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THE BONDING ACTION OF CLAYS

PART II—CLAYS IN DRY MOLDING SANDS

BY

RALPH E. GRIM AND F. LEICESTER CUTHBERT

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ABSTRACT

The Bonding Action of Clays

Part II — Clays in Dry Molding Sands

Part I of this report, "Clays in Green Molding Sands," presents a general discussion of the modern concept of the structure of clays, a fundamental classification of bonding clays based on their clay mineral composition, and results of a fundamental study of bonding clays in green sands, namely a description of the green compression strength and bulk density properties characteristic of each class of bonding clays, a theory of the bonding action of clays in green sands, and an explanation of the variations in bulk density in green sands. Part II presents a continuation of this fundamental study of bonding clays in dry sands. The objective of the work was to provide information leading to a better understanding of the properties of molding sands and bonding clays and hence to the more economical production of better castings.

Data are presented showing the relation of dry compression strength to amount of tempering water for varying amounts of each type of clay. The dry compression strength of a clay can be represented by the formula $DC = (T-M)K$ where T is the amount of tempering water, M is the amount of tempering water theoretically required before any dry strength develops, and K is a coefficient providing a comparative measure of the bonding value of a clay. K and M values are presented for each class of clays.

Sands bonded with halloysite or kaolinite clays are unique in that they develop greatly increased strength without much loss of water when rammed specimens are allowed to dry slowly. This so-called air-set strength is different from green strength or dry strength and was not found in sands bonded with montmorillonite or illite clays.

A theory of dry strength is presented based on the wedge-block concept of holding grains in place. Air-set strength develops because a certain amount of time (measured in minutes) is required for some of the tempering water to penetrate masses of halloysite or kaolinite clay and to become fixed so that a strong wedge-block is formed.

Because of air-set strength and other properties of some clays, it is difficult or for some clays impossible to predict the strength of a partially dried mold from simple green or dry strength determinations.

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THE BONDING ACTION OF CLAYS

PART II — CLAYS IN DRY MOLDING SANDS

Introduction

The present report gives further results obtained in the cooperative research project for the study of bonding clays and molding sands conducted by the Illinois State Geological Survey Division of the Department of Registration and Education and the Engineering Experiment Station of the University of Illinois under the sponsorship of the Illinois Clay Products Company, Joliet, Illinois. Part I of this same report, "Clays in green molding sands,"[6]* presents a detailed statement of the objectives of the project, appropriate acknowledgments, and certain results of a fundamental study of the bonding action of water and clays in green sands, namely:

1. A fundamental classification of bonding clays based on their clay mineral composition.

2. A description of the green compression strength and bulk density properties that are characteristic of each class of bonding clays.

3. A theory of the bonding action of clays in green sands.

4. An explanation of the variation of bulk density in green sands.

Part I also contains a discussion of the modern and generally accepted concept of the structure of clays. As a knowledge of this concept is desirable for an understanding of the data regarding dry sands, it is suggested that the reader consult Part I before considering Part II.

The results of the study of dry sands presented herein are briefly as follows:

1. A description of the dry compression strength properties that are characteristic of each class of bonding clay.

2. A theory of the bonding action of clays in dry sands.

3. A description of the compression strength properties that are characteristic of each type of bonding clay during the gradual removal of tempering water before drying is complete.

4. A description of air-set strength; the increase in strength developed in sands bonded with halloysite or kaolinite clay within a short time (one hour ±) after ramming without the loss of much tempering water.

5. A theory of air-set strength.

Samples Studied

The fundamental classification of bonding clays based on their clay mineral composition (presented in Part I of this report) separates them

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* For references, see bibliography at end of report.

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into groups with distinctive bonding properties. The classification may be summarized as follows:

Class I—Montmorillonite bonding clays

A. Clays composed of the clay mineral montmorillonite in which the aluminum is replaced by some magnesium, but not by appreciable iron, and in which sodium is the chief exchangeable ion. Bentonites from the Black Hills area belong to this class of clays.

B. Clays composed of montmorillonite in which the aluminum is replaced to a considerable extent by iron, and in which calcium and sometimes hydrogen are the chief exchangeable ions. Bentonites from northern Mississippi[4] belong to this class of clays. Many of the German bentonites[5] used in bonding molding sands also belong to this class. Some of the bonding clay used in Europe (for example, Geko) is natural calcium montmorillonite clay treated with a sodium salt to prepare a synthetic material approaching class IA.

Class II—Halloysite bonding clays

"White Clay" from the Eureka district in Utah, recently placed on the market as a bonding clay as a result of this investigation, is composed of the clay mineral halloysite and therefore belongs to this class of bonding clays.

Class III—Illite bonding clays

"Grundite" produced in Grundy County is a trade example of a bonding clay composed chiefly of the clay mineral illite.

Class IV—Kaolinite bonding clay

Fireclays produced extensively in Illinois and Ohio for the bonding trade are composed primarily of the clay mineral kaolinite.

Only some clays composed of halloysite, illite, or kaolinite have bonding properties adequate for commercial use.[8] Only certain of such clays, probably because of structural variations of the clay minerals, have relatively high bonding strength.

Five clays were selected especially so that each would illustrate the distinctive and characteristic properties of one of the foregoing classes or subclasses. With the exception of the halloysite clay, the samples are the same as those used in the study of green sands.[6] The samples studied were as follows:

1. Montmorillonite clay, Belle Fourche, South Dakota, class IA.

2. Montmorillonite clay, northern Mississippi, class IB.

3. Halloysite clay, near Eureka, Utah, class II.

4. Illite clay, Grundy County, Illinois, especially selected from underclay of Pennsylvanian age, class III.

5. Kaolinite clay, Grundy County, Illinois, especially prepared from an underclay of Pennsylvanian age different from that above, class IV.

Dry compression strengths were determined, according to the standard procedure of the American Foundrymens Association[1] (A.F.A.) for mixtures of all samples using various amounts of clay up to 15 percent prepared with varying amounts of tempering water. All moisture values are expressed in percentage of moist sample in accordance with A.F.A. standards. Strength values are based on determinations on three specimens which showed less than 10 percent variation in compression strength, according to A.F.A. standard procedure.

For the study of strength developed during gradual loss of tempering water, rammed specimens were prepared from a moldable mixture of each clay tempered with two different amounts of water. The compression strength of such rammed specimens was determined after they were allowed to stand in the air for varying periods of time. The moisture content was determined at the time of measuring the compression strength. A similar series of tests was conducted on rammed specimens allowed to remain varying lengths of time in a 100° F. oven.

Some specimens were rammed six times instead of three in order to study the effect of the amount of ramming on the strength developed during the gradual loss of moisture on drying slowly in the air and in a 100° F. oven.

Standard A.F.A. sand was used in all the experiments.

DRY COMPRESSION STRENGTH IN RELATION TO TEMPERING WATER
MONTMORILLONITE CLAY IA

The relation between dry compression strength and amount of tempering water for mixtures with various quantities of this clay is shown in figure 1. The curves show the very high dry compression strength developed in sands bonded with this class of clay, and the very great variation in dry strength with extremely small variations in amount of tempering water. A variation of less than 0.1 percent in the tempering water may cause a change of more than 10 lb. per sq. in. in the strength. Apparatus was not readily available for determining accurately very high strength so that the maximum dry compression strength was not measured for any of the mixtures.

Dry compression strength for any given amount of tempering water in a workable range can be represented by the formula $DC = (T-M)K$ when T is the amount of tempering water, M is the tempering water in percent theoretically required before any dry compression strength is developed, and K is an empirical coefficient. The value for M is indicated by the

intersection of the curves with the base line. K is the same for all amounts of clay and increases from 50 to 200 as T increases. K is essentially the dry compression strength developed per unit of tempering water in excess of that required for the start of dry strength.

Fig. 1. Dry Compression Strength versus Amount of Tempering Water in Sands Bonded with Varying Amounts of Montmorillonite Clay IA

The curves and formula indicate that dry compression strengths in excess of 100 lb. per sq. in. are developed in any mixture with as much as 4 percent of this type of clay by adjusting the amount of the tempering water. On the basis of data from other types of clay, it is probable that the maximum dry strength would increase with the amount of clay.[3]

From table 1 it can be seen that the theoretical amount of water required to start the development of dry compression strength (M) increases as the amount of clay increases. Computations indicate that the M value is equal to an amount of water slightly in excess of that necessary to develop a sheet of water two molecular layers thick on each unit of montmorillonite. Actually dry strengths below about 10 lb. per sq. in. cannot be measured so that somewhat more tempering water than the M value is required for appreciable dry strength. Since a water layer three molecules thick is rigid[6] and that in excess of this amount loses some rigidity, it can be concluded that water about equal to that which can be held rigidly is necessary for any dry strength, and that water in excess of this amount causes very rapid increase in strength. In other words a quantity of water adequate to develop incompletely rigid water on the surface of the montmorillonite units is necessary to get high dry strength values in this type of clay.

TABLE 1.—WATER REQUIRED TO START DEVELOPMENT OF DRY STRENGTH IN SANDS BONDED WITH MONTMORILLONITE CLAY IA

Percent clay	M	Molecular layers of water per unit cell at M
4	1.25	3+
6	1.4	2+
8	1.8	2+
10	2.5	2+
12	3.1	2+
15	3.75	2+

Briggs and Morey[3] have published dry strength data for a clay that probably belongs to this class. Their findings are in general agreement with those presented herein except the conclusion that high clay (8 to 10 percent) content sands developed less dry strength with small amounts of tempering water than low clay content sands with the same amount of tempering water. The failure to check this point may have been the result of a slight difference in the clay or testing sand.

MONTMORILLONITE CLAY IB

As shown in figure 2, sands bonded with this class of clay require a certain minimum amount of tempering water to develop any dry strength. Above the minimum amount, dry strength increases with amount of tempering water up to a maximum value which is reached abruptly.

The maximum dry compression strength of this class of montmorillonite clays is much less than that of class IA, and considerably more water is required to develop moderate strengths, particularly in mixtures with high clay content.
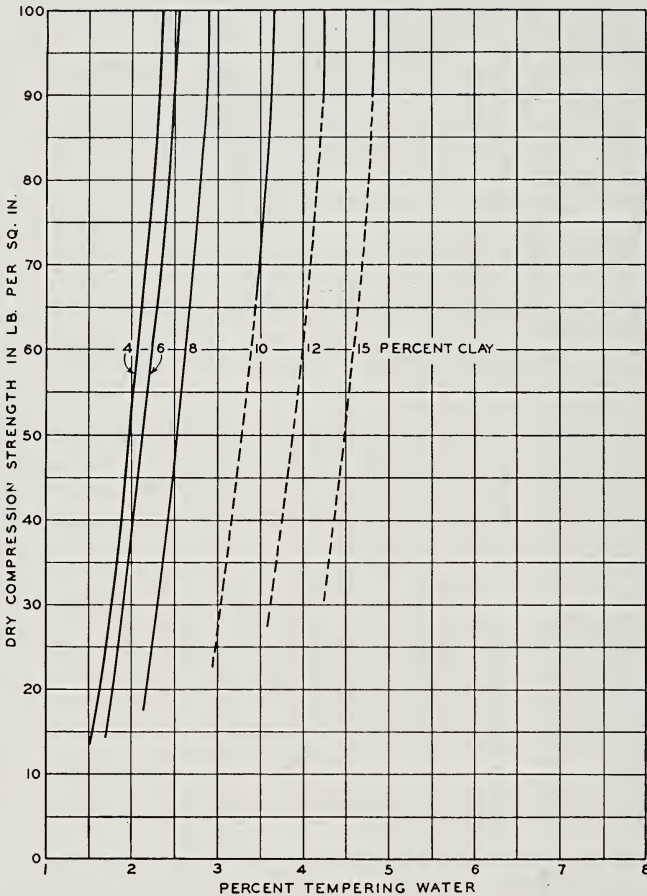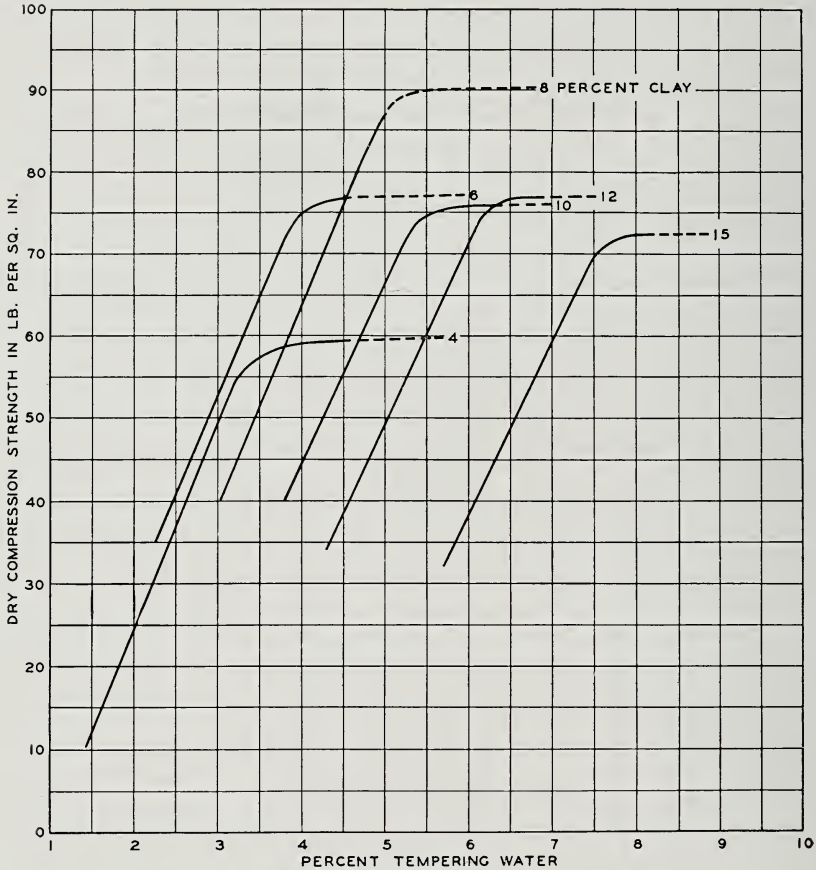

Fig. 2. Dry Compression Strength versus Amount of Tempering Water in Sands Bonded with Varying Amounts of Montmorillonite Clay IB

A striking feature of this clay is that maximum dry compression strength is about the same for mixtures containing 6, 10, 12, and 15 percent clay. The maximum values for 8 percent mixtures are slightly higher, but the difference is probably within experimental error. This means that it is impossible to get more than a certain dry strength with this class of

montmorillonite clay regardless of the amount used. The use of more clay merely makes it necessary to use more tempering water to develop the same maximum dry strength.

TABLE 2.—WATER REQUIRED TO START DEVELOPMENT OF DRY STRENGTH AND AT MAXIMUM DRY STRENGTH IN SANDS BONDED WITH MONTMORILLONITE CLAY IB

Percent clay	M	Molecular layers of water per unit cell	
		At M	At maximum D.C.
4	1	2+	8+
6	1	2−	6+
8	1.5	2−	5+
10	2	2+	5+
12	2.7	2+	5+
15	4.2	3	5+

Using the formula $DC = (T-M)K$, K is about the same for all contents of clay and, unlike class IA montmorillonite clay, does not vary with the amount of tempering water. K is equal to about 22 which is an intermediate value, that is, the rate of increase of dry strength with tempering water is less than that for illite, kaolinite, or montmorillonite IA clays, but greater than that for halloysite clays.

This type of clay requires somewhat more water than M amount before a mixture is obtained from which a specimen can be made for testing. Actually about 1 percent additional tempering water is required, and with this amount, water slightly in excess of that required to develop 3 molecular water layers per unit cell of montmorillonite is present. It has been suggested[6] that this type of montmorillonite holds water layers 4 molecules thick with complete rigidity, and it seems, therefore, that some dry strength develops before there is enough water to provide incompletely rigid water. However, this is not a certain conclusion for this class of clays because not all of the unit cell surfaces of montmorillonite may be available to water so that the amount actually present on available surfaces may be greater than computed values.

Maximum dry compression strength is developed when there is water equivalent to more than 5 molecular layers per unit cell of montmorillonite. This is more water than can be held in a completely rigid condi-

tion. In general it would seem that the development of relatively high dry strength of any class of clay requires incompletely rigid water between the clay units, probably so that adjustment of clay units can take place easily. It would seem further that a certain amount of water would provide all possible adjustment of flakes so that water in excess of the given amount would not cause greater strength.

FIG. 3. DRY COMPRESSION STRENGTH VERSUS AMOUNT OF TEMPERING WATER IN SANDS BONDED WITH VARYING AMOUNTS OF HALLOYSITE CLAY

HALLOYSITE CLAY

The curves in figure 3, showing the relation of dry compression strength to tempering water for various amounts of halloysite clay, indicate that this class of clay develops low dry strength. However, as will be shown presently (page 27) halloysite clay has high air-set properties, so that strengths greater than dry strength are developed without much loss of

tempering water when a rammed specimen stands for some minutes in the air. Also, this class of clays is unique in that complete removal of water on drying does not increase the strength above that which will develop with considerable retained water (page 28).

The maximum dry compression strength increases as the amount of clay increases and is about directly proportional to the amount of clay. Unlike other classes of clay the maximum strength is attained gradually rather than abruptly.

Applying the formula $DC = (T-M)K$, K varies from 8 in 4 percent mixtures to 16.5 in 15 percent mixtures. The value for K is lower than that of any other class of clay, which means that the strength changes only slightly with variations in the amount of tempering water. This may be a valuable property because it means that the amount of tempering water in plant practice does not require very critical control.

TABLE 3.—WATER REQUIRED TO START DEVELOPMENT OF DRY STRENGTH AND AT MAXIMUM DRY STRENGTH IN SANDS BONDED WITH HALLOYSITE CLAY

Percent clay	M	K	Molecular layers of water per unit cell	
			At M	At maximum D.C.
4	1.8	8	2+	5
6	2.2	9.5	2+	4+
8	2.4	13.5	2-	4
10	2.6	13.5	2-	3+
12	2.9	16.5	1+	3+
15	2.9	16.5	1+	3+

A striking feature of this class of clays is the low M value, that is the small amount of tempering water necessary to start dry strength. Not all the surfaces of halloysite are readily available to water, and, as shown by the air-set property, some time is required for water to penetrate to such surfaces as are available. Therefore the water layer to be found on each available surface is undoubtedly considerably greater than that given in table 3.

By the same reasoning the water layer per available halloysite cell surface is probably greater at maximum strength than the values given in table 3. In any case the amount of water is probably considerably larger than that which is held rigidly.

As shown in figure 4 illite clays develop high dry compression strength
—higher generally than any other class of clays except montmorillonite
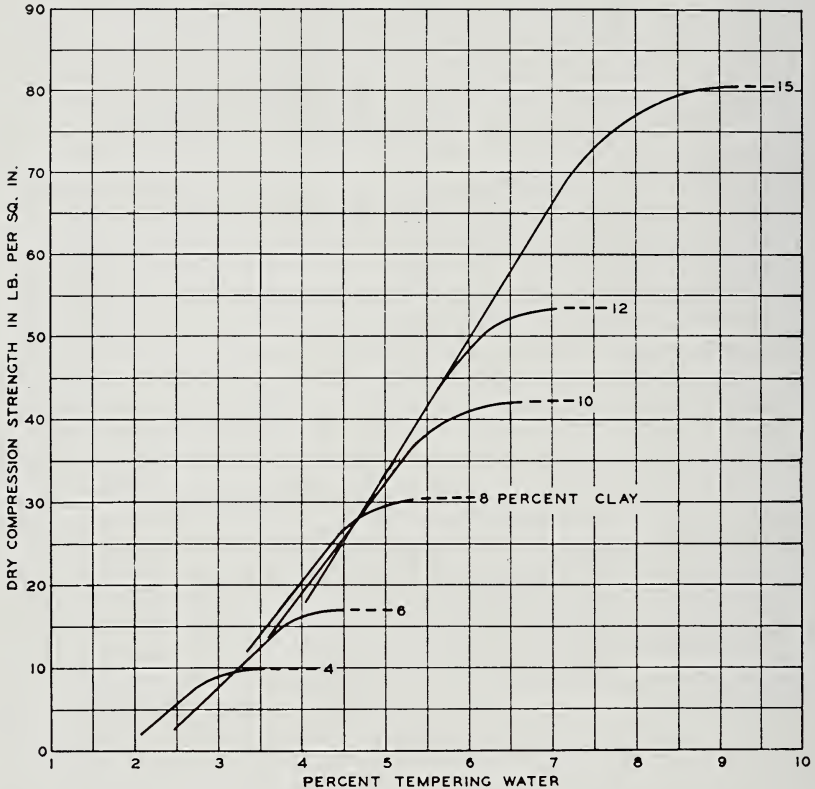clay IA. The maximum dry strength increases with the amount of clay

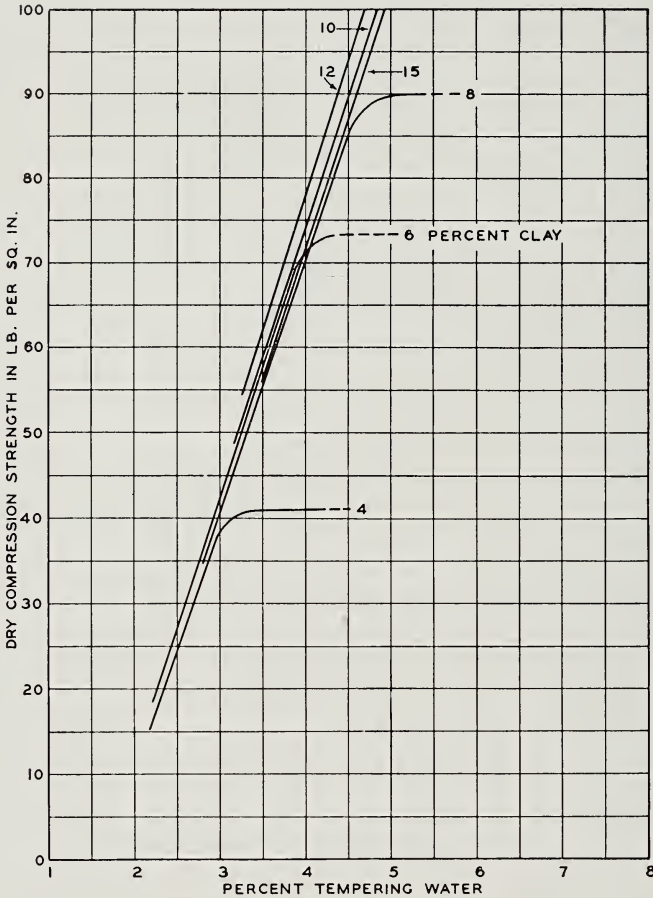Fig. 4. Dry Compression Strength versus Amount of Tempering
Water in Sands Bonded with Varying Amounts of Illite Clay

and develops abruptly. A distinctive character of this class of clays is
that maximum strength is developed with relatively small amounts of
tempering water.

In the formula DC = (T—M)K, K is constant at about 30 for all
amounts of clay, and likewise M is about the same (1.6) regardless of the

amount of clay. That is, the amount of water necessary to begin the formation of dry strength does not increase as the amount of clay increases, and the rate of increase of strength with increasing tempering water is the same for all amounts of clay.

The fact that M and K are always the same means that in this class of clays a certain dry strength develops at a given moisture content regardless of the amount of clay, provided it is in excess of a minimum value. Thus, at 3.5 percent tempering water, sands with 6, 8, 10, 12, or 15 percent clay all develop about the same dry strength, 56 to 62 lb. per sq. in. Stated another way, if a sand with 70 lb. per sq. in. dry strength is wanted, it can be obtained in any mixture with from 6 to at least 15 percent clay when 4 percent tempering water is used. An explanation for this characteristic is given later in this report.

There is very little penetration of water between the illite units so that no computations of thickness of water layer per unit cell are justified.

KAOLINITE CLAY

As shown in figure 5 the maximum dry compression strength obtainable with kaolinite clay is reached abruptly and increases with the amount of clay in the mixture. In general this class of clay yields slightly less dry strength than illite clays, and slightly more water is required to develop equivalent strength in a given mixture. The dry strength is less than that of montmorillonite clay IA, but is greater than that of montmorillonite clay IB in mixtures with more than 10 percent clay, because the maximum attainable dry strength of montmorillonite clay IB remains constant in mixtures with large amounts of clay. Clays of the illite and kaolinite classes, in which the strength continues to increase with the clay content, develop higher dry strength than montmorillonite clay IB in high clay content sands.

In the formula $DC = (T-M)K$, M is equal to about 1.6 for all amounts of clay at least to 15 percent, which is the same as the M value for illite clays. K is the same for all amounts of clay and is equal to 23. This is less than the K value for illite clays, which means that the variation of dry strength with tempering water is more gradual in kaolinite clays.

As in the case of illite clays, since M and K are essentially the same for all amounts of clays up to 15 percent, the dry compression strength will be the same in all mixtures tempered with the equal amounts of water regardless of the amount of clay, provided the clay is more abundant than a certain minimum amount. This property of illite and kaolinite clays is valuable in foundry practice.

Computations of the thickness of water layers per unit cell cannot be justified because there is little immediate penetration of water between the unit cells of kaolinite.

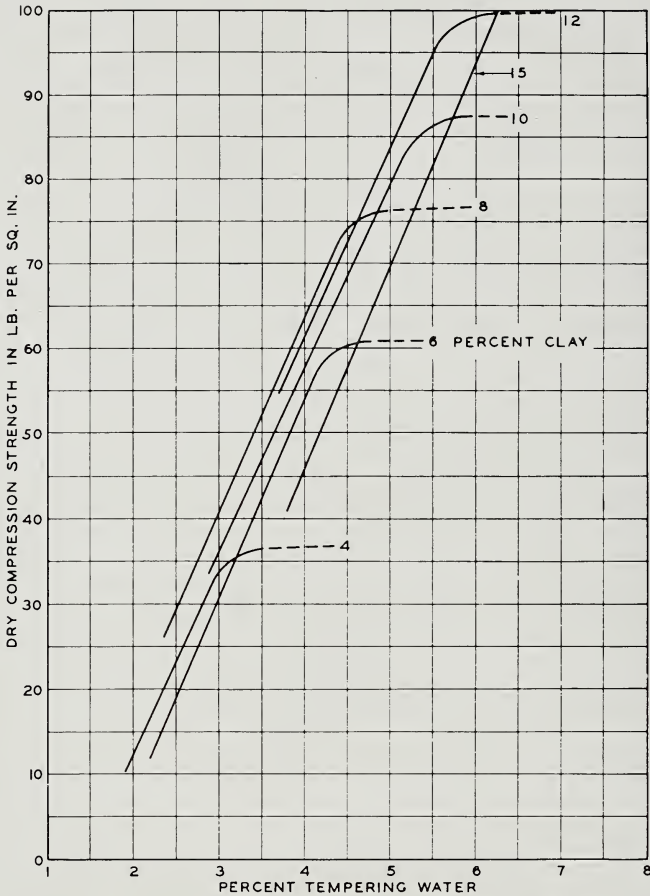Fig. 5. Dry Compression Strength versus Amount of Tempering Water in Sands Bonded with Varying Amounts of Kaolinite Clay

Dry Compression Strength in Relation to Amount and Type of Clay

The maximum dry compression strength attainable in mixtures bonded with halloysite, illite, kaolinite, and probably also montmorillonite IA clays increases with the amount of clay in the mixture. An inspection of

the data in table 4 shows that the maximum possible dry compression strength for mixtures with a given clay content varies with the kind of bond as follows: Montmorillonite IA > illite > kaolinite > halloysite. Montmorillonite clay IB is unique in that maximum attainable dry strength increases as the amount of clay increases up to about 8 percent, but with larger amounts of clay there is no further improvement in strength. The maximum dry strength of sands bonded with up to 8 percent montmorillonite clay IB is about equal to that of sands bonded with equal amounts of illite. With more than 8 percent clay, illite bonded sands have a higher maximum strength.

The K value is much higher for montmorillonite clay IA than for any other class of clay—that is, the dry compression strength shows the largest change with variations in amount of tempering water. In this clay, variations of 0.1 percent water cause changes of 5 to 20 lb. per sq. in. in dry strength. Halloysite clay has the lowest K value—variations of 0.1 percent water cause changes of only 0.8 to 1.6 lb. per sq. in. in dry strength. The K values for montmorillonite IB, illite, and kaolinite clays are intermediate but are much closer to halloysite clay than to montmorillonite clay IA.

The M value, the theoretical amount of water required to begin the development of dry strength, increases with increasing amounts of clay in the montmorillonite and halloysite clays. Since montmorillonite clay IB and halloysite clay also have low K values, rather large amounts of water are required to develop much dry strength in mixtures bonded with these clays. A condition is rapidly approached wherein the sands are so wet that no more adjustment of clay mineral flakes is possible with additional water, and as a consequence the maximum dry strength is relatively low (pp. 5, 8). In the case of sands bonded with montmorillonite clay IA, the K value is so high that extremely high strength is developed in sands with relatively low moisture contents.

In sands bonded with illite or kaolinite clay, the M value is low and constant so that, even though the K value is moderate, high maximum dry strength is attained in mixtures with relatively large clay contents containing moderate amounts of tempering water.

Illite and kaolinite clays are unique in that both the M and K values are constant for all amounts of clay studied. As indicated previously this means that a certain dry strength develops at a given moisture content *regardless of the amount of clay*, provided it is in excess of the amount that develops a maximum strength at the moisture content used.

TABLE 4.—MAXIMUM DRY STRENGTH, K AND M VALUES FOR MIXTURES WITH DIFFERENT AMOUNTS OF BONDING CLAY OF EACH CLASS

Percent clay	Montmorillonite clay IA			Montmorillonite clay IB			Halloysite clay			Illite clay			Kaolinite clay		
	Max. D.C.	M	K	Max. D.C.	M	K	Max. D.C.	M	K	Max. D.C.	M	K	Max. D.C.	M	K
4	100+	1.25	50–200	60	1	22	10	1.8	8	41	1.6	30	37	1.6	23
6	100+	1.4	"	77	1	"	17	2.2	9.5	73	"	"	61	"	"
8	100+	1.8	"	90	1.5	"	30	2.4	13.5	90	"	"	77	"	"
10	100+	2.5	"	76	2	"	42	2.6	13.5	100+	"	"	88	"	"
12	100+	3.1	"	77	2.7	"	53	2.9	16.5	100+	"	"	100	"	"
15	100+	3.75	"	73	4.2	"	80	2.9	16.5	100+	"	"	100+	"	"

THEORY OF DRY COMPRESSION STRENGTH

The theory of dry compression strength that seems to fit best with the experimental dry strength data for the different classes of clay and that agrees with the facts and theories of green strength and air-set strength is as follows:

Wedge-block-shaped masses at the junctions of the sand grains hold the grains in place and give rise to dry compression strength. The strength of the wedge-block and, therefore, the amount of dry compression strength is determined by the homogeneity and uniformity of the wedge-block. A relatively small completely homogeneous wedge-block composed of uniformly sized and arranged flakes will provide greater dry compression strength than a larger one composed of a mixture of large and small particles with a random arrangement because in the latter case planes of weakness must be present because of the nonuniform character.

The function of the tempering water is to separate the clay mineral particles and to act as a lubricant so that, on ramming, movement can take place between them. As a result a homogeneous structure can be formed which on drying will provide a dense and therefore strong wedge-block. Dry compression strength in general increases with the amount of tempering water because more water gives more separation and lubrication of the clay particles and consequently results in a more homogeneous wedge-block. The K value is a measure of the speed of the separating and lubricating effect of the water.

There is, of course, a limit to the perfection of the wedge-block that can develop with increased amounts of tempering water. As the amount of water is increased, a point is reached where all possible separation of clay mineral particles is attained and they are completely lubricated. Obviously more water cannot lead to the formation of a stronger wedge-block. There is, therefore, a maximum dry strength for a given amount of clay, i.e., a strength which is not increased by the further addition of tempering water.

MONTMORILLONITE CLAY IA

In the presence of water this type of clay breaks down easily and completely into clay mineral flakes approaching unit cell dimensions and therefore of about equal size. A wedge develops with this class of clay that is composed entirely of flakes of approximately the same size and shape. The tempering water penetrates easily between flakes and separates each from its neighbor. The first tempering water entering between the flakes tends to develop a definite structure, and as a consequence the water is rigid. As the water layers between the montmorillonite flakes increase in thickness, the rigidity of the central part of the water layer

decreases. An important effect of this water relationship is that the individual flakes tend to become arranged in the wedge with their flat surfaces parallel and separated by about equal thicknesses of water. On drying, a wedge develops that is composed of flakes of about equal size and shape lying parallel one on top of the other. The character of the clay leads to the formation of a practically homogeneous wedge with a minimum number of planes of weakness. The wedge is therefore very strong, and very high dry compression strength is characteristic of this clay.

Because water penetrates between all the individual units that make up this clay, it follows that the amount of water necessary to start the development of dry strength (M value) should increase with the amount of clay. The M value means that a minimum amount of water is required to get sufficient separation and lubrication of flakes so that adjustments can take place between them leading to homogeneity in the wedge and thereby strength. It is shown in table 1 that the M value increases in such a way that the water per unit of clay is about the same for all amounts of clay. It is shown further that this minimum thickness is about equal to the thickness at which the rigidity of the water begins to decrease. This is in accord with expected conditions since more water would be required than that held with complete rigidity before there could be any lubricating action and adjustment of the individual flakes.

The high K value of this class of clays indicates that once there is enough water separating each flake so that there is the possibility of adjustment of the flakes, small increments of water cause great increases in strength. This would be expected since slight increases in the amount of water and the degree of its nonrigidity would cause a great increase in the lubrication between flakes.

MONTMORILLONITE CLAY IB

This type of montmorillonite clay also breaks down in water into flake-shaped units approaching unit cell dimensions, and as a consequence, the observed increase in M value with the increase in amount of clay would be expected. As in the case of montmorillonite clay IA, the amount of water necessary to begin the development of dry strength is probably about equal to that required for the presence of some incompletely rigid water.

Since both types of montmorillonite clay seem to break down to individual clay mineral flakes in the presence of water, it would seem that they should both provide wedge-blocks of about equal homogeneity with the consequence that maximum dry compression strength would be about the same. Yet this is not the case—montmorillonite clay IA has much higher dry compression strength and also a much higher K value.

The explanation for these differences probably rests in the difference in the exchangeable base composition of the two montmorillonite clays and the resulting difference in the attractive force between the flakes and the character of the water adsorbed on the clay mineral flake surfaces. In montmorillonite clay IA, sodium is the principal exchangeable base and it is found mainly between the individual flakes of the mineral. Because sodium is monovalent, it affords little bond to hold the montmorillonite flakes together. Increasing amounts of water easily and rapidly separate the flakes because no strong force is encountered tending to hold them together. On the other hand, in montmorillonite clay IB, calcium is the principal exchangeable ion and it is also found between the unit layers. Calcium is divalent so that one valence bond is available to tie to the underlying montmorillonite layer and another valence bond to the over-lying layer. As a consequence, the unit layers are held together more securely than in the sodium montmorillonite, and more water is required to develop the same amount of lubricating action so long as the amount of water is less than the amount that provides much nonrigid water and complete lubrication. There is then a possible reason for the difference in K value for the montmorillonite clays.

A further factor rests in the character of the water adsorbed on the surface of the clay mineral surfaces. In the case of calcium-montmoril-lonite clays (IB), water probably extends to a fairly definite and limited distance from the flake surface beyond which it abruptly becomes non-rigid. In the case of sodium-montmorillonite clays, the change from rigid to nonrigid water is very gradual so that water with some degree of rigidity extends a great distance from the surfaces of the individual clay mineral flakes. The probable resulting situation is that in montmorillonite IB clay-bonded sands, a point is reached quickly on the addition of water where some nonrigid, that is, fluid, water is present, whereas in sands bonded with montmorillonite clay IA the water always (except at very high moisture contents) has some orientation. In the presence of liquid water the possible perfection of the orientation of the clay mineral flake is reduced, thereby reducing the homogeneity of the wedge and the strength that develops.

A striking character of montmorillonite clay IB is that clay contents above about 8 percent cause no further increase in strength. This means that wedge-blocks larger than a certain size cause no increase in strength. It might be expected that wedge-blocks composed of montmorillonite clays that are made up of relatively uniformly oriented individual flakes would have maximum strength at a given size of wedge-block whereas wedge-blocks of the other clay minerals would continue to increase in

strength as they increased in size because they are composed of larger units less perfectly oriented. In the latter type of wedge-block there would be planes of weakness between the clay mineral particles that would have less chance of passing all the way through a layer unit. Contrary to this line of reasoning is the probability[3] that the maximum attainable strength of montmorillonite clay IA increases with the amount of clay. It must be concluded, therefore, that a satisfactory explanation for this character is not at hand.

HALLOYSITE CLAY

In halloysite clays there seems to be some penetration of water between the individual unit laths of the mineral, and therefore the increase in M value with increasing amounts of clay would be expected. Not all the surfaces of the halloysite are available to the water, at least not immediately after mixing (see air-set strength), and therefore the variation in M value is less than for the montmorillonite clays.

A possible explanation for the very small K factor for halloysite clays is afforded by the lath-shaped units[9] that make up this type of clay, as compared to flake-shaped units in other classes of clay. Units of this shape might be expected to require a larger amount of water for a given amount of adjustment of the laths to each other than units composed of about equidimensional flakes.

Halloysite clays do not break down to individual units like montmorillonite clays, and the wedge-blocks that develop, even with maximum lubrication, are composed of larger units that are less regularly arranged. As a result, sands bonded with halloysite clay have lower maximum strength than those bonded with the montmorillonite clays.

Halloysite clays are unique in that maximum dry compression strength is not attained abruptly, but gradually with increasing amounts of tempering water. Halloysite also develops outstanding air-set strength, and the two characteristics go together. Because the reaction between water and halloysite is relatively slow, a sharp point would not be expected at which there is no further increase in strength because all possible adjustment of laths was attained. By the same line of reasoning, the slow reaction between the halloysite and water may be, at least partially, responsible for the low K value.

ILLITE AND KAOLINITE CLAYS

These clays can be considered together because they have the same general dry strength characteristics.

The M value of illite and kaolinite clay is the same and it does not vary with the amount of clay. In the illite clay, water does not seem to penetrate between the individual units of the illite. All of the tempering water

is around and on the outside of aggregate masses of the clay, and some of it, not on basal surfaces, is probably not completely rigid, perhaps even when the water content is very small. The situation is unlike that in montmorillonite clays where the initial water is taken up between the clay mineral units and fixed rigidly. Therefore, from the start of the addition of tempering water, there is probably some liquid water, and this situation prevails regardless of the amount of clay. It would be expected, as a consequence, that the M value would be the same for about all amounts of illite clay. The same situations prevail in kaolinite clays except that some slight penetration of water into the kaolinite aggregates is indicated by the air-set strength.

The K factor is small for illite and kaolinite clays, because the clay aggregates are large and irregular so that a large amount of water is required for a small amount of adjustment. The kaolinite aggregates are perhaps larger and more irregular in shape than the illite aggregates, with the consequence that less water for a given amount of lubrication would be required by the illite clay. As a consequence illite clays have a slightly higher K factor.

Because illite and kaolinite clays do not break down to individual units, resulting wedge-blocks would be composed of sizable units with less homogeneity and less strength. Maximum attainable dry compression strength should, therefore, be lower than that developed in clays that break down to individual units, namely montmorillonite clay IA, and this is the case. It follows further that such relatively imperfect wedge-blocks should increase in strength as they increase in size, and as a consequence the increase in maximum attainable strength with increasing clay contents is to be expected.

Compression Strength Developed During Gradual Loss of Tempering Water

In the course of the present researches it was discovered that sands bonded with halloysite or kaolinite clays developed greatly increased strength when rammed specimens were allowed to stand in the air for short periods of time immediately after ramming. This increased strength is developed without the loss of much moisture. Such increases in strength without accompanying water losses were not found in sands bonded with the other classes of clay. Halloysite and kaolinite clays have, therefore, another type of strength in addition to green strength and dry strength which is called here air-set strength.

Unless metal is poured into a mold almost immediately after ramming or unless the mold has been dried rapidly to develop true dry strength,

the mold characteristics are frequently very unlike those that would be suggested by either green or dry strength tests. The degree that mold characteristics, which develop during an interval of slow drying, vary from those that might be predicted from green and dry compression tests is a function of the type of clay. The variation is probably greatest for those types of clay that have air-set properties. Many casting problems no doubt are the result of the fact that metal is frequently poured into a mold which has far different properties from the ones it is thought to have on the basis of green and dry strength tests.

It is therefore necessary in a fundamental study of the bonding action of clays in molding sands, to determine the strength that develops in rammed specimens when they are allowed to lose their moisture slowly. In the following pages results are presented of tests planned to investigate this point. Moldable mixtures of each type of clay were prepared at two moisture contents; one at about temper and another on the wet side of temper. Compression strength and moisture were determined on rammed specimens after they were allowed to stand in the air or in a 100° F. oven for varying periods of time up to 10 hours. By the use of air drying and oven drying at 100° F., loss of moisture at two different rates was attained, and 10 hours proved adequate for the removal of essentially all the tempering water.

All of the experiments were repeated several times in order to get trustworthy data. Even with the utmost precautions it was not possible to check results closely because of inherent difficulties in the experimental procedure, chiefly resulting from small variables that could not be controlled, such as variations in room temperature and relative humidity. It should be emphasized, therefore, that the results show only trends, but that the trends have been substantiated by repeated experiments.

The results of the experiments are presented in a series of curves showing the relation of moisture retained to compression strength and time of drying to compression strength. The moisture values given are those retained by the mixture after drying and at the time the compression strength was determined. The curves showing time versus compression strength, of course, show no absolute relationship since the position of the curve would shift with rate of drying. The shape of the curve, however, is significant for the various classes of clay. Such curves are also of considerable practical importance because a foundryman, by noting the time a mold has dried, can estimate from the curves something of the strength of the mold if he knows the kind of clay in the bond.

MONTMORILLONITE CLAY IA

As shown in figure 6, there is only a slight increase in strength accompanying the first loss of water, but following this the strength increases in direct relation to the loss of water. There is no suggestion of air-set strength, that is, development of strength without an accompanying water loss.
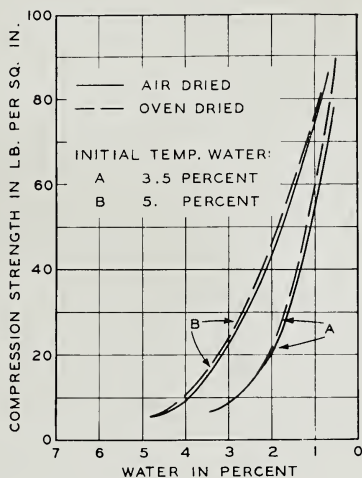

FIG. 6. COMPRESSION STRENGTH OF SANDS BONDED WITH 6 PERCENT MONTMORILLONITE CLAY IA DEVELOPED ON DRYING IN THE AIR AND IN A 100° F. OVEN TO VARIOUS MOISTURE CONTENTS

The curves in figure 6 show that the strength developed during gradual drying is dependent on the initial moisture content as well as the moisture remaining at any given time. The strength is higher, the greater the initial moisture content. Thus the data show that when sands with 6 percent clay and with initial water contents of about 5.0 percent and 3.5 percent are dried slowly until they both have 2 percent water, the strength of the former is about twice that of the latter. The explanation probably does not reside in the greater amount of time required by the wetter sand to reach 2 percent water, but in the more perfect clay wedge-block (see page 15) developed in the initially wetter sand.

Standard A.F.A. dry compression tests of montmorillonite IA clay in mixtures with 6 percent clay tempered with either 5.0 or 3.5 percent water yield values in excess of 270 lb. per sq. in., whereas similar batches with the same initial moisture content dried slowly to a very low moisture content (0.5 percent) develop only about 90 lb. per sq. in. compression

strength. This suggests that the very high A.F.A. dry strength of this class of clay is due either to an effect of the 220° F. temperature or that the rate of drying is a factor in the strength developed. It is clear that a regular A.F.A. dry compression test gives no indication of the strength in a dry sand mold unless the mold has been dried very rapidly and completely.

The curves in figure 7 show a gradual increase in strength with time of drying because of the gradual water loss with time. Increased rate of drying causes a more rapid loss of water and a more rapid increase in strength, so that after any given intermediate time the samples dried at 100° F. are stronger than those dried in the air. The samples with 5 percent tempering water show about a straight-line relationship between time and developed strength except that there appears to be an increased rate of strength development after about 8 hours when the drying is at 100° F.
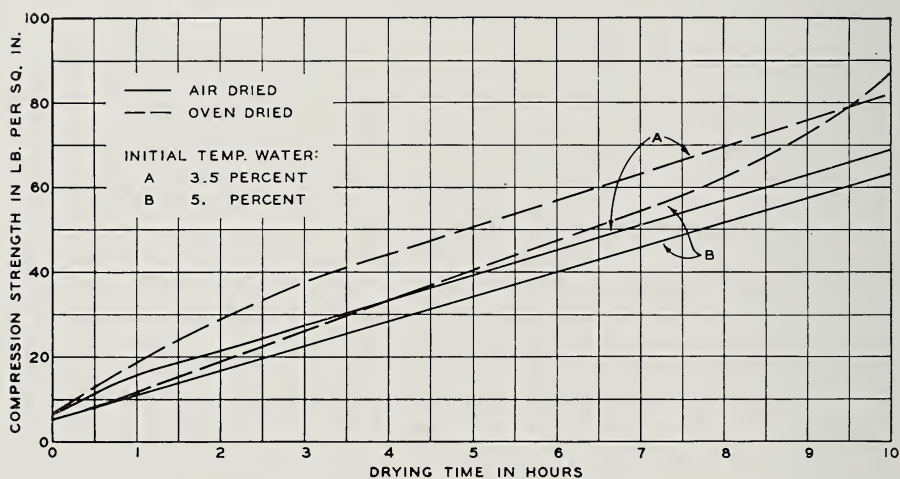

FIG. 7. COMPRESSION STRENGTH OF SANDS BONDED WITH 6 PERCENT MONTMORILLONITE CLAY IA DEVELOPED ON DRYING IN THE AIR AND IN A 100° F. OVEN FOR VARYING PERIODS OF TIME

The samples with 3.5 percent tempering water show approximately a straight-line relationship after drying about two hours. For shorter drying periods a slightly more rapid rate seems to prevail.

In sands bonded with this type of clay the strength developed on drying for any period of time up to about 10 hours for rapid drying and more than 10 hours for slow drying is greater in sands with initially lower moisture content. Thus after 6 hours drying, the batch with 3.5 percent initial water is stronger than that with 5 percent initial water. The reason

is that the drier initial sand loses water faster, so that at any given time its retained moisture is less than the initially wetter sand with a consequent higher strength. As noted above, sands starting wetter will be stronger when they arrive at the same moisture content as the initially drier sand, but it takes much longer for the wetter sand to reach a given moisture content so that for a considerable period of time the drier sand is the stronger. If sands bonded with this type of clay are not dried in the foundry very rapidly, it is usually better to work them dry as otherwise the inherent strength of the wetter sand will not be utilized.

In sands bonded with montmorillonite clay IA the strength of molds depends not only on the amount of clay and amount of tempering water, but on the amount of water retained on drying and on the rate of drying. Molds allowed to stand only slightly different lengths of time may have strengths that vary from one another as much as 100 percent.
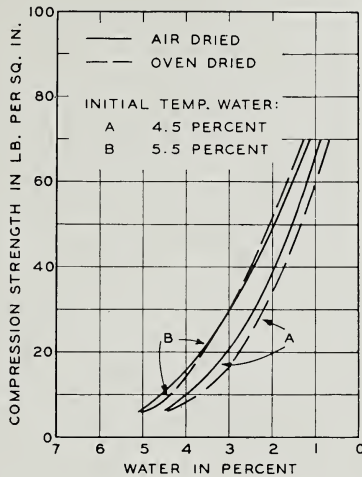

FIG. 8. COMPRESSION STRENGTH OF SANDS BONDED WITH 6 PERCENT MONTMORILLONITE CLAY IB DEVELOPED ON DRYING IN THE AIR AND IN A 100° F. OVEN TO VARIOUS MOISTURE CONTENTS

MONTMORILLONITE CLAY IB

The curves in figure 8 indicate that sands bonded with montmorillonite clay IB, like those bonded with montmorillonite clay IA, show a direct gain in strength with loss of water on gradual drying. There is no air-set strength. Such clay-bonded sands show a sharp increase in strength with the loss of the first water, even from very wet sands.

The strength developed on drying to a given moisture content varies with the initial amount of tempering water—the strength is higher in sands which have the greater initial water content.

The curves in figure 8 for air drying and drying at 100° F. show considerable variation but no constant relationship, suggesting that rate of drying is unimportant. The maximum attainable dry compression strength for a sand bonded with 6 percent of montmorillonite clay IB is about 77 lb. per sq. in. as shown in figure 2. This value is closely approached by gradual drying. Unlike montmorillonite clay IA, montmorillonite clay IB develops a strength on slow drying about equal to that of standard A.F.A. dry strength, if there is enough time for almost complete moisture loss. This further suggests that rate of drying is not a significant factor in determining the strength that develops on loss of tempering water. In this type of clay, regular A.F.A. dry compression tests are therefore fairly indicative of the strength of a mold if it is dried to a low moisture content.
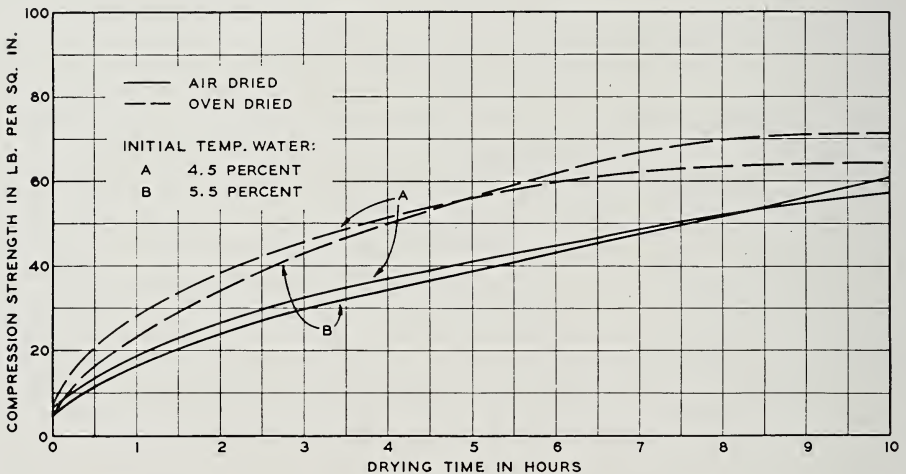

Fig. 9. Compression Strength of Sands Bonded with 6 Percent Montmorillonite Clay IB Developed on Drying in the Air and in a 100° F. Oven for Varying Periods of Time

The curves in figure 9 illustrating the relation of time to strength show a rapid increase of strength in the first few hours and then a slower gradual increase in strength with further loss of water. The initial rapid development of strength is due to the more rapid loss of water when the sands are very wet. This type of clay characteristically gains strength with the very first water loss.

The rapid (100° F.) drying curves flatten out gradually and approach, when low moisture contents are attained, the regular A.F.A. dry strength. The slow (air) drying curves show a regular and constant approach to the A.F.A. dry strength. As a consequence, after short drying periods, the more rapidly dried sands are stronger because they have a lower moisture content, whereas after long drying periods the sands have about the same strength because they have both attained about the same low moisture content.

The crossing of the curves in figure 9 means that for this type of clay, the initially wetter samples develop the higher strength after about eight hours if the drying is slow and after about five hours if the drying is rapid. Like montmorillonite clay IA, therefore, unless the mold is dried rapidly or for a long time, the greater strength will be developed if the sand is worked on the dry side of temper.

The strength of a sand-mold prepared with montmorillonite clay IB depends on the amount of clay, the amount of initial tempering water, and the moisture retained after drying. Rate of drying is not significant, and unlike montmorillonite clay IA the usual green and dry compression tests may give a fairly accurate appraisal of the strength of the sand mold.

ILLITE CLAY

The curves in figure 10 show that the strength of sands bonded with illite clay gradually increases as the tempering water is lost during slow drying without any suggestion of air-set strength. The increase in strength begins immediately with the loss of the first water. Samples with the same initial moisture content dried at 100° F. develop slightly greater strength than those dried in the air to the same moisture content. Samples with different initial moisture contents develop very different strengths when dried to the same moisture content, the initially wetter samples developing the greater strength within these limits of water content.

After 10 hours' drying in either the air or a 100° F. oven, and reducing the moisture content to about 0.5 percent, the strength is increased to about 80 lb. per sq. in. This strength is, however, still considerably less than standard A.F.A. dry strength (270 lb. per sq. in.) developed on rapid drying of similar sands at 230° F. In sands bonded with this type of clay, therefore, molds dried at a relatively slow rate do not develop the strength that would be anticipated on the basis of standard A.F.A. dry compression tests.

The curves in figure 11 show that the strength of sands bonded with illite clay increases relatively rapidly during about the first hour of drying and then more gradually. On drying only about ½ hour at 100° F. and
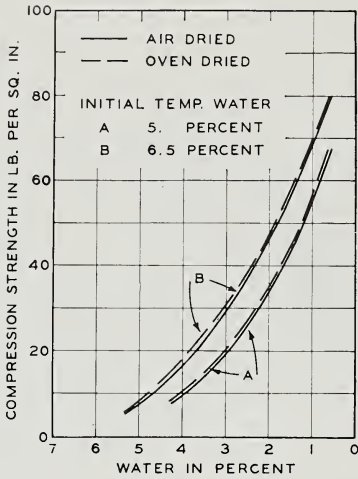
Fig. 10. Compression Strength of Sands Bonded with 12 Percent Illite Clay Developed on Drying in the Air and in a 100° F. Oven to Various Moisture Contents
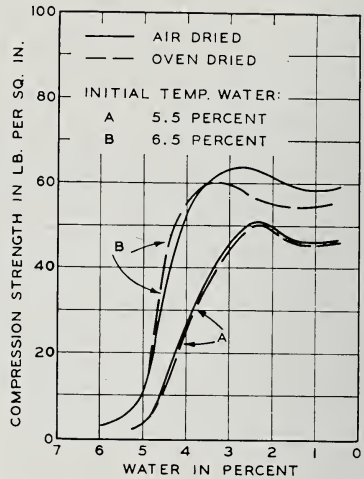

Fig. 12. Compression Strength of Sands Bonded with 12 Percent Halloysite Clay Developed on Drying in the Air and in a 100° F. Oven to Various Moisture Contents
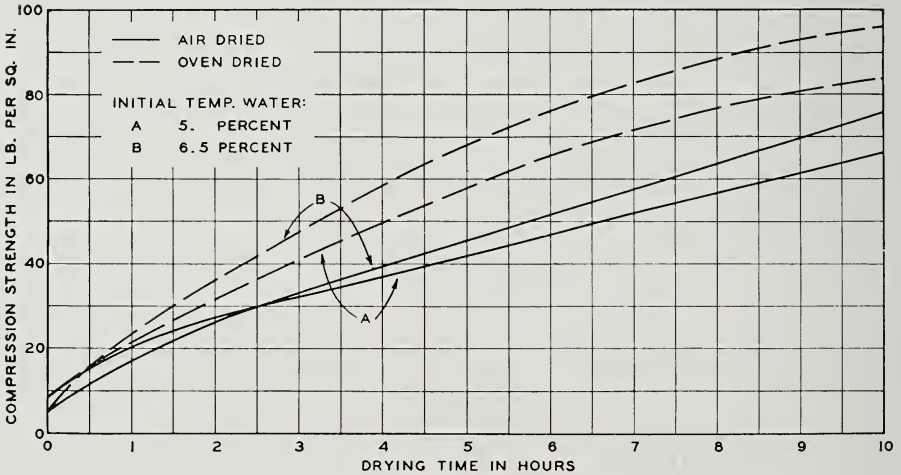

Fig. 11. Compression Strength of Sands Bonded with 12 Percent Illite Clay Developed on Drying in the Air and in a 100° F. Oven for Varying Periods of Time

2½ hours in the air the batches with the initially higher moisture content develop the greatest strength. This indicates that in foundry practice when molds are allowed to dry a few hours before pouring, stronger molds will develop from rather wet sands.

In molds prepared with sands bonded with illite clays, the strength depends on the amount of clay, the amount of initial tempering water, and the moisture content to which the mold is dried. The rate of drying is of slight importance when the drying is relatively slow. However, with slow drying, strengths equal to those obtained by standard A.F.A. dry compression tests are not obtained even after drying 10 hours in a 100° F. oven. Therefore A.F.A. dry strength tests cannot be used to determine the strength of molds that are dried slowly.

HALLOYSITE CLAY

The curves in figure 12 show that drying of halloysite clay-bonded sands causes little increase in strength until a certain definite moisture content is reached (about 5 percent for 12 percent clay mixtures) and that with further loss of water there is an abrupt increase in strength until with about 2.5 to 3.5 per cent retained water a strength about 15 times greater than green strength is developed. On drying to less than 2.5 percent water content there is a slight decrease in strength. On further slow drying to low moisture contents (0.5 percent), strengths about equal to standard A.F.A. dry strengths are obtained. The striking feature of sands bonded with halloysite clay is that they develop a higher strength when they still retain a considerable amount of tempering water (2.5 to 3.5 percent for 12 percent clay mixtures) than they do when essentially all the water is removed. This is air-set strength, and for halloysite clay-bonded sands it is higher than dry strength. Air-set strength is much greater than the maximum green strength, since the maximum attainable green compression strength at optimum moisture content in a 12 percent clay mixture using the same silica sand is about 25 lb. per sq. in.[6]

The curves in figure 12 suggest that slightly higher air-set strength develops as the rate of drying is decreased. This effect of rate of drying seems to be more pronounced in sands with higher initial water contents.

The sands with higher initial amounts of tempering water develop higher air-set strength just as they develop higher dry strength. However, the moisture content at which maximum air-set strength develops varies only slightly with the amount of initial tempering water.

Computations show that maximum air-set strength is reached when there is enough water to coat the basal surface of each unit cell of halloysite with a film of water 4 to 5 Å thick. Since not all of the basal surfaces

of the halloysite cells are available to water, the actual thickness of water on the available surface is in excess of this value, perhaps about 6 Å or the thickness of a water layer 2 molecules thick.

It is interesting that maximum green strength is attained when the computed water per unit basal surface is 7 Å thick whereas for maximum air-set strength the computed thickness is 4 to 5 Å. The difference is about 3 Å or the thickness of a single molecular layer. This may well be a fortuitous situation because the most probable theory of air-set strength suggests that many more basal surfaces are coated with water at air-set strength than at green strength.
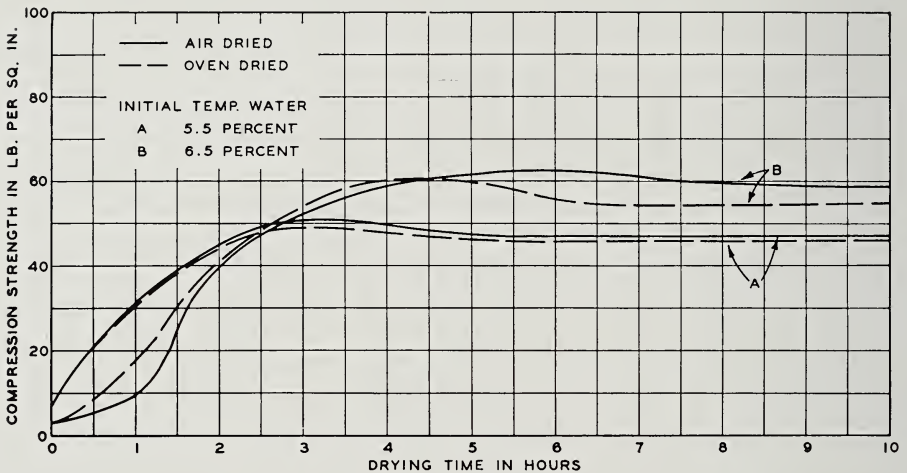

FIG. 13. COMPRESSION STRENGTH OF SANDS BONDED WITH 12 PERCENT
HALLOYSITE CLAY DEVELOPED ON DRYING IN THE AIR AND IN A
100° F. OVEN FOR VARYING PERIODS OF TIME

The curves for the sands bonded with halloysite clay illustrating the relation of drying time to compression strength (fig. 13) show the rapid increase in strength after very short periods of time followed by a slight decrease with longer periods of time. The wetter sands show a very slight increase at first and then a very rapid increase. Since the maximum air-set strength develops with a definite amount of retained water, a longer drying period is required for the wetter sands to reach maximum air-set strength because there is more water to evaporate. The curves again suggest that slightly higher air-set strength develops as a result of a slower rate of drying.

The crossing of the curves is a consequence of the fact that initially wetter sands develop the higher air-set strength. From 2½ to about 3½

hours' drying is required before the wetter sands develop the higher strength. More rapid drying reduces only slightly the time required for the development of maximum air-set strength in wet sands.

The compression strength of sands bonded with halloysite clay is determined by the amount of clay, the amount of initial tempering water, and the moisture content attained on drying. Because this type of clay possesses great air-set strength, the last factor is very significant. Also because of air-set strength, standard A.F.A. determinations of green and dry compression strength may be meaningless in that they do not reveal the true strength characteristics of the clay nor are they apt to give a clue to the strength of an halloysite clay-bonded sand mold as it is produced and used in actual foundry practice.
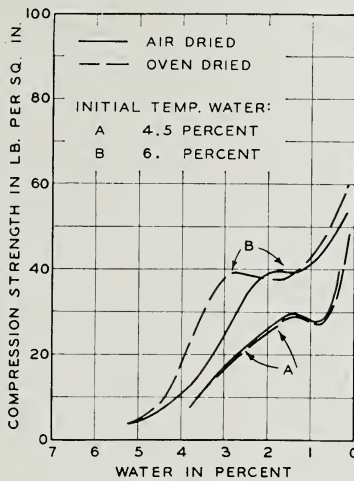

Fig. 14. Compression Strength of Sands Bonded with 10 Percent Kaolinite Clay Developed on Drying in the Air and in a 100° F. Oven to Various Moisture Contents

KAOLINITE CLAY

The curves in figure 14 show that sands bonded with kaolinite clay, like sands bonded with halloysite clay, develop air-set strength. When sands bonded with 10 percent kaolinite clay are dried, the strength increases sharply until a maximum is reached when the moisture content is reduced to 1.5 to 3 percent. With further decrease in moisture content there is a slight decrease in strength, followed again by an increase in strength at very low moisture content when true A.F.A. dry strength is attained. The air-set strength developed with 1.5 to 3 percent moisture is

5 to 10 times that of green strength and ⅓ to ½ that of A.F.A. dry strength. The air-set characteristics of halloysite clay-bonded and kaolinite clay-bonded sands are somewhat different in that A.F.A. dry strength is slightly less than air-set strength in halloysite clay-bonded sands, and considerably higher for kaolinite clay-bonded sands.

An increase in the amount of tempering water increases somewhat the amount of air-set strength. Variations in the rate of drying seem to have no effect on the air-set strength in sands with relatively small amounts of tempering water. In wet sands the amount of air-set strength is also about the same, regardless of the rate of drying, but it develops at a slightly higher moisture content when the rate of drying is rapid.

Significant computations of the water per unit of kaolinite at maximum air-set strength cannot be made because the percentage of the total kaolinite surfaces that are available to water cannot be determined.
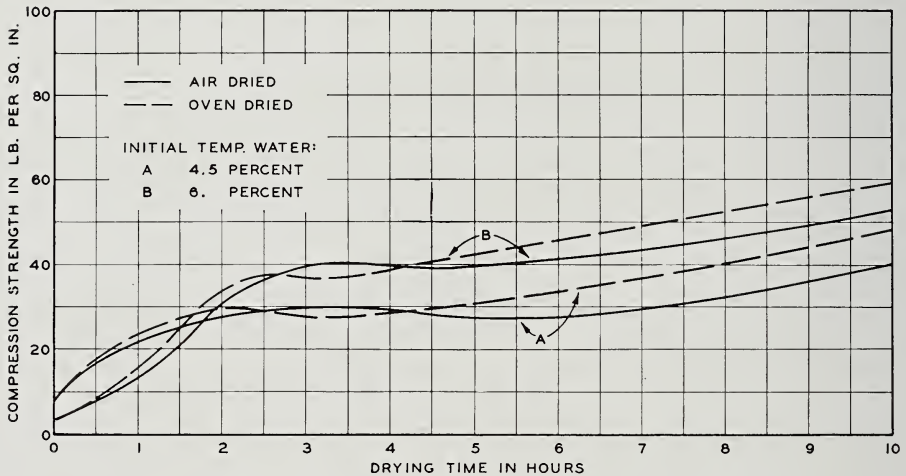

FIG. 15. COMPRESSION STRENGTH OF SANDS BONDED WITH 10 PERCENT KAOLINITE CLAY DEVELOPED ON DRYING IN THE AIR AND IN A 100° F. OVEN FOR VARYING PERIODS OF TIME

The curves in figure 15 show that maximum air-set strength is reached in the sands that have low initial moisture content in 2 to 3 hours whereas for the wetter sands 2½ to 3½ hours are required. The explanation is, of course, that some time is required to remove excess water from the wet sands before appreciable air-set strength begins to develop.

More rapid drying causes the development of air-set strength in a shorter period of time because the proper moisture content is reached more quickly. The curves in figure 15 illustrate the greater strength de-

veloped by the wetter sands, and the intermediate period between air-set strength and dry strength when the strength of the batch is lower than either air-set strength or A.F.A. dry strength.

The amount of clay, the amount of initial tempering water, and the moisture content reached on drying are the factors that determine the strength of a mold bonded with kaolinite clay. Because kaolinite clay has air-set strength, the last factor is very significant. In sands bonded with this type of clay, as in the case of sands bonded with halloysite clay, standard A.F.A. determinations of green and dry compression strength do not reveal the strength conditions in a mold unless the mold is poured immediately after it is made or after a very long period of drying.
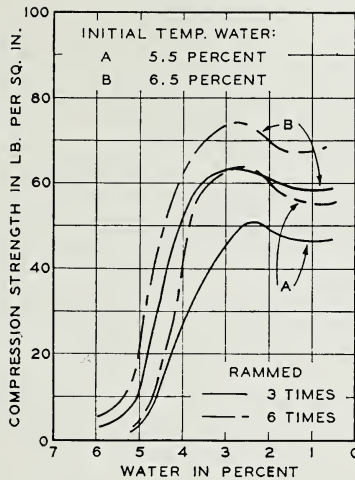

Fig. 16. Compression Strength of Sands Bonded
with 12 Percent Halloysite Clay, Rammed
3 and 6 Times, after Drying in the Air
to Various Moisture Contents

Effect of Ramming on Air-Set Strength

It is well known[2, 10, 11] that increased ramming tends to increase the strength characteristics of sand molds. Figures 16 and 17 present the results of compression tests made on two batches of halloysite clay-bonded sand from which test specimens were prepared with ramming both 3 times and 6 times. Increased ramming increases the air-set strength as well as the green and dry strengths. From the similarity of the curves for ramming 3 times and 6 times, it would seem that this increased ramming has no unusual effects on air-set strength; it does not decrease the tendency

for air-set strength to develop nor change the moisture content at which maximum air-set strength occurs. Further the curves in figure 17 indicate that the time required to develop maximum air-set strength does not change with an increase in ramming of 3 to 6 times.
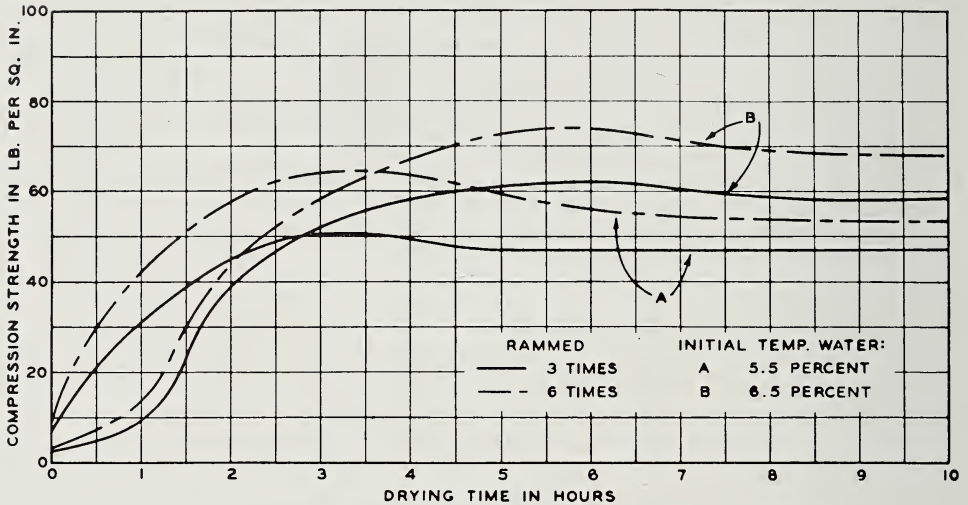

FIG. 17. COMPRESSION STRENGTH OF SANDS BONDED WITH 12 PERCENT
HALLOYSITE CLAY, RAMMED 3 AND 6 TIMES, AFTER DRYING
IN THE AIR FOR VARYING PERIODS OF TIME

THEORY OF AIR-SET STRENGTH

Air-set strength means in general that the wedge-blocks holding the sand grains in place in a rammed sample become stronger in a short period of time immediately after ramming and while a large amount of the tempering water is still retained. The problem is, then, what causes the wedge-blocks of halloysite or kaolinite clay to become stronger in the presence of water. A satisfactory theory of air-set strength must explain why this characteristic is restricted to halloysite and kaolinite clays.

It has been pointed out that there is a tendency for the tempering water associated with clay minerals, particularly that penetrating between the flake units, to become rigid because the individual water molecules take up fixed definite positions. A wedge-block built entirely of clay mineral units joined by rigid water will obviously be stronger than a wedge-block made of clay mineral units and water in which some of the water is liquid.

In sands bonded with halloysite clay or kaolinite clay, many of the basal surfaces capable of fixing water in a rigid condition are on the interior of aggregates and large crystal particles where water cannot reach them. As a consequence, immediately after ramming only part of the tempering water is rigid. The remainder is that part which has not reached a clay mineral surface capable of water fixation, and is therefore fluid.

Within a short period of time after ramming, some of this originally fluid water penetrates to clay mineral surfaces and is fixed. There is, therefore, a gradual change of some of the fluid water to a rigid condition, and as noted above this would be accompanied by an increase in the strength of the wedge-blocks and consequently of the rammed sand. While some of the originally liquid water is being fixed rigidly, some is being lost by evaporation, so that in a short time there is no liquid water in the rammed specimen. This is the condition at maximum air-set strength.

Thus in sands bonded with halloysite or kaolinite clays, some of the tempering water becomes fixed rigidly at once and some strength is developed — this is green strength. Much of the remainder of the water is at first less rigid or perhaps fluid, but some of it gradually penetrates the clay mineral and is fixed rigidly, thereby developing added strength — this is air-set strength.

Air-set strength develops because a certain amount of time[7] (measured in minutes) is required for some of the tempering water to penetrate masses of halloysite or kaolinite clay and to become fixed in a rigid condition. Sands bonded with these types of clay have a wet feel immediately after mixing because of the presence of liquid water. The wet feel disappears after air-set strength develops because the originally liquid water either has been fixed or has evaporated.

In the process of allowing sand-clay mixtures to temper before testing, there is time for the water to penetrate to many of the clay mineral surfaces. However, when mixtures are rammed the relation between various masses of clay and the individual clay mineral flakes is changed so that new interfaces develop. The actual ramming operation probably disrupts some of the lumps of clay so that additional surfaces are ultimately available to water. Further, the equilibrium between the flake surfaces and the water attained during tempering is probably disturbed by the ramming. After ramming, water penetrates to new surfaces and becomes rigid to develop a new equilibrium.

In montmorillonite clays, water penetrates easily and rapidly to about all of the clay mineral surfaces. As a consequence the water becomes

rigid at once without a time lag and there is no air-set strength. Such clays develop all the strength they will ever have in the presence of water immediately on ramming. With equivalent amounts of water, sands bonded with montmorillonite clay, unlike those bonded with halloysite clay or kaolinite clay, do not have a wet feel immediately after mixing, unless the amount of water is very great.

In illite clays, there seems to be no appreciable penetration of the tempering water into the clay mineral particles. There is, therefore, practically no water that requires a time lag after ramming in order to develop a rigid condition. Like montmorillonite clays, but because of a different character of the clay mineral, air-set strength has not been found in such clays. Sands bonded with illite clay may have a wet feel after mixing, and it does not disappear as in the case of the sands with air-set strength.

SUMMARY

1. Curves showing the relation of dry compression strength to amount of tempering water are presented for varying amounts of each type of clay. In general the curves show that dry strength increases with the amount of tempering water up to a certain water content. With further increases in the amount of water, there is no further increase in strength.

2. The maximum attainable dry strength increases with the amount of clay for all types of clay except montmorillonite clay IB. For this type of clay the addition of more than 8 percent clay causes no corresponding increase in dry strength.

3. The maximum possible dry strength of the various types of clay is in the following order: montmorillonite IA > illite > kaolinite > halloysite. At low clay contents montmorillonite clay IB is about equal to illite clay whereas at high clay contents it is no stronger than halloysite clay.

4. The rate of increase of dry strength with increase of tempering water is greatest for montmorillonite clay IA and least for halloysite clay. The other types of clay have about the same rate which is closer to that of halloysite than that of montmorillonite clay IA.

5. Water at least equal to that amount which can be held with complete rigidity is required before any dry strength is developed in sands bonded with montmorillonite clay IA. In sands bonded with montmorillonite clay IB or halloysite clay, it appears that some dry strength may develop with somewhat less water.

6. The dry compression strength of a clay can be represented by the formula $DC = (T - M)K$ where T is the amount of tempering water in percent, M is the amount of tempering water in percent theoretically required before any dry strength develops, and K is a coefficient indicating

the dry strength developed per unit of tempering water. The K value, therefore, is a comparative measure of the bonding value of a clay. K and M values are presented for the various classes of clay.

7. In illite and kaolinite clays, M (the water value at which dry strength starts) and K (the rate of increase of strength with increasing amounts of tempering water) are the same for all amounts of clay. As a consequence a certain dry strength develops at a given moisture content regardless of the amount of clay, provided it is in excess of a minimum value.

8. A theory of dry strength is presented based on the wedge-block concept of holding the grains in place. A discussion is given to show that the theory explains the distinctive dry strength properties of the individual clays and agrees with the characteristics of the various clay minerals.

9. Sands bonded with halloysite clay or kaolinite clay develop greatly increased strength without much loss of moisture when rammed specimens are allowed to stand in the air. This so-called air-set strength is a different type of strength from green or dry strength and appears to be unique for these types of clay.

10. In sands bonded with 12 percent halloysite clay, air-set strength is developed with about 2.5 to 3.5 percent retained tempering water. Maximum air-set strength is about 15 times greater than the green strength and slightly higher than the dry strength developed with similar amounts of tempering water. Increasing the amount of initial tempering water increases slightly the air-set strength that will develop.

11. In sands bonded with 10 percent kaolinite clay, air-set strength is developed with about 1.5 to 3 percent retained tempering water. It is 5 to 10 times greater than the green strength and about $\frac{1}{3}$ to $\frac{1}{2}$ that of the dry strength developed with similar amounts of tempering water. The air-set strength that will develop increases slightly with an increase in the amount of initial tempering water.

12. Sands bonded with montmorillonite clay IA, montmorillonite clay IB, or illite clay do not develop strength on drying without an accompanying loss of water, that is, they do not show any air-set strength. The increase in strength is in direct proportion to the amount of water lost, and sands with initially higher moisture contents tend to have a higher strength when dried to a given moisture content.

13. Air-set strength is explained on the basis that a certain amount of time (measured in minutes) is required for some of the tempering water to penetrate masses of halloysite or kaolinite clay and to become fixed in a rigid condition, thereby increasing the strength of the wedge-block holding the grains in place.

14. In sands bonded with montmorillonite clay IA, compressive strengths much smaller than standard A.F.A. dry strength are developed when specimens are dried slowly to very low moisture contents. In sands bonded with montmorillonite clay IB, strengths equal to standard A.F.A. dry strength are developed on slow drying to low moisture contents. In sands bonded with illite clay the strength developed on drying to a given intermediate moisture content is independent of the rate of drying, and slow drying to very low moisture contents does not develop strengths equal to standard A.F.A. dry strength. Slow drying of sands bonded with either halloysite or kaolinite clay to very low moisture contents develops strength about equal to A.F.A. dry strength.

15. Increasing the amount of ramming increases the air-set strength as well as the green and dry strengths.

16. The difficulty or, for some types of clay, impossibility of predicting the strength characteristics of a partially dried mold from the usual strength tests is discussed.

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