common defects found in commercial timber are: cross-grain, knots, splits and cracks (called "shakes"), bark or raggedness of wood at the edges of boards (called "wane"), and pitch pockets. The general requirements for yellow pine bridge and trestle timbers as given by the 1918 "Standards" of the American Society for Testing Materials furnish a good example of reasonable requirements for structural timber. These general requirements read, in part:

"Except as noted all timber shall be cut from sound trees and sawed standard size; close-grained and solid; free from defects such as injurious ring shakes and crooked grain; unsound knots; knots in groups; decay; large pitch pockets, or other defects that will materially impair its strength."

An explanation of some of the terms used in the foregoing paragraph may be of service. Ring shakes are cracks between the annual rings of the wood. "Unsound" knots include loose knots and rotten knots (knots softer than the

TABLE 10.—RELATION OF STRENGTH OF WOOD TO ITS SPECIFIC GRAVITY

Based on the investigation of Newlin and Wilson of the U. S. Forest Service, see Bulletin 676, U. S. Dept. of Agriculture.

G is the specific gravity of the wood, based on the weight oven-dry and the volume at the time of test and in the condition when tested.

Strength property	Green wood	Airy-dry wood
Static flexure:		
Unit stress at proportional limit, lb. per sq. in.	$10,300\sqrt[4]{G^5}$	$19,000\sqrt[4]{G^5}$
Modulus of rupture, lb. per sq. in.[1]	$18,500\sqrt[4]{G^5}$	$26,200\sqrt[4]{G^5}$
Modulus of elasticity, lb. per sq. in.	$2,500,000\,G$	$3,000,000\,G$
Impact flexure with 50-lb. hammer unit[2] stress at:		
Proportional limit, lb. per sq. in.	$23,500\sqrt[4]{G^5}$	$35,000\sqrt[4]{G^5}$
Modulus of elasticity, lb. per sq. in.	$3,000,000\,G$	$3,550,000\,G$
Compression parallel to grain:		
Proportional limit, lb. per sq. in.	$6,800\sqrt[4]{G^5}$	$11,000\sqrt[4]{G^5}$
Unit stress at ultimate, lb. per sq. in.	$6,900\,G$	$12,000\,G$
Modulus of elasticity, lb. per sq. in.	$2,860,000\,G$	$3,500,000\,G$
Compression perpendicular to grain:		
Proportional limit, lb. per sq. in.	$2,900\sqrt[4]{G^9}$	$5,200\sqrt[4]{G^9}$
Shear along grain:		
Unit stress at ultimate, lb. per sq. in.	$2,650\sqrt[3]{G^4}$	$3,800\sqrt[3]{G^4}$

[1] See p. 19 for definition of modulus of rupture.

[2] See p. 281 for description of impact test.

surrounding wood). Pitch pockets are openings between the fibers of the wood, extending along the grain, and containing pitch or bark. A pitch pocket more than ⅜ in. wide or 3 in. long is considered a large pitch pocket.

The Grading of Lumber.—Lumber is graded according to the number, size, and location of the visible defects it contains. For some purposes clear lumber, that is lumber without visible defects, is necessary, while for other purposes lumber with slight defects will serve. For some purposes, such as flooring, lumber is graded by its best side, while for other purposes, such as door stock, the lumber must be free from defects on both sides.

Rules for grading lumber are generally prepared by saw mills associations, or lumber manufacturers' associations covering a certain territory, an issuing rules for grading certain species of lumber.

Veneer, Plywood.—Owing to the increasing cost of hard wood there has been developed the use of boards of soft wood with very thin sheets of hard wood, glued on. These thin sheets are known as veneer, and have been very commonly used to give a hard wood surface to cheap lumber.

Quite recently the idea of built-up lumber has been extended to the development of plywood,—wood built up of this layers with the grain of successive layers at right angles, and all layers glued together with waterproof glue.

Plywood thus made has two advantages over ordinary lumber: (1) the tendency of any layer to shrink transversely to the grain under change of moisture content is resisted on account of the direction of the grain of the adjacent layers, and (2) the net shrinkage of the built-up lumber is only slightly greater than the shrinkage of ordinary lumber parallel to the grain.

The tensile strength of wood across the grain is so small as to be negligible. The arrangement of the layers of plywood gives tensile strength in all directions, the tensile strength of plywood being about half that of ordinary lumber along the grain. The arrangement of the layers of plywood also diminishes the tendency characteristic of ordinary lumber to shear along the grain. Plywood is a material of nearly uniform strength in different directions having a strength about equal to the average of the strength of ordinary lumber with the grain and the strength across the grain. As plywood is built up of thin layers it becomes feasible to use the highest grade of wood in its manufacture.

Plywood is always built up of an odd number of piles, so that the shrinkage stresses will be symmetrical about the middle layer, and there will be no tendency for them to warp the wood. Plywood may be built up of a few layers each conparatively thick, or of a larger number of thinner layers. In general the plywood built up of the large number of layers is moren early homogeneous in its elastic action, but is more expensive to make.

Basswood, redwood, poplar, maple, birch, red gum are domestic woods which can be cut into the thin veneers necessary in making plywood, and from which satisfactory plywood can be made. Basswood, redwood, and poplar veneers are not used for face veneers in making plywood. Table 11 gives values for the tensile strength of three-ply plywood made of various kinds of wood.

When a structure can be so designed that timber can be used as the material without danger of failure by longitudinal shear or by cross-grain tension, no other material will in general, give so light a structure. The use of plywood extends the possibilities of using the lightness of timber construction, by lessening the danger of splitting or shearing along the grain.

Plywood is already of importance in the manufacture of motor cars, street and railway cars, airplanes and boats,—all structures in which it is important to have minimum weight consistent with safety.

It is evident that the strength of plywood will be dependent on the strength of the glue joint between layers of veneer.

TABLE 11.—TENSILE STRENGTH OF PLYWOOD

Based on tests at the U. S. Forest Products Laboratory, Madison, Wis.

Species	Weight of plywood, kiln-dry,[1] lb. per cu. ft.	Moisture at test per cent.	Ultimate tensile strength of three-ply plywood, parallel to grain of faces,[2] lb. per sq. in.	Ultimate tensile strength of single-ply veneer, parallel to grain, lb. per sq. in.
Basswood.....	28	9.2	6,900	10,300
Yellow Birch..	45	8.5	13,200	19,800
Maple, soft ...	38	8.9	8,200	12,300
hard ..	46	8.0	10,200	15,300
Yellow Poplar.	34	3.4	7,400	11,100
Red gum	36	8.7	7,800	11,800
Redwood......	28	9.7	4,800	7,200

[1] About 8 per cent. moisture.

[2] Strength values given are for three-ply wood with plies of same thickness and same species: values for plywood of different make-up would not be the same as those given in the table.

Decay of Wood.—The cells of wood with the water found in them furnish food for a variety of destructive bacteria and fungi. These bacteria and fungi feed on the moist wood fiber and cause rotting of the wood. Lack of moisture diminishes the food value of the wood, and hence seasoning, which removes moisture, diminishes the rapidity of decay of wood and lengthens its life. Well-seasoned timber which is not exposed to moisture retains its strength for many years. The usefulness of the seasoning process in preserving the life of timber structures which are exposed to moisture is limited by the fact that in such structures the wood soon reabsorbs moisture, and again furnishes abundant food for the destructive bacteria and fungi. In this connection it should be noted that timber kept continuously under water does not decay, though in sea water it may be attacked by marine boring animals, such as the teredo.

Preservatives for Timber.—The decay of timber exposed to moisture can be very greatly retarded if the fibers are impregnated with some substance which is poisonous to the decay-causing bacteria and fungi. An ideal preservative for timber would be poisonous to decay-causing organism, capable of being injected into the innermost fibers of the pieces of timber treated, would be retained in the wood, and would be cheap. The two wood preservatives in common use are creosote and zinc chloride. Creosote is an oil, a product of coal-tar distillation. It is poisonous to wood-destroying bacteria, it is not soluble in water, and hence will not be dissolved out of timber of the action of rains or of flowing streams. It can be forced into the inner fibers of soft woods and of some hard woods. Zinc cholride is violently poisonous to timber-destroying bacteria, can be readily forced into the inner fibers of wood, and is cheaper than creosote. It is, however, soluble in water, and is gradually dissolved out of timber which is exposed to water.

Preservative Processes for Timber.—The simplest process of treating timber to preserve it against decay consists in simply soaking the pieces to be treated in an open tank of hot creosote or other preservative. This process does not impregnate the timber very thoroughly, and it is wasteful of preservative. This "open-tank" process is used only for treating small lots of timber where the apparatus for more thorough treatment is not available.

The general method followed in the commercial treatment of timber either with zinc chloride, or, as is more common, with creosote involves the following steps; (1) seasoning the timber; (2) steaming the timber in a large cylinder to soften the wood fiber; (3) the removal of air and moisture from the interior of the cylinder and from the wood fibers by means of a vacuum pump; (4) the connection of the interior of the cylinder with a tank of preservative (creosote or zinc chloride), the preservative rushes into the partial vacuum formed in the cylinder and penetrates some distance into the wood structure; (5) the application of pressure to the cylinder forcing the preservative into the innermost fibers of the timber; and (6) the removal of the pressure, after which the excess of preservative is allowed to drip off the timber and run into a tank.

Uses of Treated Timber.—The treatment of railway ties to preserve them against decay is the most widely developed application of the timber treating process. Usually the tie-treating process is carried on in a large plant, in which several cylinders about 150 ft. long by 10 ft. in diameter receive a number of small cars loaded with ties to be treated.

Timber for piles, especially for piles which are to stand in salt water, is also frequently treated with preservative. Poles for carrying electric wires, and fence posts are sometimes treated by the open-tank process over the ends which are to be placed in the ground.

The life of a soft wood railway tie untreated with preservatives varies from 5 to 8 years, creosoted it will resist decay for 10 to 14 years. If railway ties are to be used in a very dry location, zinc chloride will be almost as effective as creosote in lengthening the life of the tie.

Strength of Treated Timber.—The effect of the preservative processes on the strength of timber has been the subject of much discussion, and several series of tests on the relative strength of treated timber and untreated timber have been made. Injury may be done to the timber if the preservative process is carelessly carried out, especially is there danger of injuring the timber by excessive pressure while it is being steamed. If the preservative process is carefully carried out, tests seem to indicate that the strength of the timber is but little impaired, if at all.

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CHAPTER XVI

STONE, BRICK AND TERRA-COTTA

General Uses of Building Stone.—Since the earliest known times stone has been used as a material of construction for walls, foundations, and dams. Stone arches have been in use for many centuries. Today the use of stone masonry for purely structural purposes is of diminishing importance owing to the great development of reinforced concrete, but building stone is still used for buildings and structures in which appearance and permanence are large factors in design. Of the stone quarried in the United States about 50 per cent. is used for structural purposes, the remainder being used for crushed stone for roads, railroad ballast, and concrete.

Varieties of Building Stone.—The common building stones include granite, limestone (including marble), sandstone, and slate; there are many varieties of each of these general classes. The granites are the hardest and strongest building stones in general use, the sandstones are next in hardness and strength, and the limestones are, in general, the softest and weakest (though the stronger limestones are stronger than the weaker sandstones). The use of slate is, in general, confined to roofing and some interior work in buildings. The harder and stronger a building stone is, the more difficult and expensive it is to quarry blocks of that stone and to dress them to shape. In general, the harder stones are the more durable. The life of American stone structures before disintegration under weathering (the action of frost, chemical action from gases, etc.) is estimated to vary from about 12 years for soft sandstone to several centuries for the harder granites.

Stone Quarrying and Stone Cutting.—Blocks of building stone are cut or blasted from the ledges of rock which constitute a stone quarry. These rough blocks are dressed to shape in stone sheds, usually located near the quarries. The squaring and final shaping of the stone is done by cutting tools operated either by hand, or more commonly, by compressed air. Power-driven planers, lathes, and saws for shaping large pieces of stone are used to a considerable extent, especially for shaping marble.

Masonry Construction.—In laying together individual pieces of stone to form masonry, various methods are followed. The simplest form of masonry is *riprap*, which consists of uncut stones piled together without any adhesive mortar between them. Riprap is used for protective embankments for streams, and for low stone walls. It has very little structural strength, and is not used for structures subjected to any great amount of load. *Rubble* masonry is made up of uncut stones piled and cemented together with a matrix of mortar. In *uncoursed* rubble the stones are piled without any attempt at regularity of arrangement; in *coursed* rubble the stones are piled in layers as regularly arranged as possible. *Squared* stone masonry is built up of blocks of stone dresssed to regular shapes. *Cut* stone masonry or *Ashlar*[1] masonry is built up of blocks of stone squared and with the faces dressed to a fairly smooth surface.

Strength of Stone and of Stone Masonry.—Stone masonry is used in structures principally to resist compressive stress. Individual blocks of stone are sometimes used to resist bending, such as the lintels for windows and doors, or as top slabs for culverts. The strength per square inch of specimens of stone is very much greater than the strength per square inch of masonry built from that kind of stone, on account of the presence in masonry of mortar joints, which are weaker than the stone. Strong stone, in general, makes stronger masonry than does weak stone, and on this

[1] By some authorities the term Ashlar is used only for cut stone masonry in which the joints are not more than ½ in. thick.

account, as well as on account of the occasional use of individual stone slabs in flexure, the strength of different kinds of stone is of importance to the structural engineer. The actual strength of stone masonry depends largely on the strength of the mortar used and on the closeness of fit between adjacent stones. Ashlar masonry is about seven times as strong as uncoursed rubble masonary.

TABLE 12.—VALUES FOR STRENGTH AND STIFFNESS OF AMERICAN BUILDING STONE

Values based mainly on test data from the Watertown (Mass.) Arsenal

Stone	Ultimate in compression, lb. pers q. in.		Modulus of rupture (computed ultimate in cross-bending), lb. per sq. in.		Ultimate in shear, lb. per sq. in.,	Modulus of elasticity (flexure), lb. per sq. in.,	Weight (av.), lb. per cu. ft.
	Range	Av.	Range	Av.	Av.	Av.	
Granite . . .	15,000–26,000	20,200	1,200–2,200	1,600	2,300	7,500,000	165
Marble . . .	10,300–16,100	12,600	850–2,300	1,500	1,300	8,200,000	170
Limestone.	3,200–20,000	9,000	250–2,700	1,200	1,400	8,400,000	160
Sandstone.	6,700–19,000	12,500	500–2,200	1,500	1,700	3,300,000	135
Slate		15,000		8,500		14,000,000	175

The compressive strength, the flexural strength, and the strength in shear of common American building stones are given in Table 12. Allowable loads on different kinds of stone masonry are given in Table 4.

Burnt-clay Products—Brick, Terra-cotta and Tile.—An important class of materials of construction comprises products of clay-burning kilns. The burnt-clay products include building brick, paving brick, firebrick, terra-cotta blocks and tiles, porcelains, drain pipe and sewer pipe. Clay suitable for making common building brick is very common, and large deposits are found in many locations. Special grades of clay are required for making paving brick, for firebrick, for terra-cotta, and for porcelain.

General Process of Brick-making.—The clay is first washed to free if from pebbles, soil, or excessive amounts of sand; it is then ground fine and mixed with water, after which the mixture is reduced to a plastic mass in a "pug-mill," which consists of a horizontal cylinder in which revolving blades slice up the clay, mix it thoroughly, and finally force it out. Brick-making processes are classified as stiff-mud, soft-mud, or semi-dry according to the degree of plasticity of the clay used. After treatment in the pug-mill the plastic mass of clay is molded into bricks, tiles, pipe sections, or blocks. For tiles, sewer pipe, drain pipe, and hollow building blocks this molding is usually done in metal molds under heavy pressure. For bricks the molding is sometimes done in molds, but the method commonly used consists in forcing through a die a ribbon of clay with a cross-section of the size of a brick. From this ribbon bricks are cut off by means of wires. The molded bricks, blocks, or tile are dried for a period varying from a few hours to several days, after which they are burned in kilns for about a week. After burning, the bricks are allowed to cool slowly in the kiln for a period of several days.

Classification of Building Brick.—The bricks from different parts of a brick kiln vary markedly in quality. *Arch* brick or *hard* brick are those which from their position in the kiln have been overburned; they are apt to be warped out of shape by the excessive burning; *red* brick or *well-burned* brick make up the standard output of a brick kiln; *salmon* brick or *soft* brick are underburned brick, which are weak and unsuitable for use except for masonry filling. *Pressed* brick (*repressed* or *face brick*) are brick which after drying and before burning are subjected to heavy pressure in molds. This pressure makes the brick more nearly perfect in shape. It also rounds the corners. Pressed bricks are much more costly than common bricks and are used mainly where appearance is of great importance. The standard size of building brick is 2 in. by 4 in. by 8 in.

Paving Brick and Firebrick.—Paving bricks are usually made from shale (clay hardened to rock-like structure) and in the process of manufacture a higher temperature of burning is used than in making building brick. This temperature for paving brick is so high that the burned clay has a slightly vitreous (glassy) surface. The standard paving brick is 8 to 9 in. long, 3½ to 3¾ in. wide, and 3¾ to 4¼ in. thick.

Firebrick capable of resisting high temperatures may be divided into acid, basic and neutral firebrick. *Acid* firebricks, used for such purposes as the lining of acid-steel furnaces are made from selected fireclay or from a mixture of a silica-bearing material (sand or ganister) and lime. Acid firebricks are burned at a very high temperature. *Basic* firebricks used for the lining of basic-steel furnaces are made from clay mixed with some substance containing magnesium or aluminum (magnesia or bauxite). Basic firebricks are also burned at a very high temperature. Neutral firebricks are made of a mixture of chrome iron and fireclay.

Terra-cotta.—Terra-cotta is made in the same general way as is brick. The raw material is carefully selected clay. Hard terra-cotta cuilding blocks, fireproofing material, and tile are made by burning the clay at such a high temperature that the resulting product has a slightly vitrified surface. Hard terra-cotta is a strong, brittle material. Porous terra-cotta, sometimes called terra-cotta lumber, is made by burning a mixture of clay and straw or sawdust. The combustible straw or sawdust burns out leaving the material light, porous, and tough. Nails and screws may be driven into porous terra-cotta, and a wood saw can be used to cut it. Fig. 74 shows typical forms of terra-cotta units used for building blocks, for fireproofing and also shows typical forms of terra-cotta lumber.

Drain Tile and Sewer Pipe.—Drain tile is made from carefully selected clay. The clay is burned at comparatively low temperatures, and the resulting material is porous so that soil moisture will readily pass through the walls of the drain tile. Drain tile are usually molded by forcing through a die a tube of clay, and cutting off suitable lengths with wire.

Sewer pipe is burned at such high temperatures that the surface of the pipe is slightly vitreous, and in addition a waterproof glaze is given to the surface by the addition of salt during the process of burning. If made without socket ends, sewer pipe is molded as is drain tile; for pieces of sewer pipe with socket ends a separate mold is

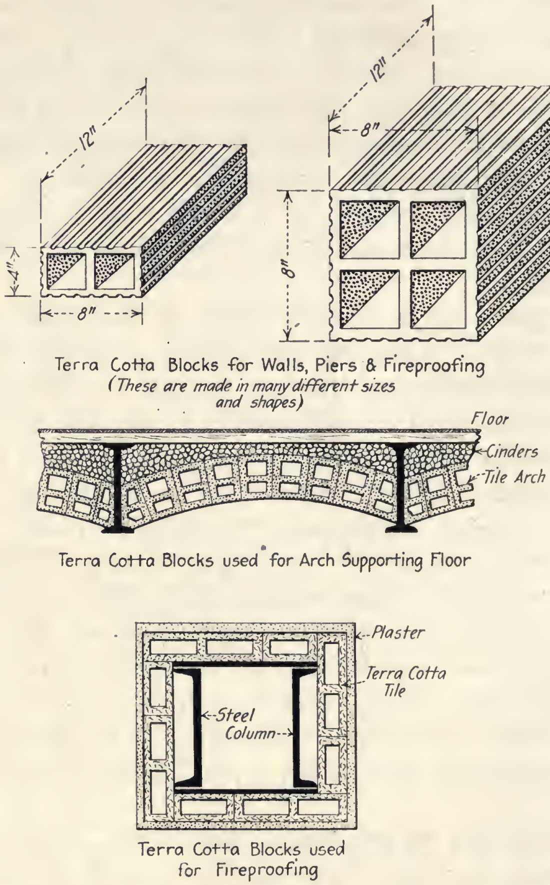

FIG. 74.—Typical forms and uses of terra-cotta blocks.

used for each piece. Sewer pipe is not porous and is used for locations where it is not desired to have the pipe absorb water from the surrounding soil. The joints between different pieces in a line of sewer pipe are made tight by the use of Portland-cement mortar.

Strength of Porcelain and Stoneware.—The strength of porcelain and stoneware, both special burnt clay products, is of importance, especially in connection with the design and use of strain-insulators—insulators for electric transmission lines, which have to carry the load brought on them by the weight of spans of wire. Test data for the strength of porcelain and stoneware are very few. The results of a series of tests by Prof. J. E. Boyd at the Ohio State University indicate that for porcelain the ultimate tensile strength is not less than 3000 lb. per sq. in., and for stoneware, from 1100 to 2200 lb. per sq. in.: the ultimate compressive strength for porcelain and for high grade stoneware is about 20,000 lb. per sq. in., with a proportional limit at about 7000 lb. per sq in.: the modulus of elasticity for both tension and compression is about 10,000,000 lb. per sq. in. for porcelain, and about 7,500,000 lb. per sq. in. for stoneware.

Sand-lime Brick.—Sand-lime bricks are not burnt-clay products, but as they are made of the same standard size as are clay building brick, and as their uses are the same as those of building brick, they will be mentioned here. Sand-lime bricks are made of a finely ground mixture of slaked lime and sand. The materials, thoroughly mixed, are pressed into shape in molds, after which they have sufficient stiffness to hold their form under their own weight. The molded bricks are carried on small cars into a long cylinder where they are subjected to steam at a pressure of about 120 lb. per square inch for a period of about 10 hr. The action of the steam causes cementing action between the lime and the sand, and when the sand-lime bricks are taken from the steam cylinder they have a fairly high strength. The strength of sand-lime bricks increases for some months after they are made. Sand-lime bricks are used for general building purposes. The strength of sand-lime brick is about three-quarters that of ordinary clay building brick.

Strength of Brick and Terra-cotta and of Brick Masonry and Terra-cotta Masonry.—As in the case of stone masonry brick masonry is always used in compression. The compressive strength per square inch of brick masonry is much less than the compressive strength of the individual bricks. In general, strong bricks make stronger masonry than do weak bricks, but the quality of mortar used, the closeness of fit between adjacent bricks, and the care used in laying the brick, all are important factors in the strength of brick masonry. In walls, foundations, and pavements cracks occur most commonly along the mortar joints. When individual bricks break they nearly always crack across by flexure rather than crushing by compression, and the flexural strength of individual bricks is a better general index of their quality than is the compressive strength.

Tests of compressive strength of brick masonry have been made at various testing laboratories. Table 13 gives the summarized results of a number of such tests. Table 4 gives allowable working loads on brick masonry.

Table 13 gives the summarized results of two series of tests of terra-cotta block piers made at the University of Illinois.

Durability of Brick and of Terra-cotta Masonry.—Brick masonry and terra-cotta masonry if well made from good materials are as nearly permanent as any structural material. However, they may finally suffer disintegration under weathering, and usually the freezing and consequent expansion of absorbed water is a prominent factor in the disintegrating process. Porous brick absorbs much more water than does hard-burned brick, and porous brick, in general, weathers poorly. Lime and other salts are dissolved out of brick masonry which is exposed to the weather and sometimes streaks of lime are deposited on the surface of the masonry as the result of this leaching-out action. Sand-lime brick, which when new are nearly white, and other light-colored brick are particularly liable to show disfigurement by the leaching out of salts.

The mortar joints in either stone or brick masonry are especially liable to damage by weathering. Pointing masonry consists in filling the edges of the joints to the depth of about an inch with rich mortar packed in as compactly as possible. This pointing offers resistance to the action of the weather at the joints, and increases the endurance of the masonry.

TABLE 13.—STRENGTH IN COMPRESSION OF BRICK PIERS AND OF TERRA-COTTA BLOCK PIERS

The values given are based on test data from Watertown Arsenal, Cornel University, U. S. Bureau of Standards (Pittsburgh Laboratory) and the University of Illinois.

The weight of masonry may be taken as about 5 lb. per cu. ft. less than the weight of the stone or brick used.

Brick or block used	Mortar	Ultimate in compression, lb. per sq. in.
Vitrified brick........	1 part Portland cement, 3 parts sand	2,800
Pressed (face) brick...	1 part Portland cement, 3 parts sand	2,000
Pressed (face) brick...	1 part lime, 3 parts sand	1,400
Common brick.......	1 part Portland cement, 3 parts sand	1,000
Common brick.......	1 part lime, 3 parts sand	700
Terra-cotta block.....	1 part Portland cement, 3 parts sand	3,000

Test data for piers built of sand-lime brick are lacking, but, judging from test data for individual brick, sand-lime brick piers might be expected to be about three-quarters as strong as piers built of common brick.

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CHAPTER XVII

CEMENTING MATERIALS: GYPSUM, LIME, NATURAL CEMENT, AND PORTLAND CEMENT

Cementing Materials.—A number of substances possess the property when mixed to a paste with water of hardening into a solid under the chemical and crystallizing actions set up in the paste. Such substances are very valuable to the structural engineer. Walls, foundations, piers, and other structural units may be constructed by filling molds with the paste and allowing it to harden into a solid of the desired shape, or the paste may be used as a binding material for the units of brick or of stone masonry. The principal cementing materials used in structural work are gypsum, lime (including quicklime, hydrated lime, and hydraulic lime), natural cement, and Portland cement.

Gypsum.—Gypsum is a combination of sulphate of lime with water of crystallization ($CaSO_4 + 2H_2O$). Large deposits of impure gypsum rock are found in various localities in the United States. If gypsum rock is subjected to a temperature exceeding 212°F. a portion of the water of crystallization is driven off, and the solid residue left, when finely ground, is capable of reabsorbing water and hardening into a solid mass. The nature of the product depends on the purity of the raw materials, upon the temperature used in driving off the water of crystallization, and upon the addition of foreign ingredients to retard or accelerate the set. The products of the calcination of gypsum rock are marketed under a variety of names, such as plaster of Paris, dental plaster, hard wall plaster, Keene's cement, and gypsum plaster.

Manufacture of Gypsum Products.—The general process of preparing gypsum products as used in the United States consists in: (1) grinding gypsum rock, which is the raw material most commonly used; (2) calcining a charge of ground gypsum rock at a temperature varying from 270° to 400°F.; (3) fine grinding of the calcined product; (4) for some gypsum products the addition of substances which retard the setting of the calcined powder when mixed with water. Gypsum plaster to be used for wall finish is rendered more plastic by the addition of clay or of hydrated lime. The cohesiveness of such plaster is increased by adding hair or shredded wood fiber.

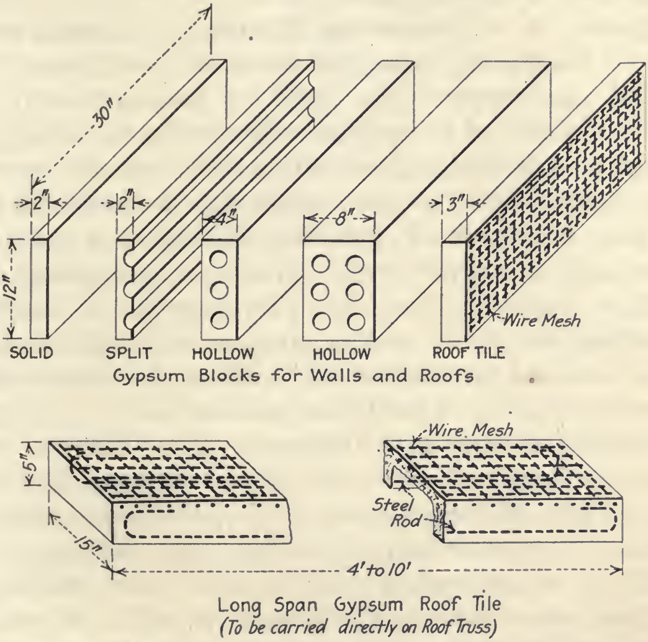

FIG. 75.—Typical forms of gypsum blocks and gypsum tile.

Structural Uses of Gypsum Products.—As a structural material gypsum plaster is very light, is a good fire resistant, is inexpensive, and possesses a fair degree of compressive strength. Its general use is for structural members in which lightness or fire-resisting qualities are of prime importance. Gypsum plasters are widely used for wall finish. Gypsum blocks are used for building curtain walls in buildings (curtain walls are those carrying no load from floors above them), for roof slabs, and for fireproofing around columns. Typical forms of gypsum blocks and tile are shown in Fig. 75. Structural gypsum weighs not more than 80 lb. per cubic foot. The lightness of gypsum makes it possible for workmen to handle large-sized blocks, which makes the work of wall-building or of roof-laying quicker. For roof slabs and floor slabs a mixture of gypsum and wood fiber reinforced with steel wire is used. Gypsum mortar is used for the binding of gypsum fireproofing, and for hard wall finish.

Gypsum as a Fireproofing Material.—Gypsum makes a good fireproofing material for steel structures. The strength of gypsum is destroyed by long-continued heat when the water of crystallization is finally driven off, but a great deal of heat is required to evaporate the water of crystallization, and as the evaporation proceeds the gypsum does not crack or spall, but its surface is converted into an anhydrous powder which acts as an excellent heat insulator, retarding the further evaporation of water of crystallization of the inside layers of gypsum. Gypsum blocks are used for fireproofing in much the same manner as is shown in Fig. 74 for terra-cotta blocks.

Strength of Structural Gypsum.—The ultimate compressive strength of test cylinders of gypsum has been found to vary all the way from 70 lb. per square inch up to 3,000 lb. per square inch depending upon the amount of water used in mixing the gypsum paste, the completeness of drying out of water after the gypsum paste had set, the amount of foreign ingredients mixed with the gypsum to retard its rate of setting, and the temperature used in calcining the gypsum rock. For highest strength the least possible amount of water should be used in mixing the gypsum paste. From 33 to 38 per cent. of water is necessary to make gypsum paste sufficiently plastic to fill molds properly, and this percentage of water is more than sufficient to hydrate the gypsum. For gypsum from the same source of raw material uniformity of consistency of gypsum paste insures a good degree of uniformity of strength.

With care in mixing and drying out, gypsum can be produced regularly with a compressive strength of 1,400 lb. per square inch. However, when practicable tests should be made to determine the strength of any lot of gypsum blocks or other structural members.

Gypsum gains its full strength in a few hours if carefully kiln-dried, and air-cured gypsum gains strength so rapidly that forms may be removed the day after the gypsum is poured. Gypsum is weakened by prolonged exposure to water, and should not be used where it will be kept as oak for considerable periods of time.

The modulus of elasticity for structural gypsum is about 1,000,000 lb. per square inch. The stress-strain diagram for gypsum is very nearly a straight line up to the ultimate.

Lime.—The basis of the cementing action of lime mortar, natural cement, and Portland cement is the absorption of water and subsequent hardening of calcium oxide or calcium hydroxide. Calcium oxide (CaO) is known as *quicklime.* It is prepared by heating limestone which is mainly calcium carbonate ($CaCO_3$). Under the influence of heat carbon dioxide is driven off leaving calcium oxide or quicklime. The heating or "burning" of lime is carried on in a brick-lined stack known as a lime kiln. Fuel, usually bituminous coal, is burned on grates at the side of the stack; limestone is fed into the top, the hot gases pass through the limestone, and the quicklime which is produced is removed at the bottom. In another type of kiln alternate layers of limestone and coal are fed into the top of the stack. Quicklime must not be left exposed to the air. If it is so exposed it absorbs carbon dioxide and is then transformed to powdered calcium carbonate (air-slacked lime) and is useless for cementing purposes.

Hydrated Lime.—If quicklime is mixed with about one-third its weight of water it is changed from calcium oxide to calcium hydroxide ($Ca(OH)_2$). This change is accompanied by the evolution of considerable heat and by a very great increase in volume. The product is a fine white powder, which when mixed with more water absorbs water of crystallization and hardens. If it is attempted to use lime as a mortar unmixed with other substances the great shrinkage which takes place while the hardening process goes on causes wide cracks in the hardened mass. A mixture of 1 part lime and 2 parts sand is commonly used to make lime mortar.

Two methods of making lime mortar are in use: in one, quicklime is brought to the place where mortar is to be used, and is mixed with water, or "slaked" on the job by the workman; in the other method the quicklime is slaked at the kiln under expert supervision, and the amount of water necessary for complete slaking, carefully computed, is added. The slaked lime is ground fine, screened through a fine sieve, and packed in bags. On the job this hydrated lime is mixed with sand and water to form mortar.

Lime mortar will not harden under water nor in any place unless air has free access to it. Its principal uses are for the binding material for brick masonry and stone masonry, and for plastering interior walls.

Natural Cement.—During the construction of the Eddystone lighthouse in England the engineer in charge, John Smeaton, discovered that by burning a limestone containing some clay there was produced a lime which would harden under water. This product known as "hydraulic" lime is still widely used in Europe. In America there have been discovered large deposits of argillaceous (clay-bearing) limestone which, when heated to about 2,000°F. give off carbon dioxide, leaving a clinker. This clinker is known as "natural" cement. It will not slake in air, and when mixed with water it hardens either in air or under water. Natural cement varies greatly in quality depending on the clay content of the limestone deposit. It is cheap, and is used to a limited extent for mortar for masonry and for concrete work where strength is not a prime requisite. Its use is decreasing in this country; Portland cement is now generally used rather than natural cement.

Puzzolan Cement and Slag Cement.—In some countries where there are deposits of volcanic ash a cement is made by grinding up clayey material from this ash and mixing it with hydrated lime, giving a hydraulic cement. As such deposits of volcanic material differ greatly in quality the resulting cement is a rather variable material. Puzzolan cement is of historic importance, being widely used in the days of the Roman empire, but except for occasional local use near deposits of suitable volcanic ash it is not much used today.

A cement in which ground blast furnace basic slag is mixed with hydrated lime was formerly quite commonly used. Portland cement has almost entirely displaced it. Slag cement should be carefully distinguished from Portland cement made with blast furnace slag as an ingredient.

Portland Cement.—To the engineer the most important of the cementing materials is Portland cement. This is an artificial mixture of lime-bearing material with clayey material. The mixture is burned to a clinker at a temperature of incipient fusion and afterward ground to a fine powder. Portland cement does not deteriorate to any appreciable extent in dry air, it hardens in air or under water, and in hardening Portland-cement mortar shrinks much less than do other kinds of mortar.

Raw Materials for Portland Cement.—The lime-bearing material used for Portland-cement manufacture is some form of calcium carbonate ($CaCO_3$); limestone, marl, or chalk are the materials commonly used. The clayey materials include clay, shale, and blast-furnace slag (which contains some calcium carbonate also). In the Lehigh Valley region Portland cement is produced from cement rock, which is a natural mixture of limestone and shale in nearly the right proportions for making Portland cement. In the Illinois River region there are found alternate layers of limestone and shale. In the Ohio region great beds of marl furnish the lime-bearing ingredient, and in the Dakota region chalk is used. Near the great pig-iron centers blast-furnace slag furnishes the clayey ingredient and some of the lime, and a very pure limestone is used to furnish the remainder of the lime-bearing ingredient.

Manufacture of Portland Cement.—Fig. 76 shows in diagram the process of making Portland cement. The lime-bearing ingredient and the clayey ingredient for making Portland cement are first crushed to pebble size (unless the raw material is found in a finely divided form). After the crushing the material is dried in horizontal rotary driers. The ingredients are then ground finer in rotating cylinders containing steel balls, which are known as "ball mills," and then are mixed in the proper proportion, which is determined by chemical analysis. After the mixing a third grinding takes place. This is carried on in a rotating tube mill filled with flint pebbles, and the material is reduced to a fine powder. The fine powder is then carried to hoppers from which it is fed into rotary kilns about 120 ft. long. These kilns make about one revolution per minute, and are heated by a burning blast of powdered coal. They are slightly inclined, and the material which is fed gradually travels from one end of the kiln to the other, and is heated to incipient fusion at a temperature of about 2,700°F. At the discharge end of the kiln the clay and lime have been burned to a hard lumpy clinker. This clinker is carried to storage bins where it is cured for about 10 days, after which it is crushed in a rock crusher and then ground into small pieces, in some form of coarse-grinding mill ("preliminary mills" in Fig. 76). At this stage of the process a carefully calculated amount of gypsum is added to retard the rapidity of setting of the finished product. The final step in the production of Portland cement is the grinding of the ingredients in tube mills to a very fine powder.

The above process of Portland-cement manufacture is the one most commonly used in this country, and is known as the dry process. When marl is used as the lime-bearing ingredient the clay and the marl are mixed wet, and the ingredients are pumped into the kiln, drying of the wet mixture taking place in the first part of the progress through the kiln. This process is known as the wet process.

Portland cement is usually packed for shipment in cloth bags, each containing 1 cu. ft. of cement, which

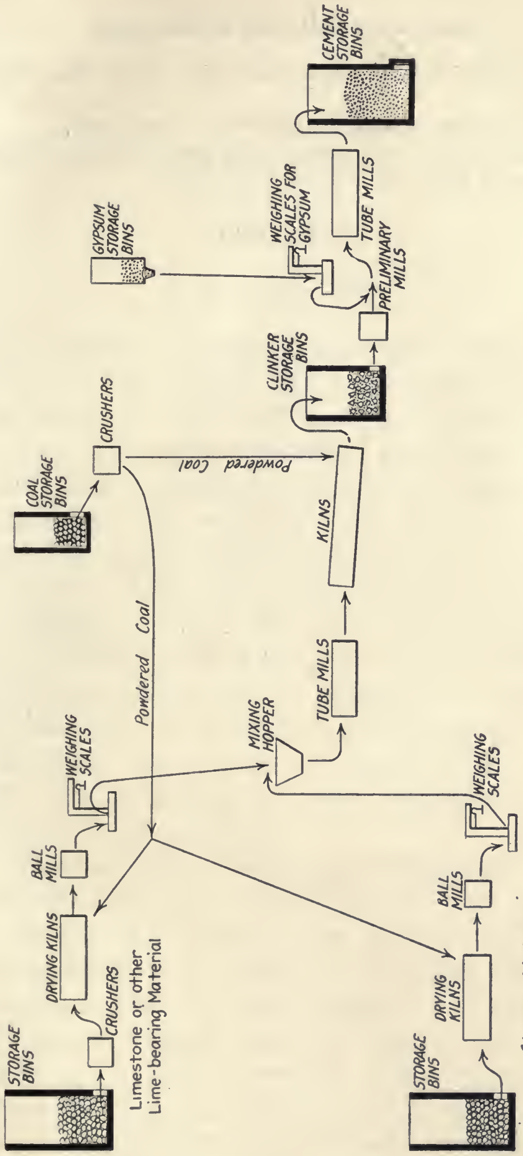

FIG. 76.—Diagram of the process of manufacture of Portland cement.

weighs about 94 lb. Four bags of cement are equivalent to 1 bbl.

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CHAPTER XVIII

CONCRETE

BY H. F. GONNERMAN

Portland Cement Concrete.—Concrete consists of a mixture of cement, water and non-cementing, or inert materials, such as sand and gravel. Portland cement, because of its uniformity, reliability, and strength is generally used as the cementing material in making concrete. Natural and puzzolan cements are used to a very limited extent and then only in special kinds of work. If Portland cement unmixed with other solid materials were used in making buildings, bridges, and other structures, such construction would be very costly and moreover the cement after hardening might show a tendency to crack badly. In order, therefore, to produce an economical and satisfactory building material the Portland cement is always combined with a relatively large proportion of inert, solid material called *aggregate.*

Plain Concrete and Reinforced Concrete.—Concrete is a brittle material and like nearly all other brittle materials is much stronger in compression than in tension. Its tensile strength is so low that it is usually neglected in making computations of the strength of concrete structures. Concrete construction in which concrete alone is used is known as *plain* concrete. Plain concrete is used for massive construction work or for parts of structures carrying only compressive load. Heavy foundations, massive dams, piers, heavy walls, massive arches, sidewalks, and narrow pavements furnish examples of plain concrete construction.

In concrete structural members in which there exists tensile stress the strength to resist such stress is furnished by embedding steel bars in the concrete. Such concrete construction is known as *reinforced* concrete. Some of the principal examples of the uses of reinforced concrete are: beams, columns, footings, floor slabs, roofs, bridges, reservoirs, culverts, chimneys, light arches, and retaining walls. Reinforcing steel is also used in concrete structures such as wide pavements in which stresses due to temperature changes would cause injurious cracks in plain concrete. The somewhat complex mechanics of reinforced-concrete structures will not be taken up in this book.

Concrete Aggregates.—The quality of the aggregates used in making concrete is of very great importance. There is as much likelihood of poor concrete resulting from poor aggregates as from poor cement. Where it can be done the aggregates to be used should be tested by making sample test pieces of concrete, using the aggregates and a good grade of cement, and comparing the strength of these test pieces with that of other test pieces made up with cement from the same lot and with aggregate known to be of good quality.

In general, the qualities which are desired in a material to be used as aggregate in making concrete are : cleanness, hardness, durability, toughness and structural strength. The material should also have proper gradation of size of particles. Among the materials commonly used as aggregate in making concrete are: sand, gravel, broken stone, limestone screenings and cinders. Blast furnace slag has also been used for the aggregate in concrete with satisfactory results. For special purposes other materials than those just mentioned are sometimes used; for example, in the construction of concrete ships a lightweight aggregate consisting of burned clay has been used. By using this material a strong concrete approximately three-fourths as heavy as the ordinary stone or gravel concrete was obtained thus reducing materially the dead weight of the vessel and thereby increasing its carrying capacity.

Aggregates are commonly classed as *fine aggregates,* and *coarse aggregates* depending on the maximum size of the particles composing them. Material having particles ranging in size from the very smallest dust particles to particles about ¼ in. in diameter is called fine aggregate. Sand, gravel screenings, and stone screenings are generally used for the fine aggregate in concrete. Aggregates having particles ranging in size from ¼ in. in diameter to 1½ in. or more are called coarse aggregates. Gravel and broken stone are used in large quantities for coarse aggregate.

In order to produce a dense, economical and strong concrete it is always necessary to use a mixture of fine and coarse aggregate. A mixture of fine aggregate (generally sand), cement and water is known as *mortar.*

To obtain the best results it is essential that both fine and coarse aggregate be clean and *well graded.* An aggregate is said to be well graded when it contains particles or grains ranging in size from the finest to the largest, or coarsest, with the coarser particles predominating. When stone screenings are used for fine aggregate they should be free from dust and the particles should be of angular shape. Particles which are thin, flat and elongated are easily broken. Careful tests have shown that sands having rounded grains are as suitable for fine aggregate in mortar and concrete as are sands having sharp angular particles.

Concrete is frequently given a special name from the kind of aggregate used; thus we have broken-stone concrete, gravel concrete, cinder concrete, blast-furnace slag concrete and rubble or cyclopean concrete (concrete in which part of the aggregate consists of pieces of unbroken rock, sometimes several feet in diameter).

Undesirable Ingredients in Concrete Aggregates.—As previously stated only clean aggregates should be used if the best results are to be obtained. In general, it may be said that most of the trouble experienced with faulty mortar or concrete is due to the presence of undesirable ingredients in the fine aggregate used which is ordinarily a sand. The effect of impurities in the sand on the strength and other properties of mortar and concrete are generally dependent upon the character of the impurities, the richness of the mixture and the grading of the sand. Clay, silt and loam are usually considered undesirable ingredients in concrete aggregate and when present in any considerable amount they should be removed by washing the aggregate before it is mixed with the cement. Some experimenters have found that lean mortars may be helped by the addition of small quantities of fine, pure clay as it increases the smoothness of the mixture and helps to fill voids thus increasing the density and water-tightness of the mortar. In rich mixtures, however, it may have a harmful influence since in these mixtures the cement furnishes all the fine material necessary for high density. Aggregate containing lumps of clay should never be used for mortar or concrete.

Organic material, like vegetable loam, is a very undesirable ingredient in concrete sands even when present in small quantities. Organic material in many instances has been found to retard or prevent the hardening of mortar and concrete and to reduce greatly the strength of concretes and mortars.[1] Sand suspected of containing organic matter should be carefully tested before being used.

Mica is an injurious ingredient in sand or broken stone used for concrete and only aggregates free from mica should be used. If it is necessary on account of local conditions to use aggregate containing undesirable ingredients the

[1] A simple test for detecting the presence of organic impurities in sands which may be used in the laboratory or in the field has been developed by D. A. Abrams and O. E. Harder. The test is known as the "colorimetric test" and is carried out in the field as follows: "Fill a 12-oz. graduated prescription bottle to the 4½-oz. mark with the sand to be tested. Add a 3 per cent. solution of sodium hydroxide (NaOH) until the volume of the sand and solution, after shaking, amounts to 7 oz. Shake thoroughly and let stand for 24 hours. Observe the color of the clear liquid above the sand. If the solution resulting from this treatment is colorless, or has a light yellowish color, the sand may be considered satisfactory in so far as organic impurities are concerned. On the other hand, if a solution which is dark red or black in color is produced, the sand should be rejected or used only after it has been subjected to tests for strength in a mortar or concrete."

concrete should be made richer in cement than would be necessary for clean, well-graded aggregate.

Proportioning Aggregate and Cement for Concrete.—The problem that confronts the engineer in proportioning cement and aggregate for concrete is to produce from the materials at his disposal, a concrete which shall possess certain definite physical properties with the least expenditure for materials and labor. The properties desired in the concrete are generally governed by the use to which the concrete is to be put. In concrete roads or pavements resistance to wear or abrasion is desired. In buildings concrete of high strength is desired, while in reservoirs and tanks the concrete must be strong and must also be impermeable, or watertight. In order to produce a concrete of the desired strength with the use of as little cement as possible careful consideration must be given to the proportioning of the concrete materials. The cement is always the most expensive ingredient in concrete and by properly proportioning the cement and the available aggregates it is often possible to effect a considerable saving in cement and still produce a concrete which will fulfill all the requirements for strength, abrasion, and watertightness. Generally speaking, for maximum strength, maximum resistance to passage of water, maximum resistance to wear and maximum resistance to disintegration by such agencies as acids, alkalis, or electrolytic action concrete should be of maximum *density*. Density[1] (also called "solidity ratio") of concrete means the ratio of the absolute volume of the solid particles of cement and aggregate to the volume of the resulting concrete. In any mass of sand, gravel or broken stone there are spaces between the individual particles. These spaces are known as *voids*. In dense concrete all the voids are filled and the surfaces of the individual particles are thoroughly coated with cement paste. With different aggregates there is a wide

[1] The density of mortars ranges from about 0.60 to 0.75 and the density of concretes from 0.70 to 0.90 depending on the character and grading of the aggregate, the amount of cement, and the amount of water used.

variation in the amount of cement paste required to fill all the voids and coat all the individual particles. The voids[1] in coarse aggregates graded from ¼ to 1½ in. will generally range from 35 to 50 per cent. of the volume of the aggregates. The voids in the common sands range from 28 to 40 per cent., depending on the grading of the sand and the amount of moisture which it contains. Well-graded, dry mixtures of fine and coarse aggregates which have a wide assortment of individual particles may have voids as low as 12 per cent. Aggregates in which the individual particles are of approximately equal size have a much larger percentage of voids than well-graded aggregates.

Well-graded aggregate in general makes stronger concrete for a given proportion of cement than does an aggregate in which the coarse and fine particles are nearly uniform in size. It rarely happens that natural mixtures of sand and gravel as found in banks and gravel pits have such proportions of fine to coarse particles as will make the best grade of concrete unless a relatively large amount of cement is used (see reference at end of chapter to paper by R. W. Crum). On important work it is necessary to make up an artificial mixture of sand and broken stone or gravel which shall be well graded.

Several methods are employed by engineers to determine the amount of cement and of fine and coarse aggre-

[1] When the specific gravity S, and the weight per cubic foot W of the dry material are known, the per cent. voids P may be computed from the formula $P = 100\left(1 - \frac{W}{62.4S}\right)\cdot$ The following table which is taken from Taylor and Thompson's "Concrete, Plain and Reinforced" gives average values of specific gravity for various concrete aggregates:

Material	Specific gravity	Material	Specific gravity
Sand................	2.65	Limestone.............	2.60
Gravel...............	2.66	Trap..................	2.90
Conglomerate.........	2.60	Sandstone.............	2.40
Granite..............	2.70	Bituminous cinders.....	1.50

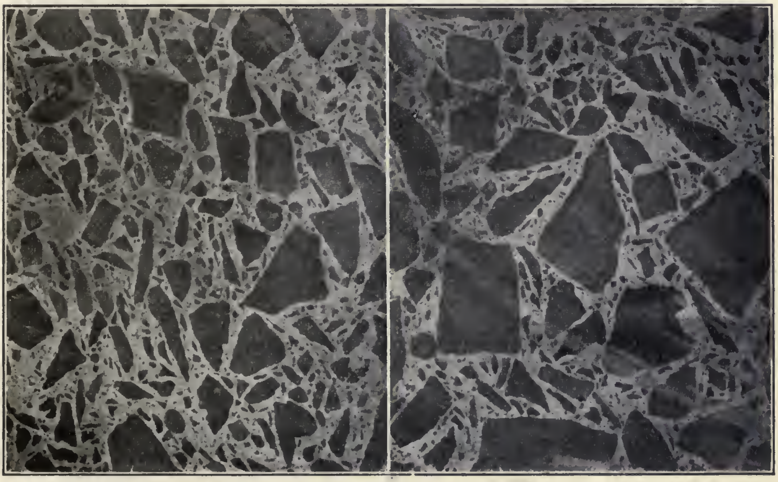
gate to be used in order to produce economically a concrete of acceptable quality. The more important of these methods of proportioning will now be described.

Proportioning by Arbitrarily Selected Volumes.—This method of proportioning is more widely used at present than any other. It consists in mixing arbitrarily selected volumes of cement, fine aggregate and coarse aggregate, the exact proportions depending on the voids in the aggregate and the use to which the concrete is to be put. In this method of proportioning it is assumed that a coarse aggregate of good quality from which the finest particles have been screened will require, for a workable concrete in which all the voids are filled, an amount of sand from 40 to 60 per cent. of its volume, or an average of 50 per cent. under ordinary conditions. Although the cement and water used will give a volume of mortar slightly in excess of the volume of the sand it is often specified that one volume of fine aggregate to two volumes of coarse aggregate be used. The ratio of the volume of cement to the volume of the fine aggregate is determined by the engineer from experience and from a consideration of the properties which the concrete should possess. Thus we often see specified 1:1½:3 (1 volume of cement, 1½ volumes of fine aggregate and 3 volumes of coarse aggregate), 1:2:4, 1:2½:5, 1:3:6: and 1:4:8 concrete. If the voids in the coarse aggregate are greater than usual the amount of sand is increased and proportions such as 1:2:3, 1:3:5, or 1:4:6 may be used. In case the voids in the coarse aggregate are low, the amount of sand is decreased and proportions such as 1:1½:4, 1:2:5, and 1:3:7 are used. For well-graded aggregate common proportions of cement and aggregate for concrete are: for very rich concrete for columns, or other structural members carrying unusually high compressive stress, 1 part cement, 1½ parts fine aggregate and 3 parts coarse aggregate; for general use for beams, floor slabs and other stress-carrying structural members, 1 part cement, 2 parts fine aggregate and 4 parts coarse aggregate; for "lean" concrete for massive work or filling, 1 part cement

3 parts fine aggregate and 6 parts coarse aggregate. All the above proportions are by volume.

Proportioning by arbitrarily selected volumes has, in general, given good results when used by experienced engineers. Large differences in results may be obtained if care is not used in handling and measuring the materials. Frequently a larger quantity of cement than necessary is used and consequently this method is not as economical as other methods in which the materials are proportioned more scientifically..

Proportioning by Voids in Aggregate.—In this method, which is occasionally used, the proportions are based upon the voids in the fine and the coarse aggregate. Having determined the voids in the fine and coarse aggregate in the condition in which they are to be used on the work, enough fine aggregate is used to fill the voids in the coarse aggregate and enough cement to fill the voids in the sand. It is assumed that the particles of cement will fit into the small voids in the sand and that the particles of sand are fine enough to fit into the voids in the coarse aggregate without increasing the volume of the latter. Since it has been found that the particles of sand will increase the volume of the coarse aggregate by pushing the particles apart it is customary to add a volume of sand from 5 to 10 per cent. in excess of the voids in the coarse aggregate, and also to use an amount of cement slightly in excess of the voids in the sand in order to provide enough paste and mortar to fill all the voids in the final mixture. Sometimes the voids in a mixture of fine and coarse aggregate are determined and then an amount of cement is used which is slightly in excess of the voids in the mixed aggregate. Another method is to use a volume of mortar having a fixed ratio of cement to sand, which is sufficient to fill completely the voids in the coarse aggregate. These methods of proportioning are not accurate since the voids in the aggregate may vary greatly because of differences in compactness due to differences in methods of handling the materials and also because the volume of the voids in the fine aggregate is greatly influenced by the amount of moisture it contains. Furthermore, if the fine aggregate contains much fine material, the particles of cement will separate the particles of the fine aggregate and since the fine aggregate generally contains particles too coarse to fit into the voids of the coarse aggregate, they in turn force the particles of the coarse aggregate apart as shown in Fig. 77 and increase its bulk. This separation of the particles of the aggregate reduces the density and strength of the resulting concrete.

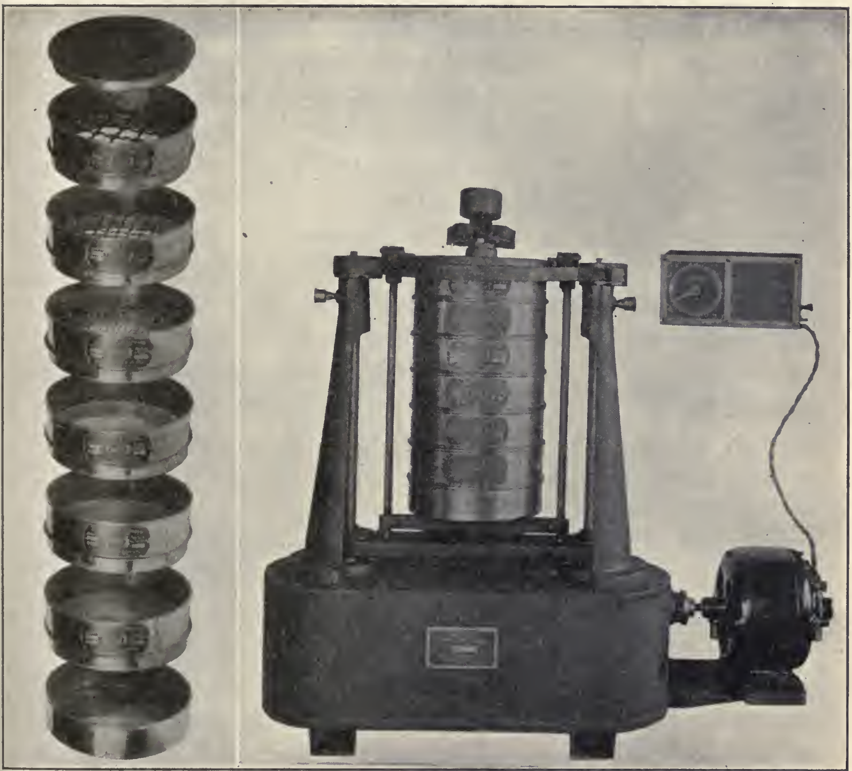


Courtesy of U. S. Bureau of Standards.

FIG. 77.—Photographs showing the wedging action of sand in forcing apart the coarse aggregate and the advantage of using a large aggregate which reduces the voids and the surface area to be coated with cement paste.

Proportioning by Trial Mixtures.—This method of proportioning is based on the assumption that with given materials and a fixed ratio of cement to total aggregate that mixture of cement, water, fine aggregate and coarse aggregate which gives the least volume of fresh concrete will give the densest and consequently the strongest concrete. Trial mixtures are prepared in order to determine the proportion of fine aggregate to coarse aggregate which will give the greatest density when mixed with the amount of cement to be used on the work and with the amount of water necessary to produce a concrete which is workable and easily placed. In making these trial mixtures all the materials used are accurately weighed and after a batch of concrete has been made it is placed a little at a time in a cylindrical measure of constant cross-section and carefully tamped or puddled. After all the material is in the cylinder the height of the fresh concrete is noted and recorded. The concrete is then removed from the cylinder and the cylinder is cleaned. A new batch of concrete is then prepared using the same weight of cement and water as before and the same total weight of fine and coarse aggregate, but changing the ratio of the weight of the fine to the coarse aggregate. This new batch of material is then placed in the cylindrical measure and the height of the fresh concrete noted. The information gained after a few trials will serve as a guide in making up other trial batches which will give dense mixtures. The process is repeated until a ratio of fine to coarse aggregate is found which gives the least height in the measure and at the same time produces a workable concrete in which all the voids are filled. The mixture which gives the least height, or the smallest yield, and at the same time gives a smooth-working concrete will be the densest which can be easily placed in the forms and should give relatively high strength. This method of proportioning when carefully carried out will give accurate results, and is a convenient method of determining the best combination of natural mixtures of fine and coarse aggregate.

Mechanical Analysis and its Application to the Proportioning of Concrete.—In the various methods of proportioning which have been described in the preceding pages the proportioning is done by what may be termed "rule of thumb" or "cut and try" methods. In these methods of proportioning no attempt has been made to determine the sizes of the various particles composing the fine and coarse aggregate for the purpose of studying the effect of variations in the sizes of particles on the density, strength and other properties of the mortar or concrete. Mechanical or sieve analysis of an aggregate consists in separating the aggregate into the various sizes of particles of which it is composed. It gives very important information on the grading of the aggregate and it enables the engineer to make intelligent use of the materials at his disposal when proportioning them for concrete. Mechanical analysis



a *b*

Courtesy of the W. S. Tyler Co.

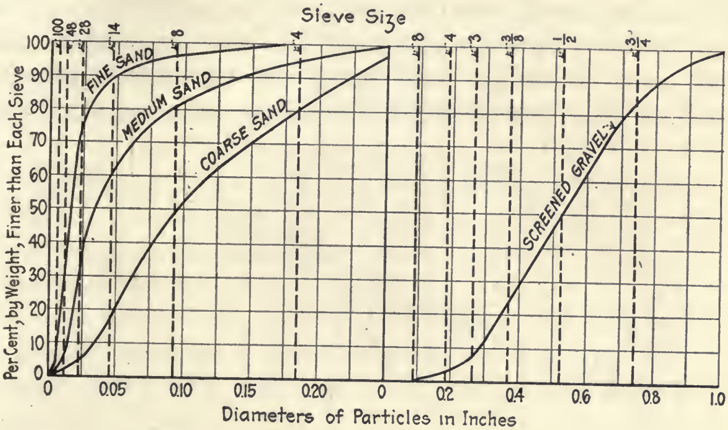
Fig. 78.—Views showing a series of testing sieves and a motor-driven sieve shaker.

is also of great aid to the engineer in establishing scientific methods of proportioning.

In making a mechanical analysis of an aggregate a representative sample of the aggregate is taken and dried after which a definite weight of the dry aggregate is placed on the uppermost of a series or nest of sieves, like that shown in Fig. 78(*a*). Each of the different sieves has openings of definite size. The sieves are shaken either by hand or by power until the sample of aggregate has been separated into its component particles by the sieves. The sieves used are so arranged that the coarsest sieve, the one having the largest openings, is at the top of the series, the sieve of next largest opening being placed immediately below it and so on, each succeeding sieve having smaller openings than the sieve immediately above it. A pan is provided at the bottom of the series to catch the material which passes the finest sieve. The number of sieves to be used in making mechanical analyses of aggregate depends largely on the character of the aggregate to be tested and the use to be made of the results. In testing fine aggregates six sieves are commonly used. In testing coarse aggregates four or five sieves are used. A sieve which is of convenient size for ordinary use is 8 in. in diameter and 2¼ in. high. Fig. 78(*b*) shows a series of sieves in a motor-driven shaker which is equipped with an electric time switch for stopping the shaker automatically after a predetermined period of time.

When the sample of aggregate after thorough sieving has been separated into the various sizes of particles, the amount of material caught or retained on each sieve and in the pan is carefully weighed. Then beginning with that caught in the pan the weights of material retained on the successive sieves are added and each sum thus obtained gives the total weight of the particles which have passed through a given sieve. For convenience in interpreting and plotting the results, the weights of material passing a given sieve are expressed as percentages of the total weight of material used in the analysis. In plotting the results of an analysis the sieve openings are generally plo ted as abscissas and the percentages passing a given sievetare plotted as ordinates. Fig. 79 illustrates the method of recording and plotting mechanical analyses of fine and coarse aggregate.

The curves in Fig. 79 are called mechanical analysis curves. They show graphically the sizes of the particles composing an aggregate, or the *granulometric composition* of the aggregate as it is sometimes called. By the use of such curves the engineer is able to tell what sizes of particles should be added or what sizes should be omitted in



SIEVE ANALYSES OF FINE AGGREGATE										
MESH	SIZE OF OPENING INCHES	WEIGHT OF PARTICLES IN GRAMS						PERCENT FINER THAN EACH SIEVE		
		RETAINED ON SIEVES			PASSING EACH SIEVE					
		FINE SAND	MEDIUM SAND	COARSE SAND	FINE SAND	MEDIUM SAND	COARSE SAND	FINE SAND	MEDIUM SAND	COARSE SAND
3	0.263	0	0	0	1000	1000	1000	100	100	100
4	0.185	0	50	200	1000	950	800	100	95	80
8	0.093	40	140	300	960	810	500	96	81	50
14	0.046	70	210	330	890	600	170	89	60	17
28	0.0232	160	250	130	730	350	40	73	35	4
48	0.0116	440	300	20	290	50	20	29	5	2
100	0.0058	240	30	10	50	20	10	5	2	1
PAN		50	20	10						

SIEVE ANALYSIS OF COARSE AGGREGATE				
SIEVE SIZE	SIZE OF OPENING INCHES	WEIGHT IN GRAMS		PERCENT FINER THAN EACH SIEVE
		RETAINED ON SIEVES	PASSING EACH SIEVE	
1 IN.	1.050	0	10000	100
3/4 "	0.742	1600	8400	84
1/2 "	0.525	3400	5000	50
3/8 "	0.371	2500	2500	25
3 MESH	0.263	1800	700	7
4 MESH	0.185	400	300	3
8 MESH	0.093	300	0	0
PAN		0		

FIG. 79.—Method of recording and plotting sieve analyses of fine and coarse aggregates.

order to improve the grading of an aggregate. By adding or screening out certain sizes of particles he is able to obtain nearly ideal material so far as grading of the material is concerned. Mechanical analyses of aggregates thus furnish the engineer with information concerning the materials which is of great aid to him in determining what proportions of different aggregates will give the best results.

Fuller and Thompson's Method of Proportioning Concrete.—Mechanical analysis was probably first made use of in this country in proportioning concrete materials by W. B. Fuller and Sanford E. Thompson who nearly twenty years ago made extensive tests to determine what combinations of sizes of particles of fine and coarse aggregates when mixed with a given percentage of cement by weight would give the densest mixture. In the experiments gravel and broken stone were used for the coarse aggregate and sand and screenings were used for the fine aggregate. Enough water was added to the various mixtures of cement

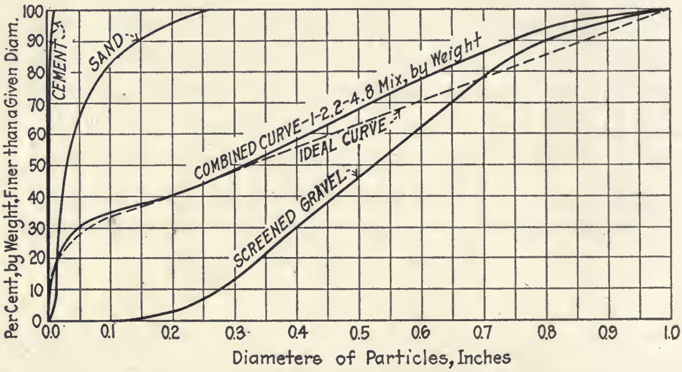
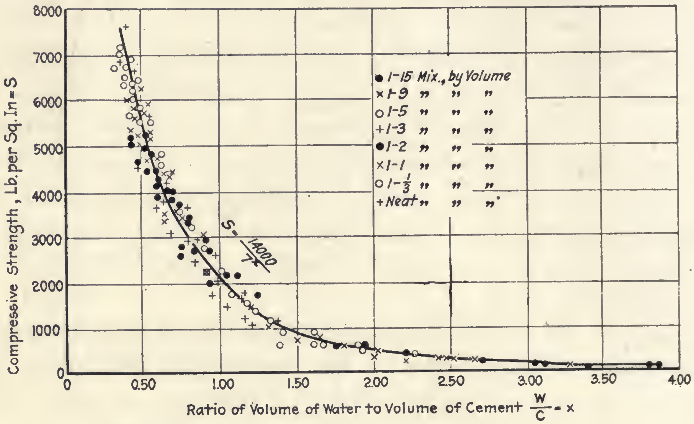


FIG. 80.—Sieve analysis curves of cement, sand and gravel also ideal and combined curves for these materials.

and graded aggregate to produce a concrete of the proper consistency. After mixing the materials the volume of the resulting concrete was carefully determined and from this volume the density of the concrete was calculated. It was found that for the materials used, the mechanical analysis curve of the mixed aggregates and cement which produced the densest, strongest and most impermeable concrete resembled a parabola and consisted of a combination of an ellipse and a straight line. In Fig. 80 is shown such an ideal curve for a mixture of cement, sand and gravel based on data obtained by the tests of Fuller and Thompson. The combined curve shown in Fig. 80 was drawn using the sieve analyses of the medium sand and screened gravel given in Fig. 79. It is seen that by mixing the cement, sand and gravel in the proportions 1:2.2:4.8 by weight, the ideal curve is fairly closely approached.

For the proportions used in the tests made by Fuller and Thompson which were 1:9 by weight, the average gain in strength obtained by grading the aggregates was about 14 per cent. The statement is made that by this method of proportioning water-tight concrete has been secured with graded materials mixed in the proportions of one part cement to three parts fine aggregate and seven parts coarse aggregate, whereas for water-tight concrete for materials which are not carefully graded, a 1:2:4 mix is generally used. It is evident that by careful grading a considerable saving in cement may be made. In general, this method of proportioning will give a dense, impermeable concrete, and on large construction work has been found to be economical provided the cost of screening and handling the available aggregates is less than the cost of the additional cement required to produce concrete of equal quality from ungraded material.

Abrams' Fineness Modulus Method of Proportioning Concrete.—In Bulletin 1 of the Structural Materials Research Laboratory, Lewis Institute, Chicago, entitled "Design of Concrete Mixtures," a new method of proportioning concrete based on the results of several extensive series of tests is advanced by the author, Prof. D. A. Abrams. The basic principle of Prof. Abrams' theory of proportioning is that with given concrete materials and conditions of test, the quantity of mixing water used determines the strength of the concrete so long as the mix is of workable plasticity. The general relation between the compressive strength and the water content of concrete as determined by Prof. Abrams from the results of an elaborate series of tests is shown in Fig. 81. The results given in Fig. 81 cover a wide range of mixes and for each mix, except the neat cement, the maximum size of the aggregates used ranged from that which passed a 14-mesh sieve to that which passed a 1½ in. sieve. Furthermore, for all mixes and gradings there was a wide variation in the amount of water used. The water content of the concretes represented in Fig. 81 is expressed as a ratio of the volume of cement used, 1 cubic foot of cement being considered to weigh 94 lb. The legend given in the diagram serves to distinguish the various mixes, but no distinction is made either between the aggregates of different maximum size or between the different consistencies used. The data for dry concretes or concretes which were not easily workable are not included in the diagram. If the data for these



Courtesy of D. A. Abrams.

FIG. 81.—Relation between compressive strength of concrete and water-cement ratio. Twenty-eight day tests of 6 × 12-in. cylinders.

concretes had also been plotted a series of curves (similar to the curve shown in Fig. 93) extending downward and to the left from the main curve would have been obtained.

Prof. Abrams makes use of sieve analysis in proportioning the aggregates in concrete mixtures and has found that there is a close relation between the size and grading of an aggregate and the quantity of water required to produce a workable concrete. Prof. Abrams has developed a method of measuring the effective size or grading of an aggregate and uses for this purpose a function which he terms *fineness modulus*. Fineness modulus is computed from the sieve analysis of the aggregate and is the sum of the percentages in the sieve analysis of the aggregate divided by 100. In making the sieve analysis the following sieves from the Tyler standard series[1] are used: 100, 48, 28, 14, 8, 4, 3/8 in., 3/4 in., and 1½ in. Table 14, which is taken from Bulletin 1, Structural Materials Research Laboratory, Lewis Institute, gives the dimensions of the sieves used and shows the method of computing the fineness modulus of fine and coarse aggregates and also of a mixture of fine and coarse aggregate. It should be noted that in the sieve

TABLE 14.—METHOD OF CALCULATING FINENESS MODULUS OF AGGREGATES (ABRAMS)

The *sieves* used are commonly known as the Tyler standard sieves.
Each sieve has a *clear opening* just double that of the preceding one.
The *sieve analysis* may be expressed in terms of volume or weight.
The *fineness modulus* of an aggregate is the sum of the percentages given by the sieve analysis, divided by 100.

Sieve size	Size of square opening		Sieve analysis of aggregates Per cent. of sample coarser than a given sieve						
			Sand			Pebbles			Concrete
	In.	Mm.	Fine (A)	Medium (B)	Coarse (C)	Fine (D)	Medium (E)	Coarse (F)	aggregate (G)[2]
100-mesh...	0.0058	0.147	82	91	97	100	100	100	98
48-mesh...	0.0116	0.295	52	70	81	100	100	100	92
28-mesh...	0.0232	0.59	20	46	63	100	100	100	86
14-mesh...	0.046	1.17	0	24	44	100	100	100	81
8-mesh...	0.093	2.36	0	10	25	100	100	100	78
4-mesh...	0.185	4.70	0	0	0	86	95	100	71
3/8-in......	0.37	9.4	0	0	0	51	66	86	49
3/4-in......	0.75	18.8	0	0	0	9	25	50	19
1½-in......	1.5	38.1	0	0	0	0	0	0	0
Fineness modulus......			1.54	2.41	3.10	6.46	6.86	7.36	5.74

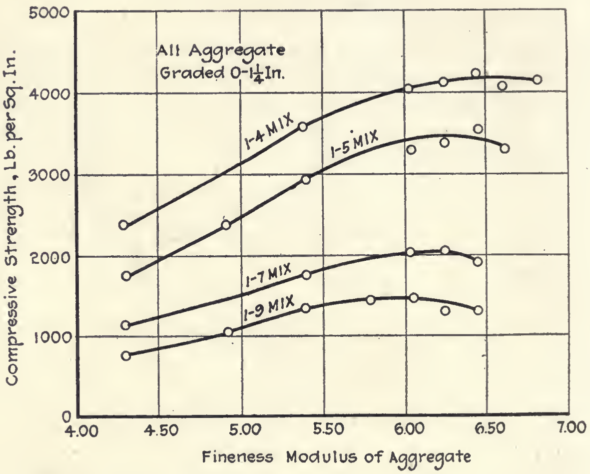
[2] Concrete aggregate "G" is made up of 25 per cent. sand "B" mixed with 75 per cent. of pebbles "E." Equivalent gradings would be secured by mixing 33 per cent. sand "B" with 67 per cent. coarse pebbles "F"; 28 per cent. "A" with 72 per cent. "F," etc. The proportion coarser than a given sieve is made up by the addition of these percentages of the corresponding size of the constituent materials.

analyses given in Table 14 the per cent. of the sample *coarser than* a given sieve is recorded instead of the per

[1] A series of sieves made of square-mesh, wire cloth by the W. S. Tyler Company of Cleveland, Ohio.

cent. *finer than* a given sieve as was done in Fig. 79. The fineness modulus of an aggregate may also be calculated by dividing the sum of the percentages passing the sieves (provided the sieves given in Table 14 are used) by 100 and subtracting the result from the number of sieves in the standard set. For example, the fineness modulus of the medium sand given in Fig. 79 is, omitting the No. 3 sieve,

$$9.0 - \left(\frac{100 + 100 + 100 + 95 + 81 + 60 + 35 + 5 + 2}{100}\right) = 3.22.$$



Courtesy of D. A. Abrams.

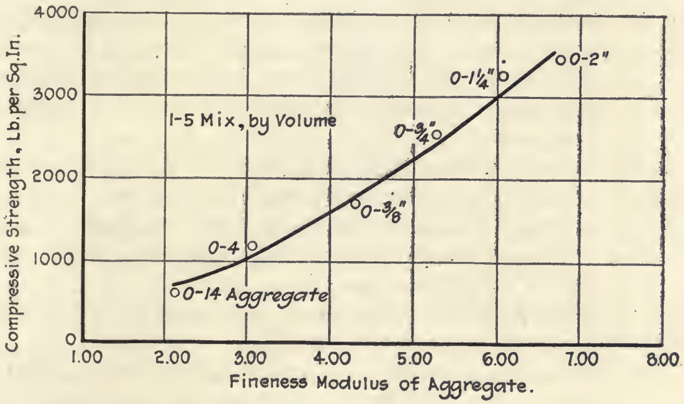
Fig. 82.—Relation between fineness modulus of aggregate and compressive strength of concrete.

Sand and pebble aggregate graded 0-1¼ in., 28-day tests of 6 by 12-in. cylinders. Normal consistency (R = 1.00).

Prof. Abrams states that mixtures of given fine and coarse aggregate which have the same fineness modulus when mixed with a given quantity of cement require the same quantity of water to produce concrete of the same workability and give concrete of the same strength so long as they are not too coarse for the quantity of cement used. Fineness modulus thus furnishes a means of judging of the concrete making qualities of an aggregate.

The relation between the fineness modulus of the mixed aggregate and the compressive strength of the resulting concrete for four concrete mixes is shown in Fig. 82. The graphs given in Fig. 82 show that as the fineness modulus increases the strength increases until the higher values of fineness modulus are reached when the strength begins to decrease. Fig. 82 also shows that the point of maximum strength occurs at higher values of fineness modulus for the rich mixes than for the lean mixes.

Fig. 83 shows the relation between fineness modulus and strength for a mixture of 1 part cement to 5 parts aggregate, by volume, when the maximum size of the aggregate



Courtesy of D. A. Abrams.

FIG. 83.—Relation between fineness modulus of aggregate and compressive strength of concrete.

28-day tests of 6 by 12 in. cylinders. Normal consistency (R = 1.00).

is varied without changing the type of the sieve-analysis curve. It will be noted in Fig. 83 that the strength increases as the maximum size of the aggregate is increased and that the height to which the curve rises appears to be limited only by the maximum size of aggregate which may be used. For the range in sizes and for the mixes ordinarily used the strength of the concrete may be assumed to increase directly with fineness modulus.

Since the quantity of mixing water used greatly influences the strength of the resulting concrete it is important that the water be carefully proportioned. The quantity of water to be used may be calculated by the following formula which Prof. Abrams has derived from the results of numerous tests and which takes into account all of the factors which affect the quantity of water required in a concrete mixture:

$$x = R\left[\frac{3}{2}p + \frac{.30n}{1.26^m}\right] + (a-c)n$$

where x = ratio of the volume of water to the volume of cement in the mix (water-cement ratio).

R = relative consistency or "workability factor." Normal consistency (relative consistency = 1.00) requires the use of such a quantity of mixing water as will cause a shortening of ½ to 1 in. in a freshly molded 6 × 12 in. cylinder of concrete upon removing by a steady upward pull the smooth metal mold in which it is cast. A relative consistency of 1.10 means that approximately 10 per cent. more water than that required for normal consistency has been used.

p = amount of water required by the cement to produce a paste of normal consistency in the standard test for cement, expressed as a ratio of the weight of the cement.

m = fineness modulus of the mixed aggregate (used as an exponent in the formula).

n = ratio of the volume of the mixed aggregate to the volume of the cement in the mix.

a = ratio of the volume of the water absorbed by the dry aggregate to the volume of the aggregate, after immersion in water for three hours. (An average value for broken limestone and for gravel may be taken as 0.02. Porous sandstones may absorb 0.08 and a very light and porous aggregate may absorb 0.25).

c = ratio of the volume of the moisture contained in the mixed aggregate to the volume of the aggregate. (For room dry aggregate $c = 0$.)

A simpler form of the above equation which is sufficiently accurate for ordinary ranges of mix and grading of aggregate is as follows:

$$x = R\left[\frac{3}{2}p + \left(0.22\,n - \frac{mn}{42}\right)\right] + (a-c)n$$

Design of Concrete Mixtures by Abrams' Fineness Modulus Method.—In designing concretes by this method the aim is to find that combination of the given materials which for a given water-cement ratio will produce a workable mixture with the use of a minimum of cement. In the bulletin previously referred to Prof. Abrams has outlined the steps to be followed in designing concrete mixes which are substantially as follows:

"1. Knowing the approximate compressive strength required of the concrete, estimate the driest workable "relative consistency" which may be used. Experience or trial is the only guide in determining the relative consistency of concrete necessary in the work. A relative consistency of 1.00 (normal consistency) is somewhat dry for most concrete work, but can be used where light tamping is practicable. A relative consistency of 1.10 represents the driest concrete which can be satisfactorily used in concrete road construction. A relative consistency of 1.20 will generally be found satisfactory for reinforced concrete construction. A relative consistency of 1.25 represents about the wettest consistency which should be used in reinforced concrete work. The size of the aggregate available, or which must be used, and other factors will furnish a guide as to the mix. The mix is expressed as one volume of cement to a given number of volumes of aggregate; that is, of the combined fine and coarse aggregate.

"2. Make sieve analysis of fine and coarse aggregate, using Tyler standard sieves of the following sizes: 100, 48, 28, 14, 8, 4, 3/8, 3/4, 1 1/2 in. Express the sieve analysis in terms of the percentages of material by weight (or separate volumes) *coarser than* each of the standard sieves.

"3. Compute fineness modulus of each aggregate by adding the percentages found in (2).

"4. Determine the maximum size of aggregate by applying the following rules: If more than 20 per cent. of aggregate is coarser than any sieve the maximum size shall be taken as the next larger sieve in the standard set; if between 11 and 20 per cent. is coarser than any sieve, the maximum size shall be the next larger "half sieve"; if less than 10 per cent. is coarser than certain sieves, the smallest of these sieve sizes shall be considered the maximum size.

"5. Assume a mix and from Table 15 determine the maximum value of fineness modulus which may be used for the mix, kind and size of aggregate, and the work under consideration.

"6. Compute the percentages of fine and coarse aggregates required to produce the fineness modulus desired for the final aggregate mixture by applying the formula:

$$y = \left(\frac{A-B}{A-C}\right) 100$$

in which y = percentage of fine aggregate in total mixture;
A = fineness modulus of coarse aggregate;
B = fineness modulus of final aggregate mixture;
C = fineness modulus of fine aggregate.

Table 15

MAXIMUM PERMISSIBLE VALUES OF FINENESS MODULUS OF AGGREGATES[1] (ABRAMS)

For *mixes* other than those given in the table, use the values for the next leaner mix.

For *maximum sizes* of aggregate other than those given in the table, use the values for the next smaller size.

Fine aggregate includes all material finer than No. 4 sieve; *coarse aggregate* includes all material coarser than the No. 4 sieve. *Mortar* is a mixture of cement, water and fine aggregate.

This table is based on the requirements for *sand-and-pebble* or *gravel* aggregate composed of approximately spherical particles, in ordinary uses of concrete in reinforced concrete structures. For other materials and in other classes of work the maximum permissible values of fineness modulus for an aggregate of a given size is subject to the following corrections:

(1) If *crushed stone* or *slag* is used as coarse aggregate, *reduce* values in table by 0.25. For crushed material consisting of unusually flat or elongated particles, *reduce* values by 0.40.

(2) For *pebbles* consisting of *flat particles, reduce* values by 0.25.

(3) If *stone screenings* are used as fine aggregate, *reduce* the values by 0.25.

(4) For the top course in concrete roads reduce values by 0.25. If finishing is done by *mechanical means,* this reduction need not be made.

(5) In work of *massive proportions,* such that the smallest dimension is larger than 10 times the maximum size of the coarse aggregate, *additions may be made* to the values in the table as follows: for ¾-in. aggregate 0.10; for 1½-in. 0.20; for 3-in. 0.30; for 6-in. 0.40.

[1] It has been found by test that there is a maximum practicable value of fineness modulus for each size of aggregate and mix. It is necessary therefore to place certain limits on the value of fineness modulus which may be used for proportioning materials for concrete mixes. Table 15 gives the limits which will be found practicable, and the purpose of the table is to avoid the attempt to secure an aggregate grading which is too coarse for its maximum size and for the amount of cement used.

(TABLE 15.—*Continued*)

Sand with fineness modulus lower than 1.50 is undesirable as a fine aggregate in ordinary concrete mixes. Natural sands of such fineness are seldom found.

Sands or screenings used for fine aggregate in concrete must not have a higher fineness modulus than that permitted for mortars of the same mix. Mortar mixes are covered by the table and by (3) above.

Crushed stone mixed with both finer sand and coarser pebbles requires no reduction in fineness modulus provided the quantity of crushed stone is less than 30 per cent. of the total volume of the aggregate.

Mix Cem.-Agg.	Size of aggregate													
	Mortars				Concretes									
	0–28	0–14	0–8	0–4	0–3*	0–⅜	0–½*	0–¾	0–1 in.*	0–1½	0–2.1*	0–3 in.	0–4½*	0–6 in.
1–12	1.20	1.80	2.40	2.95	3.35	3.80	4.20	4.60	5.00	5.35	5.75	6.20	6.60	7.00
1–9	1.30	1.85	2.45	3.05	3.45	3.85	4.25	4.65	5.00	5.40	5.80	6.25	6.65	7.05
1–7	1.40	1.95	2.55	3.20	3.55	3.95	4.35	4.75	5.15	5.55	5.95	6.40	6.80	7.20
1–6	1.50	2.05	2.65	3.30	3.65	4.05	4.45	4.85	5.25	5.65	6.05	6.50	6.90	7.30
1–5	1.60	2.15	2.75	3.45	3.80	4.20	4.60	5.00	5.40	5.80	6.20	6.60	7.00	7.45
1–4	1.70	2.30	2.90	3.60	4.00	4.40	4.80	5.20	5.60	6.00	6.40	6.85	7.25	7.65
1–3	1.85	2.50	3.10	3.90	4.30	4.70	5.10	5.50	5.90	6.30	6.70	7.15	7.55	8.00
1–2	2.00	2.70	3.40	4.20	4.60	5.05	5.45	5.90	6.30	6.70	7.10	7.55	7.95	8.40
1–1	2.25	3.00	3.80	4.75	5.25	5.60	6.05	6.50	6.90	7.35	7.75	8.20	8.65	9.10

* Considered as "half-size" sieves; not used in computing fineness modulus.

"7. With the estimated mix, fineness modulus and consistency enter Fig. 84[1] and determine the strength of concrete produced by the combination. If the strength shown by the diagram is not that required, the necessary readjustment may be made by changing the mix, consistency or size and grading of the aggregates."

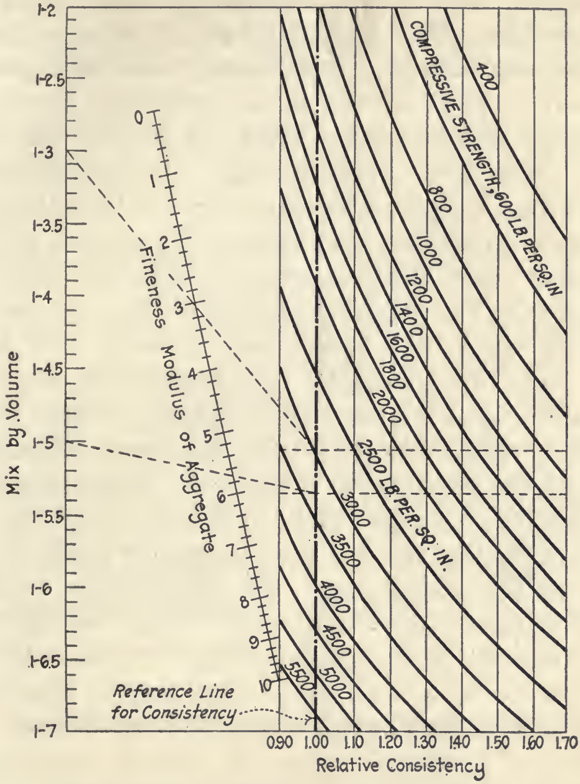
To illustrate the use of the chart given in Fig. 84 the following example is given: It is desired to know the approximate strength of a 1:3 mortar of 1.20 relative consistency made with a sand having a fineness modulus 3.00. Draw a line through mix 1:3 and fineness modulus 3.00, as indicated by the upper dotted line in the chart and mark the point where it intersects the "reference line for consistency." Through this point of intersection draw a horizontal line and read the strength at the point where this horizontal line crosses the vertical line for relative consistency 1.20. In this case the strength is approximately 2,200 lb. per sq. in. Repeating this process using the lower dotted line in the chart it will be found that a 1:5 mix made with an aggregate having a fineness modulus of 5.70 has a strength of approximately 2,400 lb. per sq. in. at relative consistency 1.20 and is therefore, slightly stronger than the 1:3 mortar given in the previous example. At normal consistency the strength of the 1:5 mix would be approximately 3,300 lb. per sq. in., or nearly 1,000 lb. per sq. in. stronger than the same mix at relative consistency 1.20. It is evident that in this case a marked increase in strength is obtained by the use of the smaller quantity of mixing water.

The development of the fineness modulus method of proportioning adds much to our knowledge of the proper use of materials when proportioning them for concrete. This method of proportioning is significant in that it is the first method to call attention to the marked influence

[1] IMPORTANT NOTE.—It must be understood that the values in Fig. 84 were determined from compression tests of 6 by 12-in. cylinders stored for 28 days in a damp place. The values obtained on the work will depend on such factors as the consistency of the concrete, quality of the cement, methods of mixing, handling, placing the concrete, etc., and on age and curing conditions.

"Strength values higher than those given for relative consistency of 1.10 should seldom be considered in designing, since it is only in exceptional cases that a consistency drier than this can be satisfactorily placed. For wetter concrete much lower strengths must be considered." In general, some allowance must be made for the high strengths obtained in laboratory tests.

of mixing water on the strength of concrete made with given materials. The fineness modulus method of pro-



Courtesy of D. A. Abrams.

FIG. 84.—Diagram for the design of concrete mixtures.

This chart is based on compression tests of 6 by 12-inch concrete cylinders; age 28 days; stored in damp sand.

The cement used gave compressive strengths in 1–3 standard sand mortar as follows, when tested in the form of 2 by 4 inch cylinders.

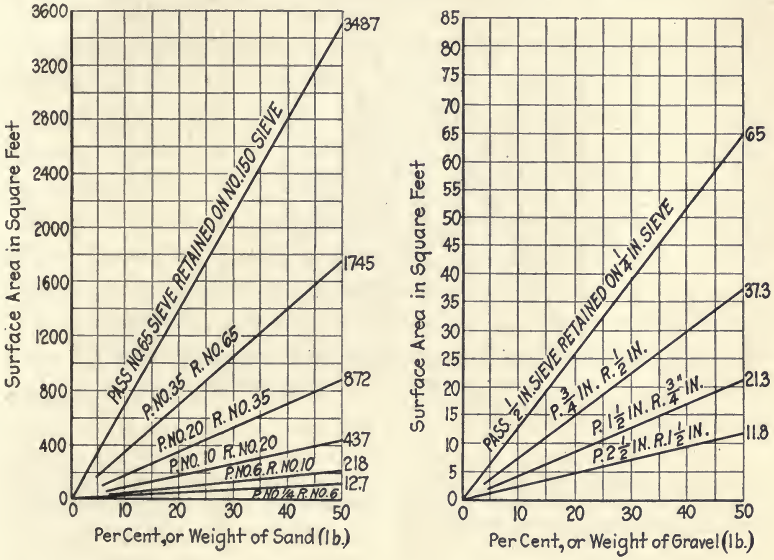
Age	Lb. per sq. in.
7 days	1,900
28 days	3,200
3 months	4,200
1 year	4,300

portioning affords a convenient means of judging the mortar-making and the concrete-making qualities of aggregates, is of wide application, and when used intelligently should effect considerable economy of material and labor.

Edwards' Surface Area Method of Proportioning Mortar and Concrete.—Mr. L. N. Edwards in a paper presented in 1918 before the American Society for Testing Materials proposed a new method of proportioning the materials of mortars and concretes which he termed the "*Surface Area*" method of proportioning. The basic principle of this method of proportioning assumes that the strength and other properties of mortars and concretes are mainly dependent upon the amount of cementing material used in relation to the total surface area of the aggregates. Mr. Edwards found from tests which he made that with materials of uniform quality this method of proportioning provided a means of securing uniformly strong mortars and concretes from sands of varying granulometric composition and that the strength of mortars was dependent upon (1) the quantity of cement used in relation to the surface area of the aggregates and (2) the consistency of the mix. Mr. Edwards also found that the compressive and tensile strengths of mortars of a uniform normal consistency made with sands of varying granulometric composition was proportional to the quantity of cement used in relation to the surface area of the aggregate and that the amount of water required to produce mortars of normal consistency was a function of the weight of cement used and the total surface area of the sand to be wetted.

Mr. Edwards determined the *approximate average* surface areas of sand and stone particles of varying sizes in the following manner: First a sieve analysis of the material was made and the average number of particles in given weights of the material retained on each sieve were counted. Knowing the number of particles in a given weight and the specific gravity of the particles, the average volume of each size of particle was computed. The surface areas of the particles were than determined from the average volume of the various sizes of particles and the shape[1] of the particles. From the data thus obtained the surface area of a given weight of particles of a given size was easily calculated.

In making practical application of this method of proportioning, the work of determining the surface area of the



Courtesy of R. B. Young.

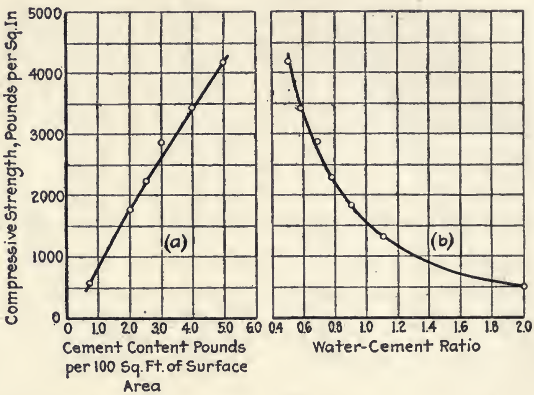
FIG. 85.—Relation between grading of pit-run sand and gravel and surface area

aggregate and the quantity of cement to be used in a given case is much simplified by the use of tables, or diagrams like those shown in Fig. 85 and Fig. 86, which are prepared from sieve analyses and tests of the materials.

In an article in Engineering News-Record by R. B. Young, a description is given of the use of the surface-area method in proportioning concrete on actual construc-

[1] In the calculation of surface area, sand and gravel particles were assumed as spherical. The particles of broken stone were assumed to be made up of one-third cubical and two-thirds parallelopipedal shapes the latter being sub-divided in order to approximate more closely the areas of the flat, elongated shapes of the broken stone particles.

tion. The diagrams in Fig. 85, which were taken from Mr. Young's article, show the relation between the grading of pit-run sand and gravel and surface area. The diagrams in Fig. 86 show the relation which Mr. Young found between the compressive strength and cement content, and the compressive strength and water-cement ratio for concrete of normal consistency using given materials.



Courtesy of R. B. Young.

FIG. 86.—Curves showing the relation between compressive strength and cement content of concrete at normal consistency; and between compressive strength and water-cement ratio.

In using this method of proportioning in the field the surface area of an economical combination (previously determined by laboratory tests) of the given fine and coarse aggregates is obtained from the diagrams in Fig. 85 after sieve analyses of the aggregates in their natural condition have been made. Knowing the minimum compressive strength desired for the class of construction in which the concrete is to be used, the amount of cement required to give this strength is determined from the diagram shown in Fig. 86(*a*). Generally a margin of safety of about 300 lb. per sq. in. is allowed to take care of field conditions. When the amount of cement to be used has been determined the amount of mixing water is calculated from the data given in Fig. 86(*b*) and from a consideration of the minimum water-cement ratio which can be used for the class of concrete desired. Allowance is made for moisture contained in the aggregates in calculating the amount of water to be used. If the consistency of the concrete is found to be too dry for the work under consideration the *water content and the cement content* of the mix are increased in the same proportion until the required mobility is obtained. In case the consistency is wetter than necessary the *cement and water* are *reduced* in the same manner. By increasing or decreasing the cement and water in the same proportion the proper water-cement ratio necessary to insure obtaining concrete of the desired strength is maintained. In order to have a check on the strength of the concrete test cylinders of standard size are made from concrete taken from the forms during the pouring operation. The cylinders are tested after curing for 28 days.

Concrete proportioned by the surface-area method has been found by tests to be uniform in quality and to give the required strength and it is claimed that the use of this method of proportioning has effected a considerable saving in cement.

Comparison of Methods of Proportioning Concrete. Proportioning by arbitrary selection of volumes, by voids in aggregate, or by trial mixtures can be carried out in the field without making a laboratory study of the available aggregates. As has been stated, these methods of proportioning are not scientific and may often result in a needless waste of cement. When used by engineers having experience in the proportioning of concrete these methods will usually give satisfactory results. Proportioning by the Fuller and Thompson method involves sieve analysis of the aggregates to be used. This method of proportioning gives reasonable insurance of a dense, strong concrete when the aggregates used are similar in character to those used in the tests upon which the method is based. Sometimes this method requires expensive, artificial grading of aggregate. The fineness modulus method and the surface area method of proportioning also necessitate sieve analysis and some involved computations, but are of wide application and appear to insure a uniform concrete of good quality without excessive cost of artificial grading of aggregate. The methods of proportioning which involve sieve analysis of aggregate may be expected to effect economy of materials when used on work of considerable magnitude. The limitations of the various methods should be carefully observed, and the fact always borne in mind that the freshly mixed concrete must be of such a consistency that it can be easily and effectively placed in the forms.

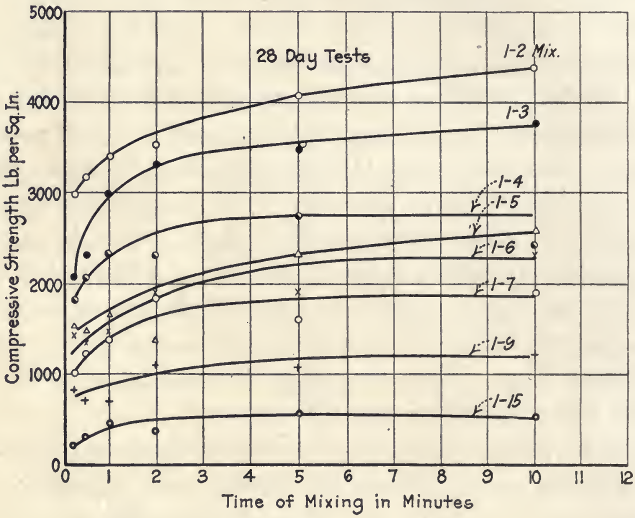
Mixing Concrete.—When the proportions of the concrete materials have been determined by one of the foregoing methods of proportioning, the proper quantities of cement, water, and aggregates for the various batches of concrete should be carefully measured in order to insure a uniform product. Cement is usually measured by weight, a bag of cement which weighs 94 lb. being considered the equivalent of one cubic foot. A barrel of cement contains four bags and is considered the equivalent of four cubic feet. The fine and coarse aggregate or the mixed aggregate is measured by loose volume. On small jobs the aggregates are measured either in a bottomless box of known volume placed on a wheel barrow, or in wheel barrows which hold definite volumes of the material when filled to a given height in a given manner. On large structures the aggregates are usually measured in hoppers of known capacity.

The quality and amount of water used in mixing concrete is of great importance. The water should be free from oil, acid, alkali and organic matter. Good results will be obtained when the amount of water used will give the concrete such a consistency that it will flow sluggishly into the forms. Concrete made too wet is low in density and strength and when an excess of water is used there is danger of separation of the coarse aggregate from the mortar paste while the concrete is being conveyed to the forms. Concrete made too dry will not fill all corners of the forms and will not flow around the reinforcing bars as readily as will concrete of the proper consistency. For any given mixture the proper proportion of water should be determined by calculation and trial and the water used should be carefully measured. The water for the concrete is generally measured in buckets when hand-mixing is used. Machine mixers are provided with small tanks having a device for indicating the amount of water discharged into the mixer.

Mixing the ingredients for concrete may be done either by hand or in a power-driven mixer. Hand-mixing, which is used only on small jobs, is done on a water-tight platform. In hand-mixing, the fine aggregate is spread out in a long flat pile on the mixing platform and covered with the cement. The sand and cement are then turned over at least three times with shovels. The coarse aggregate is then added and the mass is hollowed to form a long crater into which the mixing water is poured. After adding the proper quantity of water the ingredients are again turned over and over with shovels until the mass is uniform in color and appearance. The mass should be turned over not less than six times after the water is added.

Concrete mixers are of two types, *continuous* mixers and *batch* mixers. In continuous mixers the aggregate, the cement, and the water are fed into one end of a trough and forced along the trough to the other end by means of rotating screw-paddles which mix the ingredients as they move along the trough. The proportioning of cement and aggregate is determined by the rate of supply of each. Continuous mixers can be operated cheaply and rapidly, but rarely give a uniform product.

In batch mixers definite amounts of aggregate, cement, and water are placed inside a revolving drum, which is fitted with blades projecting inward. As the drum revolves the ingredients are constantly agitated by the blades and are carried part way round and dropped back to the bottom of the drum. A thorough mixing is thus effected. A batch mixer should be run for at least 1½ to 2 minutes before the concrete is discharged, the exact time of mixing depending on the size of the mixer used. In Fig. 87 are plotted some results of tests made by Prof. Abrams at Lewis Institute to determine the effect of time of mixing on the compressive strength of various concrete mixes. The curves in Fig. 87 show that for the mixer used there was a fairly rapid increase in strength with increase in time of mixing until the 2-minute period was reached. Mixing beyond the 2-minute period generally gave but little increase



Courtesy of D. A. Abrams.

FIG. 87.—Relation between compressive strength of concrete and time of mixing. All aggregates graded 0-1¼ inches. 1.10 relative consistency.

in strength. Batch mixers properly handled produce very uniform concrete mixtures. Fig. 88 shows the general appearance of a batch mixer.

Handling and Placing Concrete.—After the concrete has been mixed it should be quickly transported in such a manner as will prevent separation of the ingredients to the place where it is to be deposited. On small structures wheel-barrows or two-wheeled carts are generally used to transport the concrete to the forms. On large structures cars, cableways and towers with inclined, open chutes are used. When towers and chutes are used the concrete is hoisted to a hopper placed in the tower at a considerable height above the work. The concrete is then fed from the hopper into the chutes at a uniform rate and it flows by gravity either directly to the place of deposit or to another hopper from which it is wheeled into place with barrows or small carts. Frequently in chuting concrete the tendency is to use an excess of mixing water in order to cause the concrete to flow down the chute readily. The use of excess

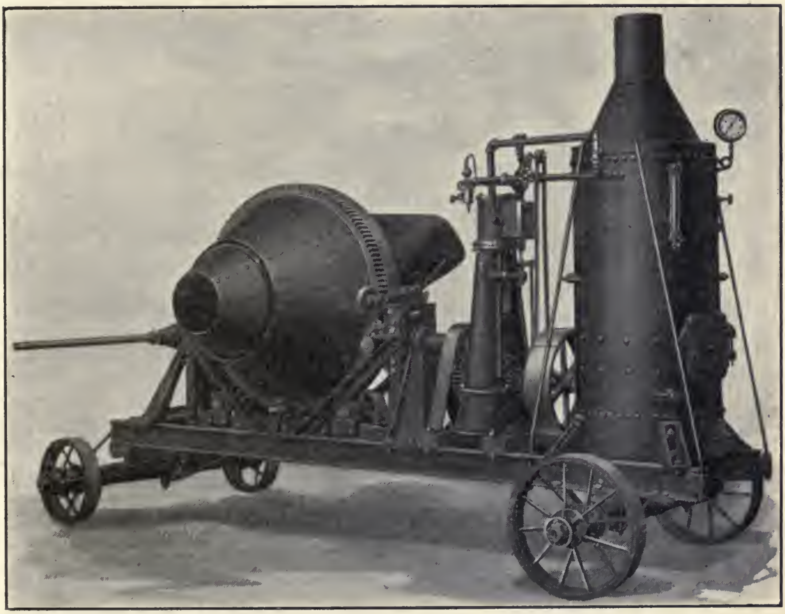


FIG. 88.—Batch mixer for concrete.

water often causes the coarser particles of aggregate to separate from the mortar. Due to this separation of the ingredients and to the fact that an excess of mixing water has a very harmful influence on the strength of concrete, this method of handling often produces a concrete which is not uniform and which is of decidedly poor quality.

In depositing concrete under water special methods have to be used in order to prevent the cement from being washed away and also to prevent separation of the various ingredients. A tremie is generally used to deposit concrete under water. A tremie consists of a tube one foot or more in diameter provided with a hopper at the top and a slightly flaring bottom, which is filled with concrete and then lowered into place with a derrick. The tube is kept full of concrete at all times and to cause a flow of concrete through the tube the discharge end is raised a few inches at a time and moved slowly about in the newly placed concrete. Concrete to be deposited under water is sometimes lowered into place in a drop-bottom bucket or in loosely-woven bags of jute or other coarse cloth. To prevent washing of the cement from the mixture and to prevent spreading of the concrete, cofferdams are frequently used to enclose the space in which the concrete is to be deposited.

Before concrete is deposited in the forms all debris should be removed from the place to be occupied by the concrete. The forms should be cleaned and then thoroughly wetted (except in freezing weather) to prevent absorption of water from the concrete. Frequently the surface of the forms exposed to the concrete are oiled in order to prevent warping and to aid in removing the forms from the concrete after it has hardened.

To secure dense and uniform concrete it should be placed in the forms evenly and without separation of the ingredients. Concrete which is of a fairly dry consistency should be placed in layers about 6 or 8 inches in thickness. For wetter consistencies the thickness of the layers may be increased to 12 inches or more depending on the shape and size of the section being poured. After placing, the concrete is puddled and spaded to remove air bubbles and to aid in securing a dense, uniform mixture. To give a smooth surface and to prevent visible voids in the finished concrete a spading tool is run up and down between the form and the fresh concrete. This permits the escape of air and also works the mortar to the forms thus giving a smooth finish to the exposed surfaces of the mass. The same result may also be obtained by pounding the forms with wooden mauls or by vibrating the forms with pneumatic hammers.

In making concrete pavements power-driven tampers and light, metal rollers are often used to compact the concrete and to aid in securing a dense product.

When concrete is to be deposited on or against concrete which has set, the surface of the set concrete is roughened and cleaned of all foreign matter and *laitance* (a light-colored, powdery substance which forms on the surface of concrete which has been mixed too wet) after which it is wetted with water. The wetted surface is then thoroughly coated with a wash of neat cement grout, or a rich mortar, before the new concrete is applied.

Curing of Concrete.—A considerable amount of water is required for the proper hydration of the cement, which goes on for several days after the concrete has become hard. It should be borne in mind that thin sheets of concrete if exposed to the air, dry out so rapidly that some of the water necessary for the complete hydration of the cement may be evaporated. In order, therefore, that concrete may set and harden properly after it has been placed it is very essential that it be protected in some way to prevent it from drying out too rapidly. The result of too rapid drying out of concrete is the failure of the concrete to gain strength normally with the lapse of time, moreover shrinkage stresses are set up which may cause serious cracks in the surface of the concrete. Sprinkling two or three times a day, covering with canvas which is wetted from time to time and covering with moist sand or earth are methods employed to insure proper curing conditions. In warm weather the concrete is kept wet for at least two weeks after pouring. Allowing the forms to remain in place helps to retain the moisture in the concrete and prevents too rapid drying. Newly placed concrete pavements are sometimes protected from the direct rays of the sun by means of light, wooden frames covered with canvas. After the concrete has thoroughly set the pavement is covered with moist earth or with water. To hold the water on the pavement small dikes of earth are built along the sides of the pavement and also across the pavement at frequent intervals.

In Fig. 89 are plotted the results of tests made at the University of Illinois on concrete cylinders of different consistencies which were stored under different conditions. The graphs in Fig. 89 show that the air-stored specimens of normal consistency gained but little in strength with lapse of time. On the other hand, for the specimens of normal consistency stored in damp sand, there was a gradual increase in strength with age. This was also true of the specimens of other consistencies which were stored in damp sand. At the age of five years the air-stored speci-

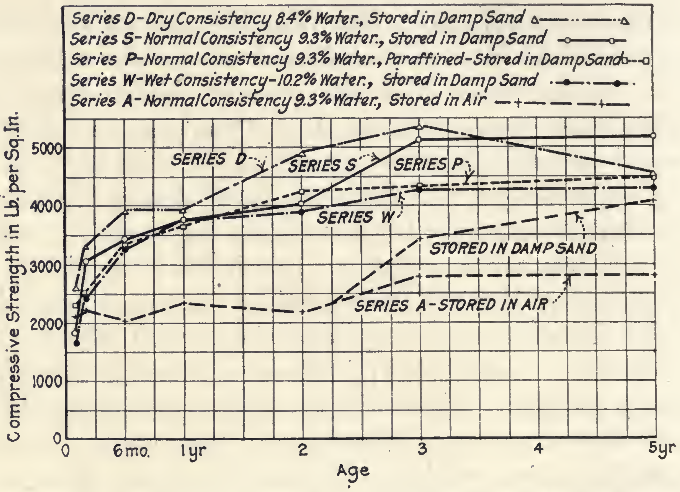


FIG. 89.—Effect of storage condition on compressive strength of concrete at various ages. Proportions, 1:2½:3½, by weight.

mens were only about one-half as strong as the specimens of like consistency stored in damp sand. Attention is called to the considerable increase in strength with age of the specimens which were transferred from air-storage to damp-sand storage when they were two years three months old.

A good, general rule for concrete construction is to use as little water for mixing as will give a workable concrete, and to use plenty of water on the concrete after it has set.

Effect of Low Temperature on Newly Made Concrete.—Concrete subjected to low temperatures while being poured or within a few days after being poured is greatly reduced in strength. The hydration of the cement, with consequent hardening of the concrete, is retarded, and if actual freezing of the concrete takes place the strength may be permanently impaired. Fig. 90 based on the results of tests by A. B. McDaniel at the University of Illinois shows the general effect of low temperature on the strength of concrete. When it is necessary to lay concrete in cold weather the bad effects of low temperature of the surround-

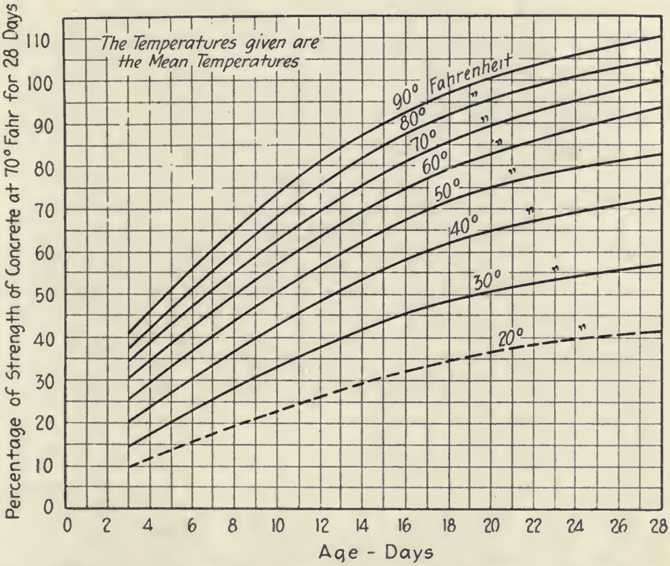


FIG. 90.—Effect of temperature on the strength of concrete. *From Bulletin* 81, *Eng. Exp. Station, Univ. of Illinois by A. B. McDaniel.*

ing air may be minimized by heating the stone, the sand, and the water used, and by covering the concrete as soon as it is laid with canvas, burlap, straw, sawdust, or manure. Structures poured in cold weather are often enclosed in canvas, the enclosed space being heated for a few days with small open stoves or with pipe lines supplied with live steam, in order that the concrete may set and harden properly.[1]

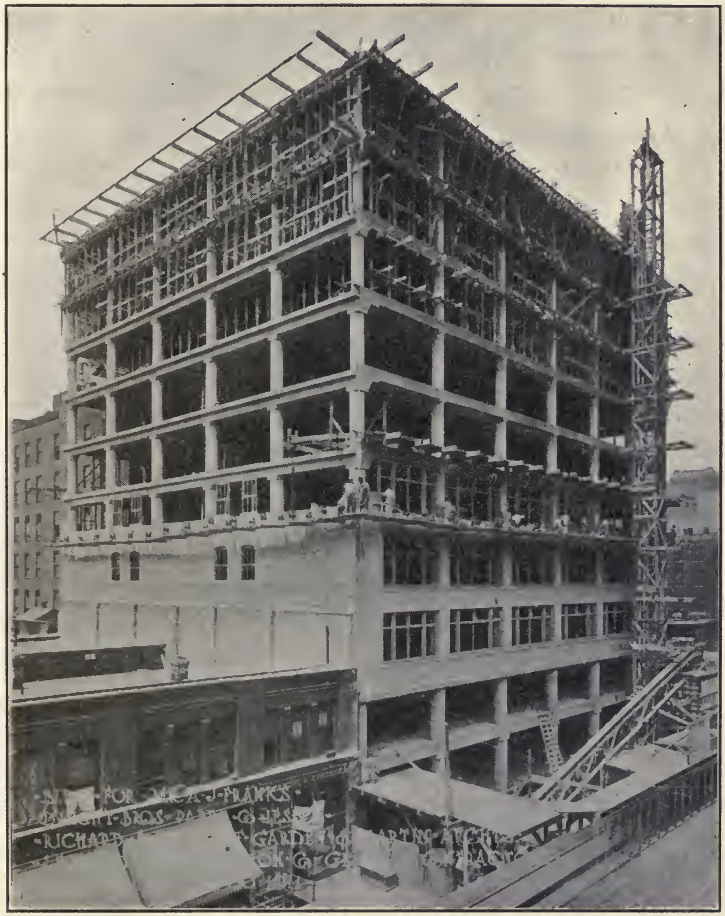
[1] The addition of salt to the mixing water lowers the freezing temperature of concrete but increases the danger of disintegration, especially if there is danger of electrolysis by stray electric currents. In general the use of salt or other chemicals to prevent freezing is not to be recommended.

16

Molds and Forms for Concrete.—The units which make up a concrete structure, beams, columns and the like, are sometimes cast separately, and afterward fitted together to form the structure. This is the *unit* system of casting. In the unit system of casting concrete it is frequently feasible to use metal forms and by their use to produce members of fine surface finish which are very uniform in size. In structures made up of separately cast units the strength of the joints between members must be carefully considered.

Concrete blocks for building walls, concrete drain tile, and concrete sewer pipe are made in metal molds. Such concrete units are frequently made of very dry concrete, (See Fig. 93 page 247) which, by thorough tamping or pressing, is given sufficient rigidity so that it can be removed from the mold in a few minutes after tamping. The molded block or pipe unit is transferred to a room where it is exposed to steam or to water-saturated air for a few days, after which it has gained sufficient strength to be transferred to a storage yard for further curing. Concrete blocks are usually made hollow and are of a great variety of shapes and sizes.

When a concrete structure is made, not of separate units, but of one mass of concrete it is said to be *monolithic* (literally "single-stone"). In monolithic concrete construction forms, usually of wood, are set up for a considerable section of the complete structure, and the concrete is mixed and poured into these forms. After a period of 10 days or 2 weeks (a longer period may be necessary in cold weather) the forms are removed leaving the concrete structure in place. In constructing concrete buildings the forms are set up for a story at a time. Fig. 91 shows a building being constructed one story at a time by the monolithic system. For the lower seven stories the concrete has hardened sufficiently to allow the removal of the forms, in the eighth story are seen the timbers supporting the floor of the ninth story, in the ninth story the concrete has been poured, but has not hardened sufficiently to allow the removal of forms; on the roof, concrete is being poured. The removal of forms from a monolithic concrete structure should be done very carefully. Many serious accidents have been caused by the premature removal of forms.



Courtesy of Leonard Construction Co.

Fig. 91.—Reinforced concrete building under construction.

Before removal of the forms an examination of the surface of portions of the concrete should be made to make sure that it has attained a good degree of hardness, then supports and forms should be removed over a small area only, while careful watch should be kept for signs of undue settlement or deflection of the concrete as its support is removed. If no signs of failure are observed more forms may be removed.

Strength of Concrete.—Concrete is a brittle material and like all brittle materials is stronger in compression than in tension with a strength in shear intermediate

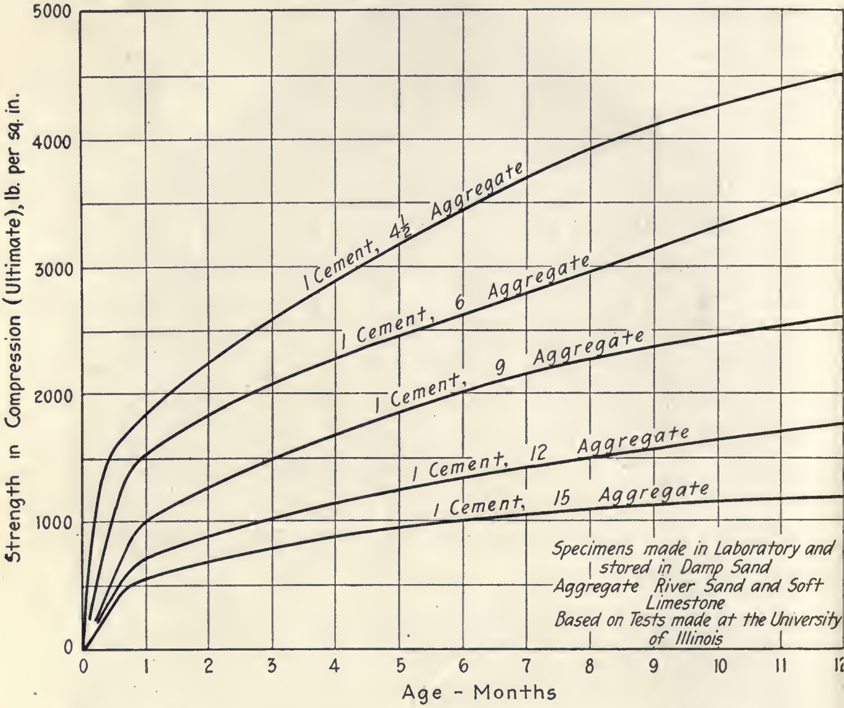


FIG. 92.—Strength of concrete of varying age and proportions of cement to aggregate.

The proportions given for the aggregate are the volumes of the sums of the fine and coarse aggregates, which were measured separately.

The modulus of elasticity of concrete varies from about 1,000,000 lb. per sq. in. to 4,000,000 lb. per sq. in., averaging about 2,000,000 lb. per sq. in. for concrete made up of 1 part cement to 6 parts aggregate.

between the tensile strength and the compressive strength. The tensile strength of concrete is so low (100–300 lb. per sq. in.) that it is not considered in the design of reinforced-concrete structures. The shearing strength of concrete is of importance because shearing stress is set up in the concrete near the supports of reinforced-concrete beams, in footings, and around columns in flat slab floors. The strength of the *bond* which exists in reinforced concrete between the concrete and the steel is of great importance since lack of bond will prevent the two materials from working together as intended and thus seriously impair the strength of structural members.

For concrete made of good materials under normal temperature conditions three very important factors in determining its compressive strength are: (1) age, (2) richness of the concrete in cement and (3) amount of mixing water used. Well made concrete tends to grow stronger with the passage of time, but the rate of increase of strength diminishes rapidly after a few weeks. Fig. 92 shows the change of strength with time for several mixtures of concrete. The test specimens were made under laboratory conditions and stored in damp sand. From the diagrams it may be seen that concrete 1 year old is about 2.5 times as strong as concrete 1 month old and is about twice as strong as concrete 2 months old. Under ordinary conditions concrete can not be counted on to gain much strength after a year. Fig. 92 also shows the general effect of the proportion of cement upon the strength of concrete. Table 16 is from the report of the Joint Committee on

TABLE 16.—STRENGTH OF PORTLAND CEMENT CONCRETE IN COMPRESSION

The values given are from the report of the Joint Committee on Concrete and Reinforced Concrete. They are based on data of test specimens in the form of cylinders 8 in. in diameter by 16 in. long, made and stored under laboratory conditions and tested when 28 days old. All values are in pounds per square inch.

Aggregate	Proportion of cement to aggregate				
	1:3[1]	1:4.5[1]	1:6[1]	1:7.5[1]	1:9[1]
Granite, trap rock	3,300	2,800	2,200	1,800	1,400
Gravel, hard limestone, hard sandstone	3,000	2,500	2,000	1,600	1,300
Soft limestone, soft sandstone	2,200	1,800	1,500	1,200	1,000
Cinders	800	700	600	500	400

[1] Total volume fine and coarse aggregates measured separately.

Concrete and Reinforced Concrete and gives values which should be obtained for concrete 1 month old when made with good workmanship and good materials. For concrete which is to be subjected to direct compression the simplest and cheapest way to add strength is in nearly all cases to increase the proportion of cement in the mixture. Table 17 gives the average results of a large number of tests made at the University of Illinois on the strength of concrete in shear. The average strength in shear is slightly greater than one-half of the compressive strength for rich concrete and a somewhat greater proportion of the compressive strength of lean concrete.

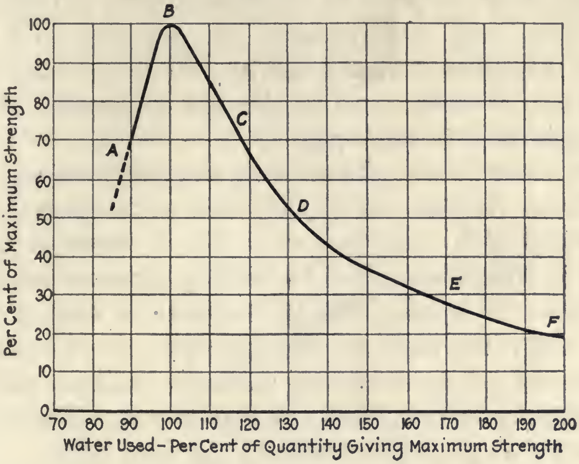
Table 17.—Strength of Portland Cement Concrete in Shear

The values given below summarize test results given in *Bulletin* No. 8 of the Engineering Experiment Station of the University of Illinois. All concrete was made and stored under laboratory conditions and tested when 60 days old. The aggregate used was torpedo bank sand and soft limestone.

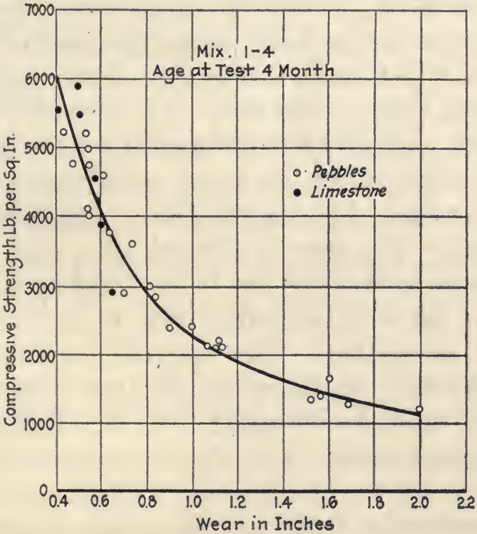
Proportion of cement to aggregate	Ultimate lb. per sq. in.		Ratio of strength in shear to strength in compression
	Shear	Compression	
1:6[1]	1,290	2,430	0.532
1:9[1]	1,090	1,290	0.842

[1] Total volume fine and coarse aggregates measured separately.

The curve shown in Fig. 93, which is plotted from the results of tests made by Prof. Abrams at Lewis Institute, shows the general relation between the strength of concrete and the amount of mixing water used. The curve in Fig. 93 is a composite curve which summarizes the results of compression tests on various mixtures of cement and mixed aggregate, the grading of the mixed aggregate being the same for all mixes. It will be noted that the strength increases rapidly with increase in the quantity of mixing water over the range on the curve indicated by *AB*. With further increase in the amount of water the strength falls off rapidly as indicated by the portion of the curve *BCDEF*. Concretes made with the quantity of water represented by the portion of the curve *AB* are too dry and stiff for most purposes but could be used in making building blocks, drain tile and other concrete products requiring a dry



Courtesy of D. A. Abrams.
FIG. 93.—Effect of quantity of mixing water on strength of concrete.



Courtesy of D. A. Abrams.
FIG. 94.—Relation between compressive strength and wear of concrete.

mixture. The proper amount of water for concrete road work corresponds to that at *C*. The amount of water used in building construction very frequently corresponds to that portion of the curve from D to F and it is evident that only about 30 per cent. of the available strength is obtained with such wet mixtures. In general, in reinforced concrete construction good results will be obtained when the amount of water used produces a concrete which will flow sluggishly into the forms.

Fig. 94 which is also plotted from the results of tests made by Professor Abrams shows the relation between the compressive strength and the wear for a concrete mixture such as is commonly used in making concrete roads and pavements. It is seen that the amount of wear decreases rapidly with increase in the strength of the concrete. The amount of wear of the concrete in these tests was determined by testing blocks of concrete in a Talbot-Jones rattler with an abrasive charge of cast-iron balls.

Results of tests of strength of the bond between concrete and steel bars are given in Fig. 95 which is plotted from tests made by D. A. Abrams at the University of Illinois. The values given are the loads per square inch of embedded surface of bar which cause marked slip between plain round steel bars and various mixtures of concrete. There are on the market various forms of special reinforcing bars for reinforced concrete which are rolled with projections which are for the purpose of giving the bars a positive anchorage in the concrete. The tests of Abrams show that the effectiveness of such anchorage lies in its holding power after some slip has taken place rather than in any tendency to prevent slip altogether. The following quotation from Abrams' published results gives the requirements for a well-designed, special reinforcing bar, or "deformed bar" as it is sometimes called.

"In a deformed bar of good design the projections should present bearing faces as nearly as possible at right angles to the axis of the bar. The areas of the projections should be such as to preserve the proper ratio between the bearing stress against the concrete ahead of the projections and the shearing stress over the surrounding envelope of concrete. Failure by shearing of the concrete should be avoided.

The tests indicate that the areas of the projections measured at right angles to the axis of the bar should not be less than say, 20 per cent. of the superficial area of the bar. A closer spacing of the projections than is used in commercial deformed bars would be of advantage. Advocates of the deformed bar would do well to recognize the fact that in a deformed bar which may be expected to develop a high bond resistance, a certain amount of metal must be used in the projections which probably will not be available for taking tensile stress."

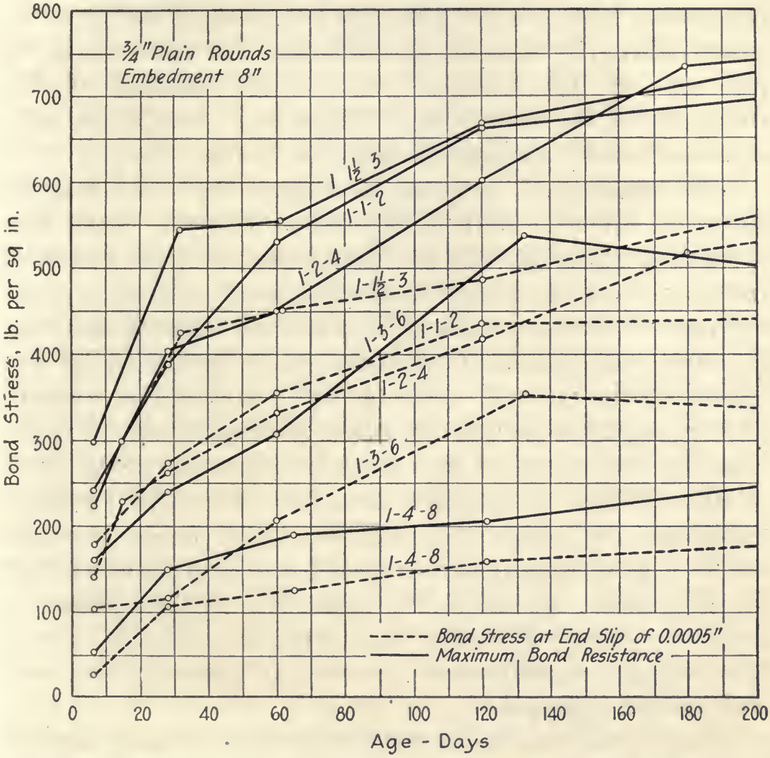


FIG. 95.—Strength of bond between concrete and steel. (*From Bulletin* 71, *Eng. Exp. Station, Univ. of Illinois by D. A. Abrams.*

Working Stresses in Concrete.—The following statement of allowable working stresses gives the values recommended in the report of the Joint Committee on Concrete and Reinforced Concrete.

Allowable axial unit stress in compression on concrete piers and short columns, 22.5 per cent. of the ultimate compressive strength of the concrete.

Allowable unit stress in the extreme compression fibers of beams, 32.5 per cent. of the ultimate compressive strength of the concrete (adjacent to the supports of continuous beams this value may be increased to 37.5 per cent.).

Allowable unit stress in shear (punching), 6 per cent. of the ultimate compressive strength of the concrete.

Allowable unit stress in bond between concrete and steel reinforcing bars; for plain bars, 4 per cent. of the ultimate compressive strength of the concrete; for drawn wire, 2 per cent. of the ultimate compressive strength of the concrete; for the best types of "deformed" bars, 5 per cent. of the ultimate compressive strength of the concrete.

Disintegration of Concrete, Waterproofing.—A few structures of concrete and of reinforced concrete have disintegrated under the action of sea water, of alkali water, of frost, or under the action of electrolysis from stray electric currents from street railway and electric lighting systems. In such cases the disintegrating action seems to be due mainly to the porosity of the concrete and to the presence of free moisture in the concrete. Frequently poor workmanship and the use of poor materials have also contributed to the failure of concrete structures by disintegration. Structures in which a properly placed, dense concrete made of good materials was used have been little affected by the above agencies. The simplest way to insure a concrete which will resist disintegration is to use a relatively high proportion of cement and carefully selected, well-graded aggregates.

A dense concrete resists the percolation of water through it. A 1:2:4 concrete made with well-graded aggregate is practically watertight for ordinary pressures. In general, the impermeability or watertightness of concrete increases with increase in amount of cement, with increase in maximum size of aggregate, with increase in thickness of wall, with decrease of pressure, and with increase in age. Other important factors which affect the watertightness of concrete are: the consistency of the mix, the thoroughness of mixing, the manner of placing and compacting the concrete and the manner of curing the concrete. It is essential that cracking of the concrete due to shrinkage in setting and to temperature changes be avoided in water-tight construction. Consequently reinforcing steel and expansion joints must be generally be provided to aid in preventing the formation and extension of cracks.

Various waterproofing compounds to be mixed with concrete materials, and waterproofing coatings to be spread on concrete are on the market. Some of these are effective when carefully used but in many cases the use of a rich, dense concrete of the proper consistency will render the structure practically waterproof, and resistant to disintegrating influences.

Use of Concrete for Fireproofing.—Concrete makes excellent fireproofing material for steel columns and girders and structures made of concrete are very resistant to destruction by fire. Under the action of heat the surface of the concrete is dehydrated, and the evaporation of the water chemically combined with the cement keeps down the temperature of the inner layers of concrete. The dehydrated surface of the concrete is rendered weak and porous by the heat but the injury rarely extends over an inch or two into the concrete; moreover, the dehydrated surface is an excellent heat insulator, and affords increased protection to the inner layers of concrete. From 2 to 2½ inches of good concrete is generally considered sufficient thickness of fireproofing for steel work. In reinforced concrete structures, columns and girders are usually protected by a minimum thickness of 2 in. of concrete, beams and walls by a minimum of 1½ in. and floor slabs by a minimum of 1 in. A study of the action of reinforced concrete buildings when subjected to fire, and fire tests of reinforced concrete columns under load indicate that aggregates made up of highly silicious materials, such as sandstones, pebbles, quartz and granite pebbles, are less resistant to the action of heat than are aggregates such as limestone, trap rock, blast-furnace slag and burned clay. Experience and tests also show that round columns are less seriously affected by fire than are square columns.

One marked advantage which concrete possesses as a fireproofing material for steel lies in the fact that its coefficient of expansion is very nearly the same as that of steel, so that there is less danger of spalling off under the action of heat for concrete fireproofing than there is for fireproofing materials whose coefficients of expansion differ widely from that of steel.

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CHAPTER XIX

RUBBER, LEATHER, BELTING, ROPE

Rubber, General Characteristics.—The special field of usefulness of rubber as an engineering material depends on three salient characteristics: (1) its value as an electrical insulator, (2) its impermeability to water and gases, and (3) its ability to withstand great deformation without serious structural damage. As an electrical insulator rubber is used in very large quantities for insulating covering for electric wires and for insulating bushings and plates. The waterproof and gas proof qualities of rubber make it widely used for hose for water, for compressed air and for gas, and, together with its ability to withstand great deformation, make it the material universally used for pneumatic tires for vehicles. Its ability to withstand great deformation makes it useful in members whose function it is to "take up" shocks in machines and structures, such as buffers and tires for vehicle wheels.

Production of Rubber.—All the rubber in commercial use is produced from a fluid which exudes from the outer wood of several species of tropical trees and shrubs. Artificial, or synthetic, rubber has been made as a laboratory experiment, but up to the present time the cost of making artificial rubber is far in excess of the cost of "natural" rubber. The rubber industry is well developed in Central America and the tropical countries of South America, especially Brazil, and in Ceylon, the Malay Archipelago, the Dutch East Indies, and central Africa.

The fluid from which rubber is made exudes from a special system of ducts in the outer wood of the rubber-producing tree or shrub, and is quite distinct from the ordinary "sap" of the tree. This fluid is known as latex. The latex is gathered in buckets and coagulated into a solid mass by heat, by the addition of chemicals, or by churning. This mass after being "cured" or antisepticized by smoking is the "crude" rubber which is the raw material for the manufacture of rubber goods. The crude rubber is washed and shredded by knives, then mixed with sulphur (and other ingredients varying for the special service the manufactured rubber is to perform) into a "dough," and this dough is rolled into sheets or pressed into shapes and "vulcanized" by the combined action of heat and pressure. For thin sheets the vulcanizing may be accomplished by treating the crude rubber sheet with a solution of carbon bisulphide. The percentage of sulphur used in vulcanizing determines whether the rubber shall be hard or soft. A high percentage of sulphur gives hard, brittle rubber, and a low percentage gives soft rubber. For a good grade of soft rubber a combination of 92.5 per cent. crude rubber with 7.5 per cent. of sulphur is not uncommon.

Physical Properties of Rubber.—The physical properties of different kinds of rubber vary over a wide range. Soft rubber will stretch from six to ten times its original length without breaking, while very hard rubber is almost as brittle as cast iron, though it may be made flexible by the application of heat as low as that of boiling water. Fig. 96 gives stress-strain diagrams for typical samples of good quality soft rubber, for poor quality soft rubber, and for hard rubber. The wide difference between the shape of the stress-strain diagram for soft rubber and the typical stress-strain diagrams shown in Fig. 14 and 15 is noteworthy. The reversal of curvature at the end of the stress-strain diagram for rubber is especially worthy of note.

Fig. 97 gives a typical diagram for soft rubber in compression. It is to be noted that this diagram is slightly concave toward the stress axis—the reverse of the diagrams shown in Fig. 14 and 15.

The maximum unit tensile stress carried by good quality soft rubber varies from 800 to 1200 lb. per sq. in. Poor quality soft rubber may fail in tension at a stress as low as 200 lb. per sq. in. In compression rubber shows no well-defined ultimate strength. The safe working limit of compression for good quality rubber may be taken as a

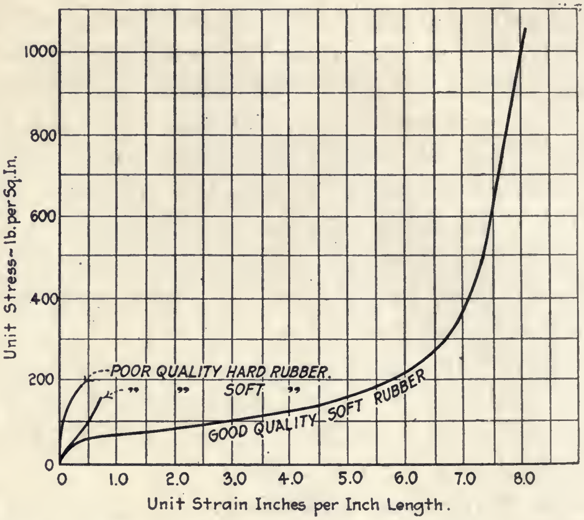

FIG. 96.—Stress-strain diagrams for rubber in tension.

compression to one-half the original height of the rubber; this corresponds to a stress of about 500 to 800 lb. per sq.

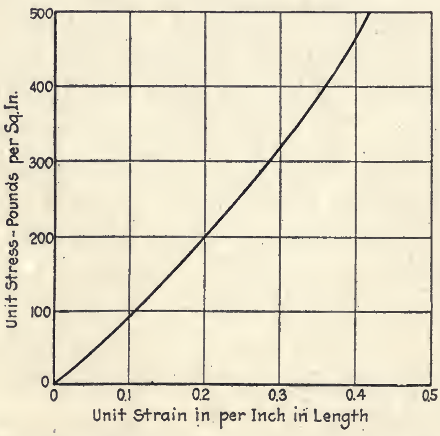

FIG. 97.—Stress-strain diagram for soft rubber in compression.

in. The great flexibility of rubber renders it generally unsuitable for resisting flexure or torsion.

Energy absorbed by Rubber under Stress.—Volume for volume or weight for weight rubber under stress can absorb very much more energy than can steel or any other metal. Taking the sample of rubber whose stress-strain diagram is shown in Fig. 96 at a stress of 200 lb. per sq. in the extension is 5.80 inches per inch original length. The energy required to produce this stretch is approximately $0.5 \times 200 \times 5.80 = 580$ inch-pounds per cubic inch of material.

For the sample whose stress-strain diagram in compression is shown in Fig. 97 the energy required to compress the rubber to one-half its original thickness is approximately 151.5 inch-pounds per cubic inch of material. These values may be compared with the energy necessary to stress spring steel in tension or compression up to a working stress of 50,000 lb. per sq. in. Taking E for steel as 30,000,000 lb. per sq. in. the unit strain corresponding to 50,000 lb. per sq. in. is 0.00167 and the energy required to produce this strain $0.5 \times 50000 \times 0.00167 = 41.7$ inch pounds per cubic inch of material.

For structural steel stressed up to 16,000 lb. per sq. in. the energy required is 4.27 inch-pounds per cubic inch of material. The energy per cubic inch of material required to produce a safe working stress is a measure of the shock—absorbing capacity of the material, and the figures given in this paragraph show that for tension members (such as pneumatic tires) rubber, volume for volume, will absorb about ten times as much energy as spring steel, and for compression members, such as buffers, rubber, volume for volume, will absorb about 3.75 times as much energy as will spring steel.

"Mechanical Hysteresis" of Rubber.—In common speech rubber is spoken of as highly elastic. Using the technical definition ofs elasticity given on p 3 rubber is not perfectly elastic. Moreover, if rubber is subjected to a cycle of stress (see p. 42) a considerable amount of the energy required to deform the rubber is lost in mechanical hysteresis. Fig. 98 gives stress-strain diagrams for cycles of stress for two typical samples of rubber. The amount of energy lost in mechanical hysteresis is measured by the shaded area for each diagram. The hysteresis loss is considerable even when the rubber is loaded and unloaded at a slow rate, and it is much larger when rubber is subjected to rapidly applied cycles of stress. The stress-strain diagram for rubber is greatly affected by the speed of loading.

The energy lost in hysteresis is such members as pneumatic tires on automobiles running at high speed is sufficient to produce appreciable heat, which in itself tends to weaken the rubber. The energy lost in mechanical hysteresis in

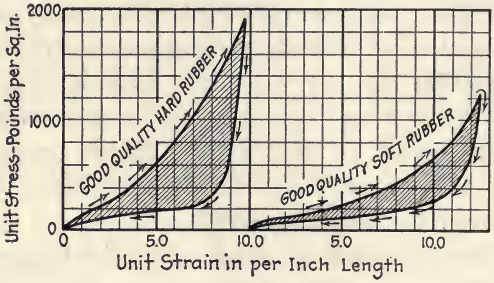

FIG. 98.—Stress-strain diagrams for rubber subjected to a cycle of stress.

rubber tires, rubber belting and other rubber parts subjected to rapid changes of load may play an important part in shortening the life of such parts.

Deterioration of Rubber.—Under the action of air and of light vulcanized rubber tends to become hard and brittle with the lapse of time. This is illustrated by the gradual loss of "stretch" in rubber bands left lying on desks for some time. Rubber is little affected by dilute acids, by water, or by dilute alkalies, but is readily "rotted" (rendered brittle) by oils. The deterioration of rubber depends to a considerable extent to the presence of foreign ingredients, such as chalk or zinc oxide, which are frequently mixed with rubber and sulphur before vulcanizing. Rubber is inflammable and melts at about 370 degrees Fahr. It cannot be used at high temperatures.

Leather.—As an engineering material leather is used in two forms, rawhide and tanned leather. Rawhide is the salted hide of animals, usually ox-hide. It is used for gears, belt lacing, and for some belts, though tanned leather is the usual material for belting. Rawhide is a tough strong material with little capacity for "stretch." Rawhide gears have about the strength of cast iron gears under steady load, and a higher strength under shock. Rawhide gears operate with very little noise.

Tanned leather is prepared by treating raw hides with a tanning solution prepared from oak bark. Leather is used for belting and for hydraulic packings. Leather suitable for good quality belting is obtained from the part of hides left after cutting away the belly. Belting is built up by cementing or riveting together strips of tanned leather. Single ply belting is made from one thickness of leather, two-ply belting from two thicknesses of leather and so on. Single ply leather belting is about 0.23 inches thick and two-ply leather belting is about 0.34 inches thick.

Weight and Strength of Leather Belting.—Leather weighs about 0.035 lb. per cu. in., its specific gravity is very nearly unity. The ultimate tensile strength of good quality leather belting is about 3800 lb. per sq. in., which corresponds to a strength of about 900 lb. per inch width for single ply belting and about 1300 lb. per inch width for two-ply belting. Under a tensile load of 2250 lb. per sq. inch applied for an hour belting should stretch not more than 13.5 per cent. of its original length.

Strength of Belt Joints.—If the free ends of a piece of belting are fastened together by chamfering, lapping, and cementing the strength of the joint can be made nearly equal to that of the leather. Joints in belting are, however more commonly made by lacing the free ends together with rawhide strips, with wire, or by using some special form of flexible metal connection. The best joints (with the exception of cemented joints) are made by the use of special lacing machines which thread a spiral of steel wire through each free end of the belt. The two spirals are dovetailed together, and a pin of metal or of raw-hide is run through the two spirals making a hinge joint.

Ordinary laced joints in belting have about one-third the strength of leather; joints made by the use of special lacing machines may have strength as high as one-half the strength of the leather.

Canvas Belting, Rubber Belting.—Woven canvas belting is made in four, six, eight, and ten-ply thicknesses. It weighs from 0.03 lb. per cu. in. to 0.05 lb. per cu. in. depending on the waterproofing and sizing material used. It is about as strong as leather belting, but has not so much "stretch" nor so high a coefficient of friction between itself and the surface of pulleys as leather belting. It is used mainly for agricultural machinery.

Rubber belting is made on a foundation of woven duck, impregnated with rubber. Its special feature is its resistance to moisture, and it us used for driving machinery in damp locations. Rubber belting weighs about 0.045 lb. per cu. in. and has an ultimate tensile strength of about 900 lb. per sq. in.

Rope.—Rope is made by straightening and twisting together the fibers of certain plants, especially the fibers of hemp; it is also made from cotton yarn. Manila hemp rope has a weight w, measured in pounds per foot of about

$$w = 0.32\,d^2$$

in which d is the diameter of the rope in inches. The ultimate tensile strength ($T.S.$) of good quality Manila hemp rope is given by the equation

$$T.S. = 100\,d^2(81\text{-}9d)$$

For rope made from cotton yarn the equation for weight in pounds per foot is

$$w = 0.26\,d^2$$

and the equation for tensile strength is

$$T.\ S. = 4600\,d^2$$

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CHAPTER XX

TESTING AND INSPECTION; TESTING MACHINES

Growing Importance of Testing.—In the earlier days of the steel industry—or of any of the industries for the production of materials of construction—the consumer in deciding from whom to buy his material depended mainly on the reputation of the producer. Some well-known "brand" of steel or cement was purchased in order to insure good material. As the industries developed and the products of manufacturers become standardized, it became necessary to establish standards of quality for materials, and to devise tests which should determine the acceptability or non-acceptability of any shipment of material. The significance of the trade-mark decreased, while that of the testing laboratory report increased. Today the systematic testing of quality has become a recognized part—small, but important—of the system of manufacturing and marketing the materials used for machines and structures.

The use of testing as a basis for acceptance of shipments of materials is very common today, and is becoming more and more common every year. The use of test results as a criterion for acceptability renders possible the use of a selected quality of certain kinds of material, which, if not submitted to test, would not be trustworthy for structural use. An illustration of this is furnished by the use of reinforcing rods for concrete which are made from re-rolled rails. Some shipments of such re-rolled rods are not of good quality, and unless samples from a shipment are tested, it is not safe to use such re-rolled material. If samples from a shipment are tested and the test results show strong, non-brittle material, it is safe to use such material.

In general, tests furnish a better criterion of quality of material than is afforded by the general reputation of the manufacturer.

The Testing Engineer.—As the practice of judging the acceptability of shipments of materials from the results of tests becomes more and more the general rule, the work of the testing engineer who plans and conducts such tests becomes of increasing importance. His service to the public is no small service; he safeguards buildings, bridges, ships, machines, and roads against danger of failure on account of poor material, he makes possible the use of new materials, and widens the field of use of well-known materials. The testing engineer should possess the highest integrity, and should have a clear understanding of the mechanics of materials and of the general properties of known materials. He must not only be proof against any outside influence tending to cause him to report dishonest results, but also against self-deception and prejudgment as to the outcome of tests. Having made tests carefully, he must possess the courage to stand by the results of the tests, whatever those results may be. He should exercise tact and sound judgment in interpreting the results of tests, and in order that he may do so, he should have a clear understanding of both the content of and the reasons underlying the codes of standards for materials, and the methods of testing used.

Definition of Terms.—*Inspection* of materials of construction comprises the examination for surface defects, for correctness of dimensions, for methods of manufacture, etc., and also the making of tests to see whether materials possess the required qualities. *Testing* includes the making of standard tests to determine whether materials possess required qualities, and also the making of special tests of materials to determine properties not thoroughly known. Tests of material comprise chemical analyses, tests of strength, hardness, toughness, and ductility, and microscopic examination. The statement of requirements as to correctness of dimension, surface finish, strength, chemical ingredients, freedom from defects of structure, etc., forms the *specification* which samples taken from a shipment of that material must "pass."

Commercial Testing.—Commercial testing consists, in general, in making tests on selected samples from a shipment of material. It is evident that the proper selection of samples is of very great importance. The samples should be taken from various parts of the shipment, and all samples should be so marked as to make identification easy and certain. Carelessness or lack of thoroughness in sampling is one of the most serious sources of trouble in commercial testing.

On the result of commercial tests depends the acceptance or rejection of large shipments of material, and the tests should be made with a high degree of precision. Commercial testing must also be rapid. The methods and apparatus used should be of the simplest character consistent with accuracy of work.

Chemical tests are very commonly used in commercial testing. In general, chemical tests are made to determine the presence of a sufficient amount of a desired ingredient (*e.g.*, carbon in rail steel) or to determine the absence of dangerous amount of an undesirable ingredient (*e.g.*, sulphuric acid in Portland cement or phosphorus in steel). A chemical analysis does not give complete information as to the nature and properties of a material. Two pieces of steel may show the same chemical composition, but in a testing machine may develop widely different strength.

Microscopic examination of the structure of a material is used in connection with commercial tests of materials, especially of metals. Microscopic examination reveals the structure and the texture of the material, and sometimes may be used to detect the presence of flaws. Microscopic tests are used as auxiliary to tests of strength and chemical tests to furnish additional experimental evidence on the structure of the material, rather than as the main tests to determine acceptability or non-acceptability.

Physical tests of samples are very commonly used to determine the acceptability or non-acceptability of a shipment of material. The commonest strength test is a tension test to destruction. Such tests are made in some form of testing machines.

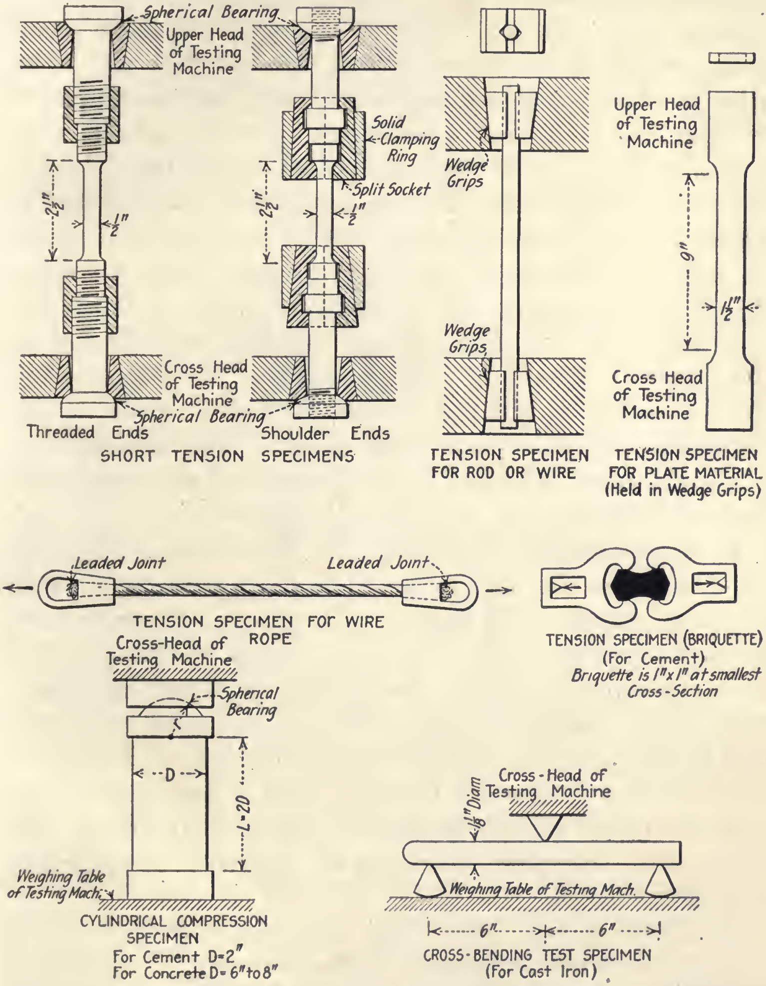

FIG. 99.—Various forms of test specimens for tests of strength of materials.

The properties of materials commonly determined in commercial tests of specimens in a testing machine are: (1) the yield point (in some cases the proportional limit),

(2) the ultimate strength, and (3) the elongation of the test specimen after rupture. For brittle materials the determination of the yield point is not made. Fig. 99 shows forms of test pieces in common use for strength tests of various materials.

Load tests, not to destruction, are occasionally used to determine the acceptability of car couplers and some other machine or structural elements and also for completed bridges, and for floors of buildings. In such service tests a load, called a proof load, is applied. This proof load is somewhat greater than the working load for the member or structure, and under such test load an examination is made to detect evidence of structural damage, such as undue deformation, flaking off of paint or scale, cracks, etc.

Impact tests are made on car couplers, rails, and some other members used in railway service. For such tests a known weight is allowed to fall through a given height striking the sample piece to be tested. The acceptability of the shipment is judged by the amount of permanent distortion, cracking, etc., developed by the blow.

Research Testing.—Research testing includes tests made to determine the properties of materials whose general qualities are not well known. Mechanical research tests include not only tension tests, but also compression, flexural and torsion tests; tests under impact load; endurance tests under repeated stress; wear tests under abrasion; and hardness tests. In addition to the study of properties of little-known materials research tests include tests made with the object of determining the form of specimen, kind of test, and procedure in testing best suited for commercial tests of materials.

Research testing does not necessarily involve more delicate or more accurate apparatus and manipulation than commercial testing. In commercial testing many arbitrary factors are present, such as size and shape of specimen, speed of testing, type of apparatus used, etc.; the important consideration is that a commercial test should be made under standard conditions. In research testing it is necessary to investigate the effect of varying conditions of testing on the results of the tests, and to determine properties of material as nearly independent of arbitrary test conditions as is possible.

Testing Machines.— Tension- Compression- Flexure Machines.—The type of testing machine in most general use in the United States can be used for tests of specimens in tension, in compression, or in flexure (or cross-bending).

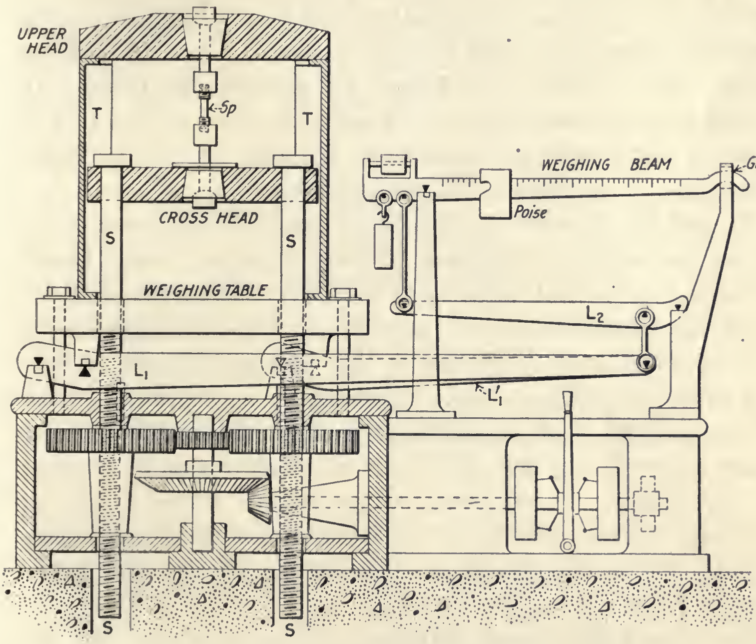

FIG. 100.—Diagram of screw-power testing machine.

Fig. 100 shows, in diagram, the arrangement of parts of such a testing machine. Power is supplied through belt-driven pulleys, or from a direct-connected motor, to a drive shaft. The power is transmitted through gearing to the main screws *S*. By means of the gearing and the screws a slow motion is given to the cross-head of the testing machine. The use of reducing gearing and screws greatly magnifies the force applied at the drive pulleys. As shown in Fig. 100, the machine is rigged for a tension test and the lower end of the specimen *Sp* is held in a socket, which is attached to the cross-head; the upper end of the specimen is held in a socket which is attached to the upper head of the testing machine. As the cross-head moves downward, the specimen is put in tension, and a downward force is transmitted by the side struts *T*, to the weighing table of the machine. The weighing table rests on the knife edges of a pair of compound levers L_1L_1' which transmit the force (reduced) to the intermediate lever L_2, which, in turn, transmits the force (still further reduced) to the weighing beam which is kept in balance by moving the poise. It should be noted for this type of machine the position of the poise on the weighing beams gives the load on the specimen *if the beam is in balance but not otherwise.*

In making tension tests it is of great importance that the device used for gripping the test specimen shall cause an axial load on the specimen, and that the stress shall be uniformly distributed over the cross-section of the specimen. The upper row of diagrams in Fig. 99 shows types of tension grips in common use. The use of a gripping device with spherical seat is desirable whenever feasible. The upper part of Fig. 99 shows the common forms of tension test specimen. It must be recognized, of course, that no gripping device will give an absolutely uniform stress distribution in the specimen; the devices shown give satisfactory results if used carefully.

The lower left hand diagram of Fig. 99 shows the arrangement of a compression test specimen in a testing machine. The test specimen is shown fitted with a spherical seated bearing block, which should always be used for a compression test. The ends of a compression test specimen should be machined to a plane surface for metal or wooden specimens or the ends should be made plane by the use of plaster of paris and a flat piece of plate glass for concrete or brick specimens. The best form of compression test specimen is a circular cylinder, though for convenience square specimens are usually used for wood, and brick or terra cotta blocks are usually tested in the form in which they are produced.

The lower right hand diagram of Fig. 99 shows a small cross-bending specimen in a testing machine, and Fig. 101 shows the arrangement of a testing machine for testing a large beam. Large testing machines are frequently equipped with a special long weighing table for flexure tests of large beams. In the flexure test shown in Fig. 99 the testing machine applies a concentrated load at mid-span of the specimen, while in the flexure test shown Fig. 101 two loads symmetrically spaced with reference to mid-span are applied to the specimen.

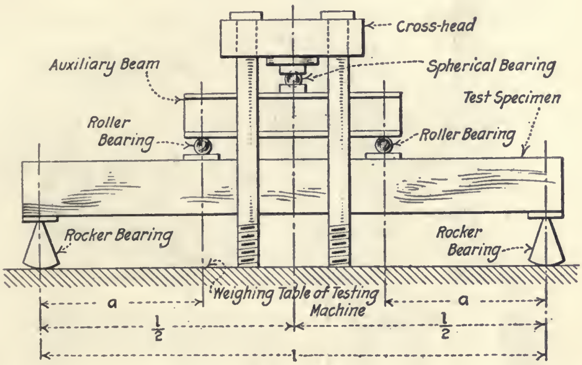

FIG. 101.—Screw-power testing machine rigged for test of beam.

For the specimen with two equal loads symmetrically spaced the shear between the loads is zero, and the bending moment for any point between them is equal to Pa (see Fig. 5). This arrangement of loading puts a considerable length of specimen under a constant bending moment, whereas with the loading shown in Fig. 99 only the cross-section at mid-span is subjected to the maximum bending moment. The two-load text subjects a greater portion of the specimen to maximum fiber stress than does the one-load test.

Fig. 100 shows the type of testing machine in commonest use in the United States. Another type which is used is shown in Fig. 102. This type is common for very large machines. Hydraulic pressure is supplied from a pump or an accumulator through the pipe W and forces the piston P and the bearing block B against the specimen S. The specimen bears against the upper head U which is adjustable for position, being moved up or down by the motor M and suitable gearing. The pressure is transmitted to vertical threaded rods T through nuts N, and thence

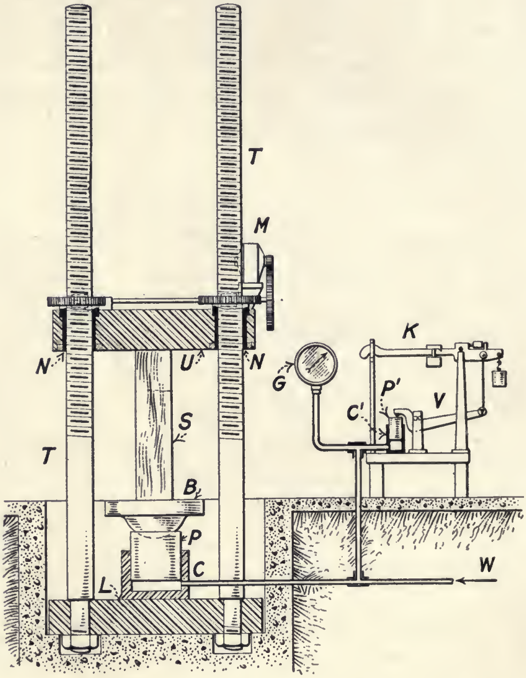

FIG. 102.—Hydraulic press type of testing machine. Machine shown is adapted for compression tests only, this type of machine can be constructed so as to make tension tests and flexure tests also.

is transmitted to the lower plate L, which takes the reaction of the cylinder C. The pressure is measured by means of a pressure gage G, or by the pressure on a smaller piston P' whose upward thrust is resisted by the weighing scale VK. Knowing the intensity of pressure the load on the specimen is obtained by multiplying this intensity by the area of the piston P. Fig. 102 shows a machine arranged for compression tests only, but machines of this type are also built arranged for tension tests. The 10,000,000-lb. compression testing machine of the U. S. Bureau of Standards at Pittsburgh Pa., which is the largest testing machine in the world, is of this type. For large machines it is necessary to use leather or hemp packings on the piston P to secure a sufficiently tight joint for operation of the machine, and the variation of the friction of the packing against the piston may cause a rather considerable error in the indications of the machine. Small machines of this type are built without packing, the pistons being carefully lapped to fit the cylinders. Such machines are

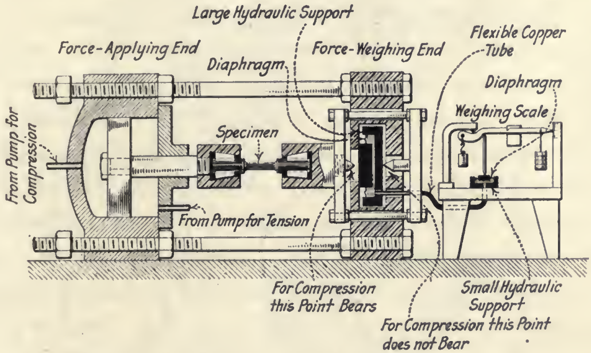

FIG. 103.—Emery type of testing machine.

as accurate as the knife-edge scale type of machine shown in Fig. 100. The hydraulic press type of machine, shown in Fig. 102 is cheaper to build than a knife-edge scale type of machine of the same capacity.

Fig. 103 shows in diagram the Emery type of testing machine. In this machine the axis of a tensile specimen or a compressive specimen is usually horizontal. The hydraulic cylinder at the left is served by a pump or an accumulator and when the piston is forced to the left tensile stress is applied to the specimen as shown; for a compression specimen the piston is forced to the right. The pull or thrust is transmitted to a hydraulic support, consisting of a short cylinder fitting with a disc fastened inside the cylinder by means of a flexible diaphragm.

This support is filled with liquid and connects through a small pipe to a smaller support which transmits the load on the specimen, reduced, to a weighing scale. In the Emery machine instead of knife edge supports the scale levers are hung on flexible steel springs.

The Emery type of machine is extremely sensitive and very costly. The advantages of a horizontal machine are ease of placing large specimens in place; the disadvantages are greater floor space required, and the inveitable bending stresses set up by their own weight in long tension or compression specimens. Flexure tests can be made more easily on a vertical machine (such as the machines shown in Fig. 100 and Fig. 102) than on a horizontal machine.

Testing machines for tension, compression, and cross-bending tests are made combining different features shown in Figs. 100, 102, and 103. For example machines are built with a hydraulic cylinder for applying load and a weighing scale for measuring the load. A common British machine uses a single lever for weighing the load rather than a system of compound levers. Another type of machine measures load by the displacement of a heavy pendulum, in a manner similar to that shown in Fig. 104 for a torsion testing machine. For testing special "arbitration bars" of cast iron special small cross-bending machines are built.

Torsion Testing Machines.—For testing the shearing strength of material the torsion test is the most suitable, because that test produces pure shearing stress in a round specimen. Torsion tests cannot readily be made on a tension-compression-flexure testing machine such as is shown in Fig. 100 and a special form of testing machine is used, Fig. 104 shows one form of torsion testing machine.

Power is applied by hand through the crank *K* (or through a drive pulley) and then through the worm *M* and gear *G* to turn the chuck *C*. The specimen *S* is fastened in two similar chunks, one at each end of the specimen, by means of self-centering jaws *J*. As the specimen is twisted it swings the heavy pendulum *P* out toward the position *P'*, and the amount of twisting moment exerted by and transmitted through the specimen is equal to Wa: W is the weight of the pendulum and a is the horizontal motion of its center of gravity. Attached to the pendulum is a finger T which shoves an indicator I along a scale E. The amount of motion of the indicator over the scale (a') is proportional to a the horizontal motion of the center of gravity of the pendulum. Hence the scale E can be graduated to read directly the amount of twisting moment on the specimen.

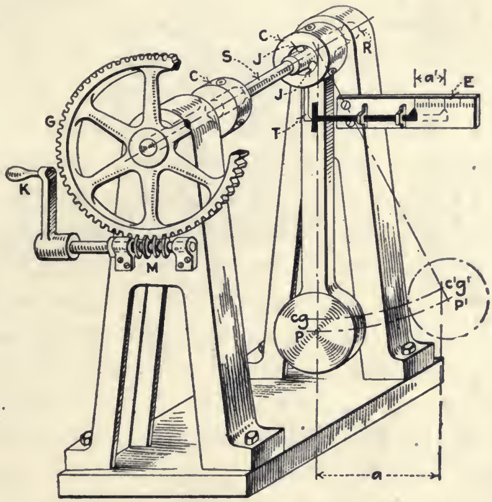

FIG. 104.—Testing machine for torsion tests.

Torsion test specimens are practically always circular in cross-section, either solid or hollow. In addition to type shown in Fig. 104 torsion testing machines are built in which the twisting moment is weighed by the use of a compound lever system and a weighing scale.

Measurement of Strain, Extensometers.—In most commercial tests there is no attempt to measure small strains in the specimen. For determining the ultimate tensile strength it is necessary merely to note the maximum load carried by the test specimen, to determine the yield point it is necessary merely to note the load at which the beam of the testing machine "drops" and stays down for a second or two as the cross-head moves downward at a uniform rate, or to note the load when visible stretch of the specimen can be detected by the use of a pair of dividers. The elongation after fracture is measured directly, and the

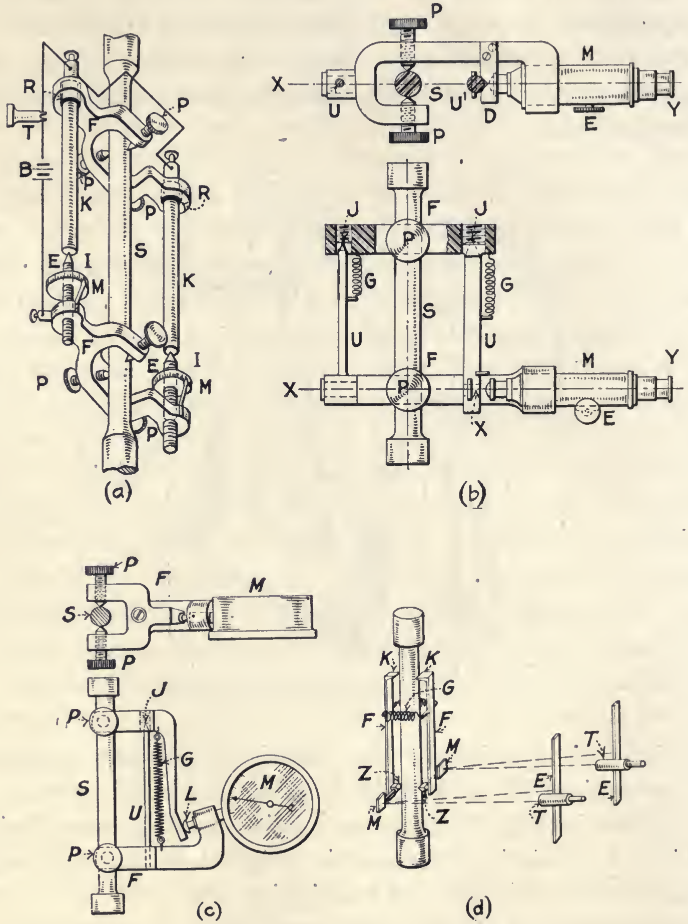

FIG. 105.—Various types of extensometers.

reduced section at fracture is measured by the use of a micrometer caliper, as is the original cross-section.

When, however, it is necessary to determine the modulus of elasticity, the elastic limit (see p. 31) or the proportional limit it becomes necessary to use some apparatus for measuring small strains. In general the apparatus used should be sufficiently sensitive to detect a change of dimension as small as 0.0001 inch. Fig. 105 shows several types of extensometers for measuring small strains in tension test specimens.

Fig. 105*a* shows an extensometer utilizing the principle of the screw micrometer. Clamps *F* are attached to the specimen *S* at the end of the gage length, each clamp by three pointed screws *P*. Micrometer screws *M* extend through the lower clamp and may be turned until their points come into contact with the side rods *K* which are held in the upper clamp by insulating bushings *R*. The contact of each micrometer screw and its side rod is determined by the establishment of electric contact through a circuit containing a telephone receiver (a small electric lamp or an electric bell is sometimes used). The difference between successive readings of the pointer *I* on the scale *E* of a micrometer gives the elongation along its axis, and the mean of the elongations shown by the two micrometers gives the average stretch of the specimen. In any accurate extensometer it is essential to determine the average stretch of the specimen.

In skillful hands the micrometer type of extensometer gives accurate results, but is is slow in use, and any but the most delicate handling is apt to disturb its attachment to the specimen.

Fig. 105*b*, shows an extensometer in which a microscope is used to measure the strains in the specimen. Clamps *F* are attached to the specimen *S* at the end of the gage length, each clamp by two pointed screws *P*. At the left hand the clamps are held a constant distance apart by the pivot bar *U*, which can turn about the axis *MZ* and whose upper end is a sharp point which bears on a conical bearing at *J*. As the specimen stretches the right hand pivot *J′* moves a distance equal to twice the average stretch of the specimen, and with the pivot *J′* moves the bar *U′* carrying a small glass plate *X* on which is a horizontal scratch made by a fine diamond point. The bar *U′* is guided in a straight path by the guide plate D. To the lower clamp is attached a microscope M fitted with an optical micrometer in the eyepiece Y, and the motion of the scratch on the plate X an consequently the stretch of the specimen is measured by means of this eyepiece micrometer.

The microscope gives direct readings without the necessity of manipulation, the long-continued use of a microscope is, however, somewhat wearying to the untrained eye. This type of attachment of extensometer to specimen gives a mechanical average of the stretch on the two opposite elements where the pointed screws P are attached.

Fig. 105*c* shows an extensometer in which the measuring unit is a micrometer dial gage which magnifies small motions by means of clockwork gears. A number of such gages are on the market. The attachment to the specimen of the extensometer shown in Fig. 105*c* is a modification of the attachment shown in Fig. 105*b*. The extensometer shown in Fig. 105*c* gives direct readings without manipulation, and gives directly the average stretch of the specimen. Usually the clockwork dial is more convenient but not quite so accurate as the micrometer screw (in skilful hands) or the microscope.

Fig. 105*d* shows an extensometer in which the measurement of strain is made by the use of the "optical lever." Clamps F are pressed against the specimen by means of springs G. The upper end of each clamp bears against the specimen through a sharp knife edge K; at the lower end of each clamp is a small steel lozenge Z to which is attached a mirror M. As the specimen stretches the lozenges Z rotate through a very small angle, an with them move the mirrors M. The motion of the mirrors is measured by means of telescopes T and scales S, the scale division reflectd into the telescope by the mirror changing as the mirror rotates. This "mirror type" of extensometer can be made to give indications of very small strains by increasing the distance of the telescopes and scales from the specimen. It is, in general, very slow to operate.

It will be noted that all the above extensometers are arranged to give either the average stretch of the specimen, or to give the stretch along two symmetrical gage lines, the average of the readings along these two lines giving the average stretch of the specimen. It is very important that extensometers should be arranged to give average stretch, especially when used to determine the modulus of elasticity. Even with the greatest care in adjustment the stress across the cross-section of a specimen is never uniform, and determinations of stretch along any one gage line are almost certain to differ from the average stretch. In very accurate determinations the stretch is sometimes measured along three symmetrical gage lines.

Various other forms of extensometer are in use, but the above examples are believed to be typical. Compressometers, deflectometers, and torsion indicators using similar measuring units are use in compression tests, flexure tests, and torsion tests. They will not be taken up in detail here.

Determination of the "Elastic Limit."—As noted on p. 32 the term elastic limit is used in practice rather loosely, and its precise meaning is not always clear. It is determined in different ways by different laboratories, and its value depends to some extent on its method of determination. The following is an outline of several methods in use for determining elastic limit, proportional limit, yield point, and other related values. In reporting a test the method used for determining elastic limit, proportional limit, or yield point should be indicated.

Elastic limit as defined in "Standard Methods of Testing" of the 1918 A. S. T. M. Standards, p. 759, is: "the greatest load per unit of original cross-section which does not produce a permanent set. (See also p. 31.)

Determination.—The determination of this limit involves the application and removal of a series of increasing loads, with a measurement of set after each one, and the plotting of sets as abscissas and loads causing set (or unit stress corresponding) as ordinates, see Fig. 106*a*. The detecting of a set depends on the sensitiveness of extensometer used. The A. S. T. M. Standards (p. 765) specify that the extensometer shall have a sensitiveness of 0.0001 in. A specification of sensitiveness *per inch of gage length* would be better. Fig. 1*a* shows the method of determining the elastic limit (denoted by *E*) from a diagram of loads and sets using 0.0001 in. as the standard of appreciable set.

Commercial Determination.—This is rarely made, but sometimes is made as a proof test, to make sure that set has *not* occurred below in certain stress. In this case appreciable set is taken as set which can be measured directly by the use of a pair of dividers, which means a sensitiveness of about 0.01 in.

Proportional limit is the load per unit of original cross-section at which deformations cease to be directly proportional to the loads.

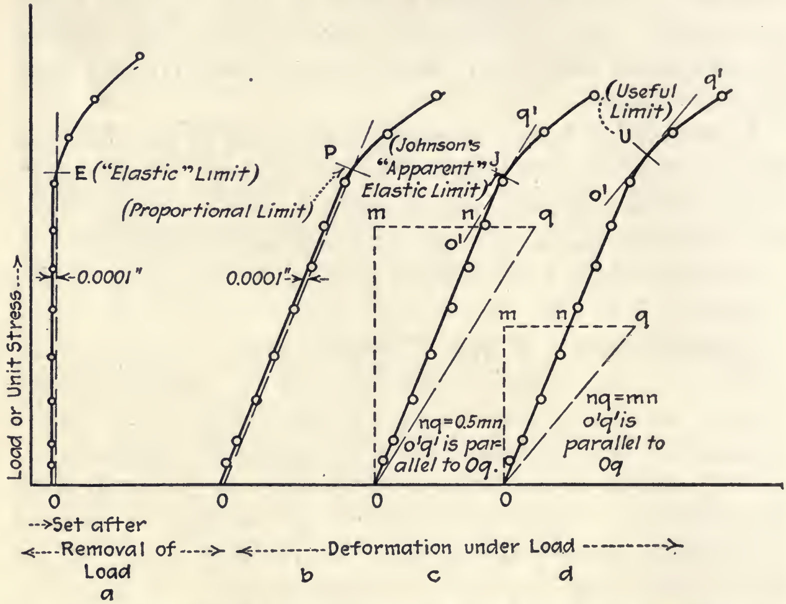

FIG. 106.—Various methods of determining elastic limit and proportional limit.

Determination.—This determination must be made from a plotted load-deformation diagram for a specimen. The A. S. T. M. Standards here also specify the use of an extensometer with a sensitiveness of 0.0001 in. Fig. 106*b*, illustrates the determination of the proportional limit, using 0.0001 in. as the limit for appreciable deviation of the stress-strain diagram from a straight line.

Johnson's Apparent Elastic Limit.—Proposed by the late J. B. Johnson. This limit is taken as that stress at which the rate of deformation is 50 per cent. greater than the initial rate.

Determination.—This limit requires a stress-strain diagram for its determination. Fig. 106*c* illustrates such a determination. The initial rate of deformation is given by the ratio mn:$0m$. nq is 0.5 of mn so that mq is 1.50 times mn, and the slope of $0q$ represents a rate of deformation 50 per cent. greater than the initial rate. $0'q'$ is drawn parallel to $0q$ and tangent to the stress-strain diagram. The point of tangency J locates Johnson's apparent elastic limit.

The Useful Limit.—Proposed by the column committee of the A. S. C. E. This limit is similar in nature to Johnson's, but it is located at that stress for which the rate of deformation is 100 per cent. greater than the initial rate.

Determination is similar to the determination of Johnson's elastic limit and is illustrated by Fig. 106*d*.

A. S. T. M. Elastic Limit.—This is a method of determining a so-called elastic limit prescribed in certain specifications for steel by the A. S. T. M. Standards (see 1918 Standards, p. 163). It is determined by the use of an extensometer sensitive to 0.0002 in., usually with a 2-in. gage length. This extensometer is attached to the specimen, and load applied at a uniform rate. The load at which the pointer of the extensometer is seen to move at an accelerated rate is taken as this limit, which is really a yield point, but is called an elastic limit. The determination of the A. S. T. M. elastic limit does not necessitate the plotting or the autographic drawing of a stress-strain diagram.

Yield Point.—This is defined as the stress at which deformation increases without any increase of load.

Determination.—It is usually determined by the drop of the beam of the testing machine as load is applied at a uniform rate, or by the halt of the pointer of a self-indicating weighing device. This method is unreliable for hard steels, as the "drop" is very uncertain.

A second method of determining the yield point is to use a pair of divides spanning the distance between two gage lines or prick punch holes, and to locate the yield point at the stress when the first stretch is visible to the eye as load is applied at a uniform rate. This method is not strictly consistent with the definition given above, but works well practically. It is rather more reliable than the "drop of the beam" method, though it would not be reliable for steels with a yield point above 100,000 lb. per sq. in. (assuming a 2-in. gage length).

Impact Tests and Impact Testing Machines.—Tests of specimens by impact are occasionally made to determine the toughness of the material under test (see p. 35 for definition of toughness). Impact tests determine the *amount of energy* required to fracture a specimen or to stress it to its elastic limit, and the results are measured in foot-pounds or inch pounds not in pounds or pounds per per square inch. No direct comparison can be made between the usual test results obtained from a "static" test of material and an impact test of material; the area under a static stress-strain diagram gives a measure of energy required for rupture and this area may be compared with the results of an impact test. The commonest impact test is a test in flexure, though impact tensile tests are also made. Frequently in testing ductile metals in flexure the specimen is notched to localize stretch and insure complete rupture: tests of notched specimens give only comparative results and great care must be taken to have all speci-

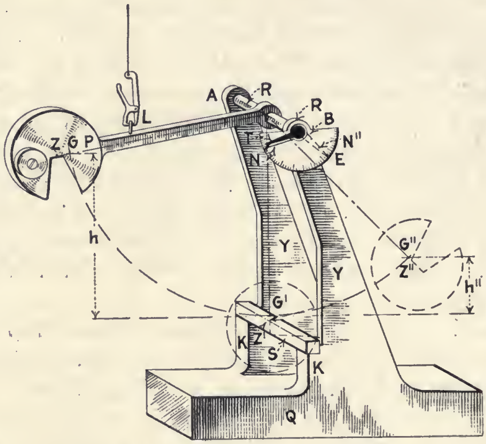

Fig. 107.—Pendulum type of testing machine for impact tests.

mens the same size, and especially to have the notches uniform in size and shape.

Fig. 107 shows in diagram a form of impact testing machine used for testings small specimens in flexure. A heavy pendulum *P* is hung in ball bearings *R*, and counterweighted so that its center of percussion[1] is at *Z* and its center of gravity at *G*. To its axis is attached an arm *T* which as the pendulum swings to the right pushes an indicating finger *N* around the scale *E*. The finger *N* does not swing back with the pendulum, but remains at its point of highest swing to the right *N''*. The specimen *S*

[1] For a method of locating the center of percussion of a pendulum see Poorman's "Applied Mechanics," p. 171.

is supported so that it bears against supports K, and as the pendulum falls the specimen is struck by the center of percussion of the pendulum. To make a test the specimen S is placed in position, the pendulum P raised to the position shown by the solid lines, held there by the latch L, and the angle initial of the pendulum read by means of the pointer N (in some machines the initial angle has a definite fixed value); the latch is released the pendulum falls, striking the specimen S, fracturing it, and then the pendulum rises to some final position G:'' this position is determined by reading the final position of the pointer at N.'' The energy utilized in fracturing the specimen is equal to $Wh - Wh$,'' in which W is the weight of the pendulum, h is the vertical fall of its center of gravity, and h'' is the vertical rise of its center of gravity after rupturing the specimen. The initial reading and the final reading of the pointer N give measures repsectively of the fall and the rise of the center of gravity of the pendulum.

Fig. 108 shows in diagram an impact testing machine in which the impact is supplied by a weight falling vertically. The weight W is raised to a predetermined height by means of a hoist D and a lifting magnet M. This height is indicated on the scale E by a pointer. The weight carries with it a pencil P which bears on the surface of a drum R which is driven at a constant speed of rotation. The specimen S receives the impact of the falling weight. Two methods of making impact tests with the drop-test type of machine are in use. In the first the weight is dropped from successively increasing heights until a permanent set in the specimen or an abnormal deflection under impact indicates that the elastic limit has been reached, or until rupture occurs. In the second method the specimen is fractured by a single blow. The pencil P traces a line on a piece of paper wrapped round the drum R.

For free fall this line is a parabola as shown in the upper part of Fig. 109, which is a typical test diagram. O in Fig. 109 corresponds to the location of the weight when striking the specimen S Fig. 108, and the lower part of Fig. 109 shows the free fall after the specimen is ruptured. In rupturing the specimen kinetic energy is taken from the falling weight and its speed is reduced; after breaking the specimen another free fall takes place. Ordinates in Fig. 109 represent distance, and, since the drum revolves uniformly,

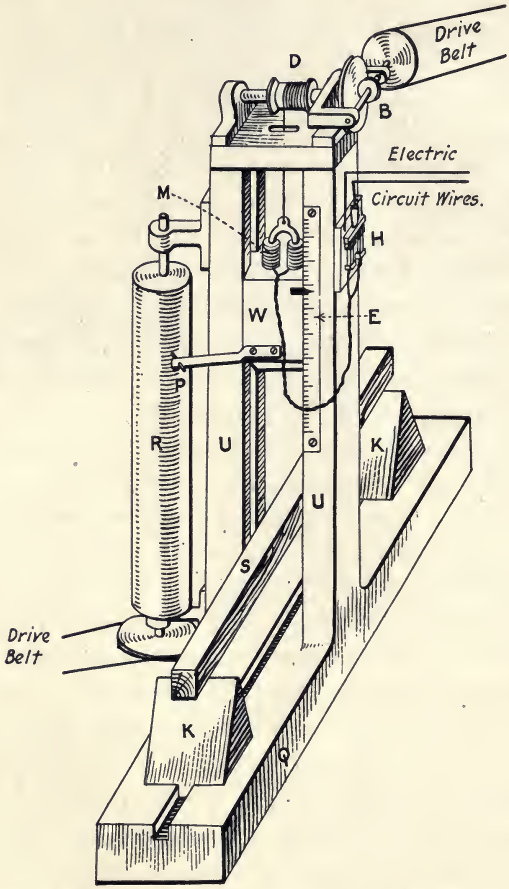

Fig. 108.—Falling-weight type of machine for making impact tests.

abscissas represent time; hence, the slope of the diagram of Fig. 109 at any point gives a measure of the velocity of the falling weight at that point. The amount of energy absorbed in breaking the specimen can be determined if the velocities at two points in the fall are determined, one before the weight strikes the specimen and one after rupture. In Fig. 109 let the first point be chosen at a and the second at b, and let the vertical distance from a to b be denoted by h. The velocity of the falling weight at a is given by the slope of the diagram at a; call this velocity v_a. Similarly determine v_b, the velocity at b. The kinetic energy of the falling weight is

$$\frac{1}{2}\frac{W}{g}v_a^2$$

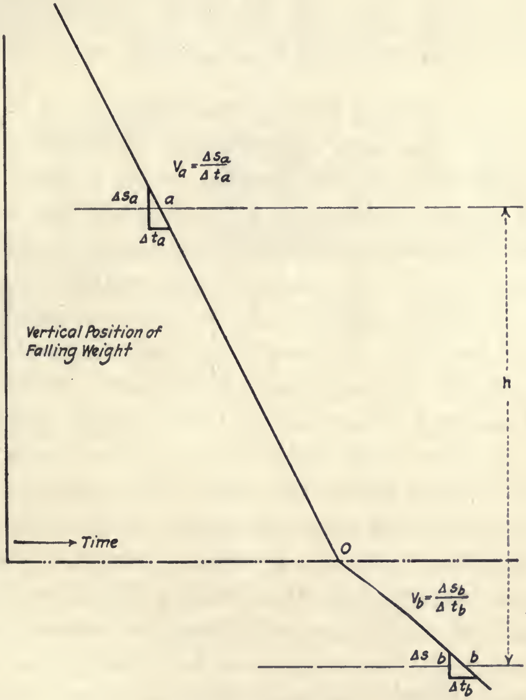

FIG. 109.—Diagram from test with falling-weight type of testing machine for impact tests.

in which W is the weight of the falling weight and g is the acceleration due to gravity (32.2 ft. per sec. per sec.). If the weight had fallen freely to b, the kinetic energy at b would have been

$$\frac{1}{2}\frac{W}{g}v_a^2 + Wh,$$

but the velocity at b is actually v_b, and the kinetic energy in the falling weight at b is

$$\frac{1}{2}\frac{W}{g}v_b^2$$

The energy which has been absorbed in breaking the test specimen is then

$$\left(\frac{1}{2}\frac{W}{g}v_a^2 + Wh\right) - \frac{1}{2}\frac{W}{g}v_b^2.$$

In this discussion, friction of the guides for the falling weight is neglected, as is the energy absorbed in vibrations of specimen, and base Q, but these losses, in general, are not large.

The type of impact testing machine shown in Fig. 108 is used for testing large specimens, especially of timber.

The significance of the results of an impact test is a matter of some uncertainty. An impact test of an unnotched specimens gives results which seem to be an index of the toughness of the material; the results of a test of a notched specimen probably also indicate toughness. The impact test has been claimed to give an index of the resistance of material to progressive breakdown under repeated stress. Localized stress arising from defects in the material seems to affect both resistance to impact and resistance to repeated stress more than they do resistance to static stress. The value of the impact test as an index of resistance to repeated stress has not been proved as yet.

Repeated Stress Tests and Testing Machines.—Tests of the strength of materials under repeated stress and testing machines for making such tests have not been standardized as have "static" tests of materials and "static" testing machines, such as are described on pages 267–273. Two types of testing machine for repeated stress tests are in fairly common use, and they are shown in diagram in Fig. 110.

In Fig. 110*a* is shown a machine which applies repeated flexural stress by means of a crank and connecting rod, and measures the bending moment applied to the specimen by means of the compression of calibrated springs. Power is furnished by a motor *M* (or from a line shaft) and a crank *C* with adjustable throw is driven by the motor. The crank is attached to a connecting rod *R* which bends a specimen *S* back and forth. The motion of the specimen is resisted by springs *G* acting through a bent lever *A*. The amount of bending moment applied to the specimen may be varied by changing the throw of the crank and is measured by the amount of compression of the springs *G*. This compression is indicated by the throw of the arm *I* to the end of which is attached a pencil which records the throw on paper wrapped round the drum *D*. The drum *D* is rotated by

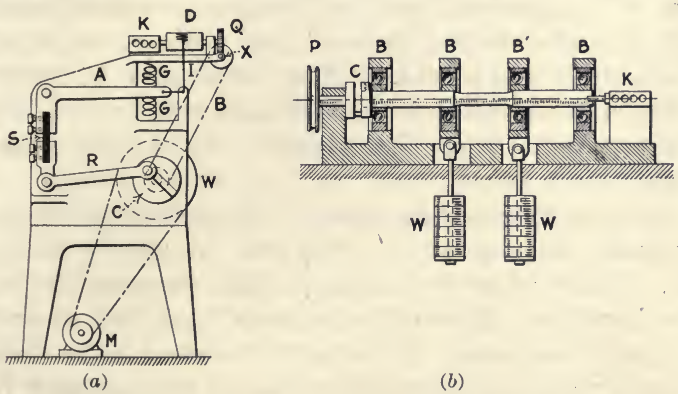

FIG. 110.—Types of testing machine for making repeated stress tests.

a worm and wheel drive from the main shaft of the machine, and there is consequently recorded on the paper a diagram whose width is a measure of the bending moment on the specimen and whose length is a measure of the number of applications of stress to the specimen. The number of applications of stress is also indicated by a counter *K*. From the bending moment the maximum unit stress applied to the specimen can be determined. Usually this type of machine is used to produce reversals of bending stress, but by varying the springs *G* other stress ranges can be applied to the specimen. The Upton-Lewis machine is the commonest example of this type of machine used in the United States.

Fig. 110*b* shows in diagram a testing machine which produces reversal of bending stress by the use of a rotating flexure specimen. The specimen S is supported on ball bearings B and driven by a pulley P. Weights are hung from a second set of ball bearings B', and these weights set up bending stresses in the specimen. The bending stress set up in the upper fibers of the specimen is compression, and in the lower fibers, tension. As the specimen is rotated the stress for any fiber changes from compression to tension, and the stress is completely reversed. The maximum unit stress for both tension and compression can be computed from the amount of weights W applied, the dimensions of the specimen, and the distances between bearings. As shown the bending moment and maximum unit stress is uniform between the two center bearings. A counter K indicates the number of reversals of stress given to the specimen, and when the specimen breaks the counter automatically stops.

Hardness Testing Apparatus.—The hardness of a material is usually defined as its resistance to plastic deformation. Various forms of test have been proposed to determine hardness. For brittle materials some form of scratch test has been used. A diamond point of some definite shape is pressed against the surface of the specimen by a known weight, and the width of scratch made as the diamond point is drawn along is measured by means of a microscope. This test gives rather variable results.

A very common type of hardness test is made by forcing a hardened steel point of definite shape into the surface of a sample of the material to be tested. A standard pressure is used and the dimensions of the indentation measured. The Brinell test is the commonest of these indentation tests. In the Brinell test a steel ball 10 mm, in diameter is forced into the material to be tested; for steel the standard pressure is 3000 kg., for softer metals 500 kg. The result of the test is given by a "hardness number," which is the quotient obtained by dividing the load by the area of the spherical impression made. This area may be determined either from the diameter or the depth of the spherical impression left in the specimen after the load is removed. The Brinell test can be made on a testing machine like that shown in Fig. 100 or, as is the more common case, a special testing machine may be used.

Another apparatus for testing hardness which is in common use is the scleroscope. In this instrument a small weight fitted with a diamond point falls from a standard height to the surface of the material under test. The height of rebound, read from a scale on the tube down which the weight falls, gives an arbitrary "hardness number" for the material. The Brinell hardness number and the scleroscope hardness number are not the same.

Both scleroscope tests and Brinell tests usually give a rough index of the ultimate tensile strength of the material tested, though the quantitative relation between hardness number and tensile strength varies for different materials. Both scleroscope tests and Brinell tests may be made without seriously injuring the material tested. It is thus possible to test the very piece to be used for a machine part or structural member instead of being compelled to rely wholly on tests of samples which are supposed to be representative of the material. Scleroscope and Brinell tests are especially useful in determining the uniformity of hardness throughout a machine part.

Other hardness tests have been proposed involving the cutting or the filing of a specimen of the material tested. Such tests have given rather unreliable results on account of the influence of even small variations in the shape and hardness of the cutting tool used.

Cold-bend Tests.—A common shop test for ductility in a metal is the cold-bend test, which is made by bending a sample strip of the metal to be tested round a mandrel of given diameter, and noting the angle of bending when the outer surface of the metal first shows a crack. This test is usually made in a shop by hammering the sample round the mandrel, or by bending in a vise or a hydraulic press. Special testing machines have been devised for making cold-bend tests quickly and easily.

Magnetic Tests of Steel as an Index of Mechanical Properties.—There seems to be a fairly definite relation between the magnetic properties of steel and the strength properties. This relation has not been developed so fully as to make standardized magnetic tests for strength properties feasible, but there is a possibility that such tests may become possible in the near future. A magnetic test could be applied to actual iron and steel parts of machines without injuring them.

A study of the uniformity of magnetic properties through out a bar of steel gives promise of being a useful test for the purpose of discovering flaws and other defects, and can be easily carried out on pieces of uniform cross-section. This test has already been applied to steel rails and to gun barrels.

There seems also to be a possibility of detecting internal flaws in metals by the use of very powerful *X*-ray tubes.

Selected References for Further Study

Unwin: "The Testing of the Materials of Construction," London, 1910. An excellent treatise by an eminent British testing engineer.

Martens (translation by Henning): "Handbook of Testing Materials," New York, 1899. Somewhat out of date but excellent in its discussion of fundamental principles. By the late director of the Prussian Royal Materials Testing Laboratory.

"Standards" of the American Society for Testing Materials," Published triennially by the society at Philadelphia (last issue, 1918). The volume has articles on standard methods of testing.

CHAPTER XXI

SPECIFICATIONS FOR MATERIALS

General Characteristics of Specifications for Materials.—The codified statement of the requirements for acceptability of a mateiral of construction makes up a set of *specifications* for that material.

Specifications for materials are formulated by individual consumers, by associations of consumers, by joint conference between producers and consumers, and by technical societies. The standard specifications for materials adopted by the American Society for Testing Materials furnish an excellent illustration of specifications systematically and carefully drawn up. Various committees of this society draw up specifications for different kinds of materials—thus there is one committee for specifications for steel, one for cast iron, one for cement, one for road materials, and so on. On each of these committees are representatives of the manufacturers of the material, representatives of the consumers of the material, and, in some cases, representatives from independent testing laboratories. The specifications proposed by these various committees are confirmed or rejected by vote of the society. The accepted specifications are then published triennially in the "Standards" of the society. The specifications of this society are very widely adopted as standard by users and manufacturers of materials.

The content of a set of specifications may be divided into four subdivisions: (1) specifications relating to methods of manufacture to be used; (2) specifications relating to finish, form and dimensions of the pieces of material in a shipment; (3) specifications for the chemical and physical properties of the material; and (4) specifications for the methods of testing to be used in determining the chemical and physical properties. Illustrations of the first subdivision are the specifications that structural steel for bridges shall be made by the open-hearth process, and that staybolt iron shall be made by the puddling process. The second subdivision is illustrated by the specifications for allowable variation between nominal and actual dimensions for dressed timber, by the specifications for classifying timber according to its straightness of grain and freedom from knots, and by the allowable variations from nominal thickness for steel plates. The third subdivision is illustrated by the requirements for maximum allowable sulphur content, and for transverse strength of gray cast iron, by the maximum allowable phosphorus content and the strength requirements for steel, and by the maximum allowable content of sulphur trioxide and the strength requirements for Portland cement. The fourth subdivision is illustrated by the specifications for Portland cement in which the methods of testing to be followed are set forth in great detail.

Specifications are never perfect. They are not drawn up for ideal material, but for material which it is possible to obtain at a reasonable cost under existing conditions of manufacture. From time to time it becomes necessary to change details of any standard set of specifications, and, in general, the requirements tend to become more and more exacting as the methods of commercial production are improved.

Summary of Tests Required for Materials.—A general statement of the content of current standard specifications for materials of construction can not be made in this chapter on account of the great space which would be required even for a summary. Table 18 gives a summarized statement of the kinds of tests which are required for the principal materials of engineering for which standard specifications have been adopted. The table is based on the "Standards" of the American Society for Testing Materials, which is a volume issued every three years. Probably the specifications in this volume cover the widest

TABLE 18.—SUMMARY OF THE TESTS REQUIRED FOR THE PRINCIPAL MATERIALS OF ENGINEERING BY THE 1918 "STANDARDS" OF THE AMERICAN SOCIETY FOR TESTING MATERIALS

Material	Process of manufacture	Chemical[1] tests	Physical tests	Special tests
Steel and Iron				
1. Steel for rails..	Bess. or open hearth	For C, Mn, max. P, max Si	Drop (impact)	
2. Steel for ry.. splice bars	Any approved process	For max. P	Tensile Cold-bend	
3. Steel for track bolts	Open hearth Electric	For C and max. P	Tensile Cold-bend	
4. Steel for track spikes	Bess. or open hearth	....	Tensile Cold-bend	
5. Structural steel for bridges, buildings, locomotives cars and ships	Open-hearth (Bess. allowed for buildings)	For max. P and max. S	Tensile Cold-bend	Tensile tests ef full-size eye-bars
6. Structural nickel steel	Open hearth	For max. C, max. Mn, max. P, max. S, min. Ni	Tensile Cold-bend	Tensile tosts of full-size eye-bars
7. Rivet steel.....	Open hearth	For Mn (for boiler rivets), max. P, max. S	Tensile Cold-bend	Quench-bend.[2] Special flattening tests
8. Carbon-steel for springs	Open hearth Crucible Electric	For C, Mn, max. P, max. S		
9. Alloy steel for springs	Open hearth Crucible Electric	For C, Mn, max. P, max. S, Cr, V, Si		
10. Reinforcing bars for concrete	Bess., open hearth, or from re-rolled rails	For max. P	Tensile Cold-bend	
11. Steel for forgings	Any approved process	For C, Mn, max. P, max. S, Ni, Cr, V	Tensile	Extensometer used to determine elastic limit
12. Steel for axles and shafts	Any approved process	For C, Mn, max. P, max. S	Tensile Drop (impact) Cold-bend	Extensometer used to determine elastic limit
13. Steel wheels for cars	Open hearth	For C, Mn, Si, max. P, max. S	....	Careful measurement of size
14. Steel tires......	Open hearth	For C, Mn, Si, max. P, max. S	Tensile	Careful measurement of size
15. Steel castings...	Any approved process (Castings for ships must be annealed)	For max. C, max. P, max. S	Tensile Cold-bend	Hammer test for soundness of castings for ships

TABLE 18.—*Continued*

Material	Process of manufacture	Chemical tests	Physical tests	Special tests
16. Steel boiler tubes	Open hearth	For C, Mn, max. P, max. S	Cold-flanging Flattening	Hydraulic pressure test
17. Welded steel pipe	Bess, or other approved process	....	Tensile Flattening	Hydraulic pressure test
18. Steels for automobiles	Any approved process	For C, Mn, max. P, max. S, Ni, Cr, Si, V	Tensile Cold-bend	Extensometer used to determine elastic limit
19. Boiler and fire-box steel	Open hearth	For C, Mn, max. P, max. S	Tensile Cold-bend	Nick bend test[3] to show structure of steel
20. Cold-drawn steel for screw stock	Bess., or open hearth	For C, Mn, max. P, max. S		
21. Charcoal-iron boiler tubes	Knobbling	....	....	Quench-bend[2] Nick-bend[3] Hydraulic pressure
22. Wrought-iron pipes	Puddling	....	Tensile Cold-bend	Hydraulic pressure
23. Staybolt iron...	Puddling	For max. Mn	Tensile Cold-bend	Etch test[4] to show structure
24. Wrought iron for bolts, bars, plates, and forgings	Puddling	For max. Mn (forgings only)	Tensile Cold-bend	Hot-bend[5] test Nick-bend[3] Etch test[4]
25. Cast-iron pipe..	....	....	Flexure	Hydraulic pressure
26. Cast-iron for locomotive cylinders	One yielding gray iron	For max. P, max. S	Flexure	Chill test[6]
27. Cast-iron car wheels	One yielding gray iron	....	Drop (impact) test	Chill test[6] Thermal test[7]
28. Gray-iron castings.	Cupola or air	For max. S	Flexure Tensile	
29. Malleable cast-iron	Air furnace Open hearth or electric furnace	....	Tensile Flexure	
Non-ferrous Metals				
30. Copper wire	....	....	Tensile	Electrical conductivity
31. Spelter (zinc)...	....	For max. Cd, max. Fe, max. Pb	....	
31. Manganese bronze	....	For Cu, Zn, Al, max. Pb	Tensile	
32. Gun metal, admiralty bronze, government bronze	....	For Cu, Sn, Zn	Tensile	
33. Bronze trolley wire	....	....	Tensile	Electrical conductivity

TABLE 18.—*Continued*

Material	Process of manufacture	Chemical tests	Physical tests	Special tests
34. Copper plates and bars	....	For Cu	Tensile Cold-bend	Hot-bend[5]
35. Seamless copper tubing	....	For Cu	Flattening and flanging tests	Hydraulic pressure
36. Seamless brass tubing	....	For Cu, max. Pb, max. Fe, max. total impurities	Flattening and flanging tests	Hydraluic pressure
37. Brass rod......	....	For Cu, max. Pb, max. Fe, max. total impurities	Flattening and cold-bend tests	
Non-metallic materials				
38. Portland cement	One involving calcining mixture of clay-bearing and lime-bearing materials to incipient fusion	For max. sulphuric anhydride, and max. magnesium	Special Tensile[8]	Soundness[9] Time of set[10] Fineness (sieve test)[11]
39. Natural cement	One involving calcining clay-bearing limestone at low temperature	....	Special Tensile[8]	Soundness[9] Time of set[10] Fineness (sieve test)[11]
40. Drain tile......	Burnt clay or Portland cement concrete	....	Special Transverse[12]	Absorption[13] Freezing and thawing[14]
41. Paving brick...	....	....	....	Rattler test for abrasion[15]
42. Yellow pine timber	....	....	....	Conformity to nominal size. For knots and other defects. For proportion of heartwood
43. Rubber-lined hose	....	Purity of rubber, max. S and other impurities	Tensile	Hydraulic pressure Adhesion between rubber and fabric covering

1. The following symbols are used for chemical elements: C, carbon; Mn, manganese; P, phosphorus; Si, silicon; S, sulphur; Ni, nickel; Cr, chromium; V, vanadium, Cd, cadmium; Fe, iron; Pb, lead; Cu, copper; Zn, zinc; Al, aluminum: Sn, tin; max. before the symbol for an element indicates that not more than a certain percentage of that element is allowable; min. before the symbol for an element indicates that a certain minimum percentage of that element is required.

2. Quench bend tests are made by heating a smple red-hot, plunging in water and then making a bend-test on the suddenly cooled specimen.

3. Nick-bend tests are made by nicking a specimen and bending it so that it fractures at the nick, revealing the texture of the material.

4. An etch test is made by polishing the surface of a specimen and etching with acid to bring out the structure, and show slag present.

field of any of the sets of specifications issued. Other societies issuing important sets of specifications for materials are: American Railway Engineering Association, Society of Automotive Engineers, Master Car Builders Association, American Foundrymens Association, National Board of Fire Underwriters, Yellow Pine Manufacturers Association, American Concrete Institute, U.S. Government Departments, especially the War Department and Navy Department.

Selected References for Further Study

"Standards" of the American Society for Testing Materials, published biennially during the even-numbered years. Contains a large number of standard specifications for materials, and for standard methods of testing.

DUDLEY: The Enforcement of Specifications, *Proceedings* of the American Society for Testing Materials, Vol. VII, p. 19 (1907).

MEAD: "Contracts, Specifications, and Engineering Relations," New York, 1916, especially Chaps. XVI and XVII and Appendix D, a bibliography of specifications.

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5. A hot-bend test is made by bending a flat specimen double on itself while at a red heat.

6. A chill test is made by casting a sample of iron in a metal mold, breaking the sample after cooling, and examining the fracture. The usual requirement is that the sample shall show a certain depth of chill from the surface.

7. A thermal test is made by pouring round a cold wheel a ring of molten iron. The wheel under test must withstand the stresses set up by the heat without breaking or without serious cracking.

8. The tensile test for portland cement and for natural cement is made on a specially shaped briquette molded from cement and water, or, more commonly from cement, sand, and water. All the details of mixing ingredients, molding briquettes, storing briquettes, and testing briquettes are definitely specified in the A. S. T. M. "Standards."

9. Soundness tests are made by exposing pats of cement to air, to water and to steam. To pass the test the pats must not crack or disintegrate.

10. The time of set is determined by noting the time which elapses before a needle of definite diameter loaded with a definite weight falls to penetrate a small block of cement more than a certain distance.

11. The fineness test is made by noting the percentage of material which passes through sieves of various fineness of mesh.

12. The test of a drain tile is made by applying a load along an element on the top of a tile laid with its axis horizontal, the tile being supported along an element at the bottom. Or instead of loading along a line the load may be applied through a sand cushion, and the tile supported by another sand cushion. In either event the tile is broken by flexure of the sides.

13. Absorption tests are made by noting the percentage of water which a dry title will absorb.

14. Freezing and thawing tests are made by subjecting the tile to alternate freezing thawing and watching for signs of disintegration.

15. A rattler test is made by placing bricks and cast iron spheres inside a cast iron "barrel" and giving the barrel a definite number of revolutions. The loss of weight of the bricks is a measure of their abrasion under wear.

QUESTIONS

Chapter I

1. Give illustrations of parts of structures or machines for which strength is the prime requisite for the material used.

2. Give illustrations of parts for which other properties than strength are of prime importance.

3. Name the kind of stress set up in: (*a*) bolts holding a cylinder head in place, (*b*) the shell of a boiler under pressure, (*c*) the eyebars in a bridge truss, (*d*) the connecting rod of a single-acting gas engine, (*e*) the connecting rod of a steam engine.

4. Give illustrations of parts of machines or structures in which stiffness is desirable; in which stiffness is not desirable.

5. Give illustrations of parts of machines or structures which may be made of brittle material; which may not be made of brittle material.

Chapter II

1. Define strain, stress, unit strain, unit stress.

2. In what units is each measured?

3. A tension specimen 0.500 in. in diameter is placed in a testing machine and load applied with the following results.

Load, lb.	Stretch in 8 in., in.
930	0.0012
1,860	0.0025
3,720	0.0050
5,580	0.0075
6,500	0.0088
6,980	0.0096
7,400	0.0110
8,200	0.0200
11,600	Maximum

Determine the proportional limit, the yield point, the ultimate.

4. Was the elastic limit determined in the above test? About what would be its value?

5. What is the theoretical stress at the point of contact of one chain link with another?

6. Give illustrations of parts of structures or machines which are likely to be subjected to accidental overload.

7. Give illustrations of materials for which the yield point is the practical ultimate strength when used in machines or structures.

8. Give illustrations of materials in which the ultimate as determined in tests is the index of strength when the material is used in a machine or a structure.

9. Explain why a spring in the draft rigging of a freight car lessens the injurious effect of the sudden pull which comes as the train is started.

10. Under shock, bolts which have their shanks turned down to the diameter of the root of the threads give better service than do bolts with shanks the diameter of the outside of the thread; explain.

11. Explain the increased strength given to steel by cold-rolling.

12. Steam-turbine rotors sometimes give trouble by becoming loose on their shafts due to the elastic expansion caused by centrigufal force. Would this trouble be diminished by making the rotors of a stronger grade of steel? Explain.

Chapter III

1. Why is a sharp corner more dangerous in a beam subjected to repeated stress than in one subjected to steady load?

2. Define cycle of stress, mechanical hysteresis.

3. State the "crystallization" theory of failure under repeated stress; the "micro-flaw" theory. Which is generally accepted today? On what evidence?

4. What is the relation of the elastic limit or the proportional limit determined by static tests to the ability of a material to withstand repeated stress?

5. Describe briefly a machine for making repeated stress tests.

6. What is the endurance limit for a material? How determined?

7. State the exponential equation for repeated stress.

8. If this exponential equation holds what would be the endurance limit for an infinite number of repetitions of stress?

9. The eyebars and chords of a railroad bridge are to be made of structural steel, and should be designed to withstand 2,000,000 repetitions of load. The load varies from dead load to live load plus dead load, and the live load is four times as great as the dead load and sets up stress in the same direction. What unit stress will be liable to cause failure: (*a*) Considering static strength, (*b*) computing the endurance limit (Johnson's formula), and (*c*) using the exponential formula? Is there greater danger of static failure or of failure under repeated stress?

10. A line shaft is to be designed to withstand 500,000,000 reversals of bending stress, and is to be made of cold-rolled steel. Allowing a "factor of safety" of 2.5 what stress in bending will be allowable: (*a*) Considering static strength, (*b*) computing the endurance limit, (*c*) using the exponential formula? Does static strength or fatigue strength govern in this case?

11. According to the exponential equation if the stress in a member was reduced to one-third its original value, how many times would the "life" of the member be increased?

Chapter IV

1. Define working stress, factor of safety.

2. Why must the working stress be less than the ultimate of the material?

3. Should higher unit stresses be allowed in a wire rope for a mine hoist or in a wire rope for a one-story freight elevator? Why?

4. Give illustrations of parts of structures or machines which are provided to give insurance against complete collapse rather than to carry stress under normal conditions.

5. Do the building laws of the city or town where you live fix allowable stresses for any materials?

6. How would you determine the allowable stress for steel in the axles of heavy trucks?

7. Give your opinion of the suitability of the material used for railway and highway bridges in the city or town where you live.

8. In your town or city is the construction of frame (wooden) buildings justifiable? Give reason for your answer.

9. What different materials are used in: (*a*) a power-driven pump, (*b*) a small gasolene engine, (*c*) a dump cart? Why is each material used?

Chapter V

1. What are the principal chemical changes involved in reducing iron ore to pig iron?

2. What is the reducing agent used?

3. What is a flux? Why is a flux necessary in reducing iron ore? What is the flux used in the process of reducing iron ore?

4. Sketch in diagram a blast furnace, giving approximate dimensions, and names of principal parts.

5. What is a hot-blast stove? Why used in connection with the blast furnace?

6. Describe briefly the regenerative process used in connection with the blast furnace.

7. Trace the air used in a blast furnace from the blowing engines to the final discharged gases.

8. How much ore, fuel, and flux is necessary to produce 1 ton of pig iron?

9. How much air is blown through the furnace for every ton of pig iron produced?

10. What is a casting machine?

11. Tell how the products of a blast furnace other than pig iron are utilized.

12. Locate the principal American iron ore deposits.

13. Locate the principal American centers of production of pig iron.

Chapter VI

1. Define wrought iron.

2. State the essential changes involved in the process for producing wrought iron.

3. Sketch in diagram a puddling furnace, giving approximate dimensions.

4. Describe briefly the process of producing wrought iron in a puddling furnace.

5. What is the source of the oxygen required for purifying the pig iron?

6. Why is the charge in a puddling furnace kept *basic* rather than *acid*?

7. What causes the "fibrous" structure of wrought iron?

8. What is a muck ball? A muck bar? A merchant bar?

9. What is charcoal iron? For what used? Why?

10. Why is wrought iron sometimes adulterated with scrap steel?

11. By what tests can wrought iron be distinguished from steel?

Chapter VII

1. Distinguish between steel and wrought iron.

2. What are the principal chemical changes which take place in the open-hearth process of making steel?

3. Sketch an open-hearth furnace in diagram, giving approximate dimensions and names of parts.

4. Describe briefly the procedure of the open-hearth steel process.

5. Distinguish between the acid process and the basic process in respect to: (*a*) raw material supplied to the furnace, (*b*) ingredients added during the process, (*c*) chemical changes taking place during the process, (*d*) ingredients in the finished product.

6. Why are different linings necessary for acid and for basic open-hearth furnaces?

7. How is the charge drawn from an ordinary open-hearth furnace?

8. What is a tilting furnace?

9. What is a charging machine? Why used?

10. What is a recarburizer? Why is a recarburizer usually used for open-hearth steel?

11. What are the functions of manganese in the recarburizer?

12. How is it determined when to tap an open-hearth furnace?

13. What fuel is used for the open-hearth furnace?

14. What limits the refining action of the open-hearth furnace?

Chapter VIII

1. What are the principal chemical changes involved in making Bessemer steel?

2. Sketch a Bessemer converter in diagram, giving approximate dimensions, and capacity per charge.

3. Describe briefly the procedure of the Bessemer process.

4. What recarburizers are used in the Bessemer process?

5. Why is a recarburizer necessary?

6. Why is the basic Bessemer process not used in the United States?

7. Compare Bessemer and open-hearth steel as to cost, reliability, and uniformity. Give reasons for your statements.

8. What is the duplex process of steel-making? Why used?

Chapter IX

1. Describe briefly the cementation process of making steel.

2. Which is the more expensive, cementation steel or open-hearth steel? Why?

3. Describe briefly the crucible process of making steel.

4. Which is more expensive, crucible steel or cementation steel? Why?

5. Crucible steel or Bessemer steel? Why?

6. Why do the cementation and the crucible processes of making steel give higher grades of steel than do the open-hearth and the Bessemer processes?

7. What is case-hardening?

8. Why does an electric furnace produce a higher grade of steel than an open-hearth furnace?

9. Why is it not feasible to conduct the entire process of steel-making in an electric furnace?

10. Sketch in diagram an arc-type electric furnace, an induction electric furnace.

11. Why would it be feasible to use electric furnaces for reducing iron or in Norway, when it is not feasible to use this process in Pennsylvania or Illinois?

Chapter X

1. In what ways is a foundry cupola like a blast furnace? In what ways different?

2. What is air furnace cast iron?

3. Which is more expensive, cupola iron or air furnace iron? Why?

4. What are the advantages of the air furnace over the cupola?

5. What is "semi-steel?" For what used?

6. Compare white cast iron and gray cast iron in structure, strength, brittleness, hardness. Which can be machined?

7. How can white cast iron be produced? How can gray cast iron be produced?

8. What is malleable cast iron? How produced? For what used?

9. Compare its strength and ductility with the strength and ductility of gray cast iron, of structural steel.

10. Why are large "sink heads" often necessary in molds for steel castings?

11. Give illustrations of machine or structural parts for which steel castings are supplanting cast iron; steel forgings.

Chapter XI

1. What is an ingot? What is a "pipe?"

2. What is the effect of a pipe on metal rolled from the ingot? What methods are used to minimize the danger of piping?

3. What is segregation? What ingredients give most trouble by segregation in steel? What are the effects of segregation in steel? How is segregation minimized?

4. What causes unsound or "honeycombed" steel? What is the effect on rolled steel of unsoundness? What methods are used to prevent honeycombing?

5. What is a soaking pit?

6. What is a blooming mill? What is a two-high mill? A three-high mill? What are the advantages fo each type of mill? What is a "universal" mill?

7. How does cold-rolled steel differ from hot-rolled steel?

8. For what is cold-rolled steel used?

9. Why do cold-rolled shafts tend to "kink" if keyways are cut in them?

10. What is the effect of annealing on cold-rolled or cold-drawn metal?

11. How is ordinary steel pipe formed?

12. What is the difference between butt-welded and lap-welded pipe?

Chapter XII

1. Illustrate by sketch the charcateristic crystalline structure of pure metals.

2. Are the crystals formed perfect?

3. How does a solution differ from a chemical compound? From a mechanical mixture?

4. What is a solid solution?

5. Describe the formation of structure which takes place when a molten alloy of tin and lead solidifies.

6. What is a eutectic?

7. Describe the solidification of a molten iron-carbon alloy containing more than 4.3 per cent. of carbon; of one containing less than 4.3 per cent. of carbon, but more than 2 per cent. of carbon; of one containing less than 2 per cent. of carbon.

8. Describe the changes in structure which occur in cooling from solidification to atmospheric temperature: (*a*) for steel containing more than 0.90 per cent. carbon; (*b*) for steel containing less than 0.90 per cent. carbon.

9. What is a eutectoid?

10. Define ferrite, cementite, pearlite. austenite, martensite, troostite, sorbite.

11. What is the recalescence point of steel, and at what temperature does it occur?

12. Why is high-carbon steel hardened when suddenly cooled?

13. Why is not low-carbon steel hardened when suddenly cooled?

14. Which is harder, oil-quenched steel, or water-quenched steel? Whv?

15. Why is the uniformity of steel in steel castings improved by annealing?

16. Why are welded joints in steel made tougher by hammering as they cool?

17. How much would the strength of steel be reduced at a temperature of 400°F.? Of 400°C.?

18. Define plastic welding, fusion welding, spot welding.

19. State three means used to produce the very high temperature required for fusion welding.

20. What process of welding would you recommend for making wrought iron chain? For mending a broken punch frame? For mending a crack in a thin steel plate? For welding together a small steel box? Give reasons in each case.

Chapter XIII

1. State the effect on the strength, and on the ductility of steel (ductility hot and ductility cold) of phosphorus, carbon, nickel, sulphur.

2. About what carbon content would be found in steel suitable for the following uses: milling cutters, boiler plate, carriage springs, bolts, shafting, razor blades, armor plate?

3. What is manganese steel? For what used?

4. What is "invar" steel? What is its approximate composition? For what is it used?

5. Name the alloy steels used where special strength is necessary.

6. Explain the hardness of "high-speed" steels at high temperatures.

7. Why is the silicon content low in basic open-hearth steel?

8. High-carbon steel is brittle and hard, gray cast iron has a high carbon content, but is brittle and soft; explain.

9. Why is a high-phosphorus cast iron suitable for use in stove foundries?

10. Distinguish between rusting and corrosion (or pitting).

11. Name three methods used to lessen the danger of corrosion in steel.

12. State the arguments advanced in favor of wrought iron as a corrosion resisting material.

13. From your own observation of structures (windmill towers, highway bridges, railway signal towers, etc.) and of water and gas pipes which is the more resistant to corrosion, wrought iron or steel?

Chapter XIV

1. Describe briefly the essential steps in the production of copper from its ores.

2. What are the principal uses of copper?

3. Compare with the strength and ductility of structural steel the strength and ductility of: (*a*) cast copper, (*b*) hard-drawn copper, (*c*) cast aluminum, (*d*) rolled aluminum, (*e*) cast zinc, (*f*) rolled zinc.

4. Name the principal uses of aluminum.

5. Why is aluminum used for long-span electric transmission wires?

6. Define brass, bronze.

7. What is the composition for maximum strength and for maximum ductility of brass? Of bronze?

8. Compare the maximum strength for brass and for bronze with that of structural steel.

9. Why is brass or bronze preferable to steel as a bearing metal?

10. Why preferable to cast iron?

11. What advantage has brass or bronze over Babbitt metal as a bearing metal?

12. What are the advantages of Babbitt metal or others of the soft bearing alloys?

13. Name several special non-ferrous alloys, give their special characteristics, and compare their strength and ductility with that of structural steel.

14. Why is cold-drawn brass more likely to give trouble by "season" cracking that hot worked brass?

15. Discuss the minimizing of the tendency of brass to give trouble by season cracking by means of "springing" brass rods.

Chapter XV

1. What are "hard" woods? "Soft" woods?

2. Name several species of each.

3. State the principal sources of supply in the United States of yellow pine, of Douglas fir, of white pine, of other soft woods, of oak, of hickory, of other hard woods.

4. What are annual rings?

5. What is heartwood? Sapwood? Spring wood? Summer wood?

6. Describe briefly the structure of soft wood; of hard wood.

7. Why is it necessary to give more attention to figuring shearing stresses in timber beams than in steel beams?

8. Give values for the strength in compression and in shear of yellow pine, Douglas fir, oak, hickory.

9. Why have wooden railway ties been found superior to metal or to concrete ties?

10. Would a higher unit stress be allowable in a piece of white pine for a strut in an aeroplane frame, or in a large bridge stringer of white pine? Why?

11. A wooden beam is supported at each end and carries a load in the middle, is a knot more injurious on the upper side or on the lower side? Why?

12. What kinds of knots are most injurious to timber?

13. About how much will the strength of air-seasoned hemlock be reduced if it absorbs water until its moisture content is 18 per cent.?

14. What is the effect of long-continued dead load on the resistance of wood?

15. If a working stress of 1,000 lb. per square inch in compression is allowed for yellow pine, and a short post is made of timber nominally 12 in. by 12 in., what is the load it can carry safely if made of sawed lumber? If made of lumber dressed on all four sides?

16. Explain the cracking and warping of timber under improper seasoning.

17. What is "quarter-sawed" wood?

18. What is a slab?

19. Which makes the better lumber? Why?

20. What causes decay of wood?

21. Why does well-seasoned wood decay less than poorly seasoned wood?

22. How do chemical wood preservatives prevent decay?

23. What are the preservatives commonly used for wood?

24. What are the advantages and drawbacks of each?

25. Give a brief outline of the process of treating wood with preservative.

26. What is the effect of the preservative process on the strength of wood?

27. How much is the life of a wooden railway tie lengthened by the use of preservative?

28. Why are white oak ties not creosoted?

29. For what general classes of structures is wood used? Give examples.

30. For what classes of structures is it unsuitable? Give examples.

31. What is plywood? What advantage does it have as a structural material over ordinary timber?

32. Why is plywood made up with an odd number of plies?

33. Why are I-beams of plywood practicable, while I-beams of ordinary timber are not practicable?

Chapter XVI

1. Name the general classes of building stone.

2. What is riprap? Uncoursed rubble? Coursed rubble? Squared stone masonry? Cut stone masonry? Ashlar masonry?

3. Give average values for strength in compression, in shear, and in cross-bending for granite, limestone, and sandstone.

4. For what general classes of structures is stone used?

5. Described briefly the general process of making brick or other burnt-clay structural material.

6. What is pressed brick? Repressed brick? Face brick? Firebrick?

7. How do paving bricks differ from building brick?

8. What is terra-cotta?

9. How is soft terra-cotta made? For what used?

10. How does sewer pipe differ from ordinary drain tile?

11. What is sand-lime brick?

12. About what load would cause failure in compression if applied to a pier 12 in. by 12. built of common brick with mortar joints? If built of face brick with Portland-cement mortar? If built of terra cotta blocks with Portland-cement mortar?

13. What causes tend to shorten the life brick masonry?

14. In what general classes of structures are the burnt clay products used?

15. How is terra-cotta used as a fireproofing material?

Chapter XVII

1. What is the general property of cementing materials which makes them useful in structures?

2. Describe briefly the production of gypsum?

3. What are the general uses of gypsum as a structural material?

4. Why are gypsum blocks made larger than ordinary bricks?

5. How does gypsum act as a fireproofing material?

6. What is the average strength in compression of carefully made gypsum?

7. What are some factors affecting this strength?

8. Outline the process of producing quicklime.

9. What is hydrated lime? For what used?

10. What is natural cement? Puzzolan cement?

11. Can lime mortar be used under water?

12. Can natural cement mortar be used under water?

13. Define Portland cement.

14. From what is it made?

15. Outline the process of its manufacture.

16. Draw a diagram showing the general scheme of a cement manufacturing plant.

Chapter XVIII

1. Define aggregate, fine aggregate, coarse aggregate, mortar.

2. Would it be advisable to use plain concrete or reinforced concrete for: (1) The foundation for a small dwelling, (2) the girders for a short-span bridge, (3) a short-span arch, (4) a long-span arch, (5) concrete building blocks, (6) concrete floor slabs? State reasons in each case.

3. Why is concrete aggregate frequently washed before being mixed with concrete?

4. Give illustrations of concrete construction for which it would be advisable to use the simpler methods of proportioning; for which the more elaborate methods, based on sieve analysis, would be advisable. Give reasons.

5. Define voids, well-graded aggregate. How and why does the use of well-graded aggregate tend towards low cost with good construction?

6. State some common proportions used for mixing the ingredients of concrete, and indicate for what class of work each would be used.

7. What is a sieve analysis of aggregate?

8. Why is a batch mixer considered better than a continuous mixer? Give an illustration of a piece of concrete construction for which you would advise hand mixing.

9. Discuss the effect of time of mixing on the strength of concrete.

10. How may the quality of concrete be injured during placing (1) on ordinary work, (2) under water?

11. Discuss the use of water (1) in mixing concrete, (2) in curing concrete.

12. What is the unit system for casting concrete? What is a monolithic structure? Why is it allowable to use leaner mixtures for making concrete blocks than for monolithic concrete?

13. Give average values for the strength of concrete in compression; in shear. Give an illustration of a concrete structural member in which shearing strength of material is important.

14. Discuss the use of "deformed" bars for concrete reinforcement.

15. Compare the ratio of working stress to ultimate given for concrete with the ratio allowable for steel; with the ratio for timber.

16. State precautions to be observed when laying concrete in cold weather.

17. What is the relation between the waterproof qualities of concrete and its resistance to disintegration? What are some causes of the disintegration of concrete?

18. What is the action of concrete under heat such as would be caused by a conflagration? Give your opinion of the relative advantages as fireproofing material of gypsum, terra-cotta, and concrete.

Chapter XIX

1. Outline the production of rubber.

2. Compare rubber with (*a*) structural steel, (*b*) white oak, (*c*) portland cement concrete with respect to: (1) Strength, (2) stiffness, (3) elastic resilience, (4) work required for rupture in tension, (5) mechanical hysteresis for a stress one-half the ultimate tensile strength.

3. What property of rubber would be a measure of ability to give good wear in the tires of a racing automobile?

4. How large an oak block would be required to absorb the same amount of energy which can be absorbed by a rubber buffer 6 inches in diameter and 2 inches thick, allowing the rubber buffer to be compressed to 1 inch thick, and allowing a stress of 3000 lb. per sq. in. in the oak. (Use stress-strain diagram for soft rubber in compression as given in text.)

5. Why is rawhide more suitable for gears than tanned leather, while the reverse is true for belting?

6. What kind of belting would you recommend for: (1) driving a tool-room lathe (2) driving a threshing machine (3) driving a dynamo from a water wheel? State reasons in each case.

7. How large a Manila rope would you recommend to replace a hoisting chain with links made from wrought iron rod ⅜ inch in diameter?

Chapter XX

1. Distinguish between the terms inspection and testing as applied to materials.

2. Discuss briefly the importance of careful sampling of materials which are to be tested.

3. Give illustrations of chemical tests used commercially in testing materials; of microscopic tests; of tests of strength; of tests of ductility; of tests of hardness; of other tests.

4. Describe briefly the mechanism of a testing machine for applying force, for weighing force, and for making tests in tension, compression, and cross-bending.

5. What are the advantages and limitations of (1) the compound-lever type of testing machine, (2) the hydraulic press type of testing machine, and (3) the Emery type of testing machine?

6. In what units are the results of an impact test of a specimen on a pendulum-type machine given? How could a comparable result be obtained from the stress-strain diagram of a specimen obtained on a "static" testing machine.

7. What kind of a testing machine would be used to obtain the shearing strength and stiffness of material?

8. What are the advantages and disadvantages of the two types of repeated stress testing machine shown in the text.

Chapter XXI

1. Why are chemical tests for phosphorus and sulphur required for many kinds of steel? Why are they not required for wrought iron?

2. Why are special quench-bend tests required for rivet steel?

3. Why are drop tests required for steel foe axles, shafts, and rails?

4. What is the reason for the requirement of a hydraulic pressure test for iron and steel pipes and tubes?

5. Why are flexure tests usually used for cast iron rather than tensile tests?

6. What is the significance of each of the several tests required for Portland cement?

7. What elementary stresses are set up in the specimen used for tests of drain tile?

8. Why is the rattler test used for paving brick?

9. What is the significance of cold-bend tests for steel and iron? What test results from a tensile test are comparable with the results of a cold-bend test?

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