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(Revised June 16, 1915.)

DEPARTMENT OF SCIENTIFIC AND INDUSTRIAL RESEARCH

DETERIORATION OF STRUCTURES OF TIMBER, METAL, AND CONCRETE EXPOSED TO THE ACTION OF SEA-WATER

FIFTEENTH REPORT OF THE COMMITTEE OF THE INSTITUTION OF CIVIL ENGINEERS

Being a general description of the experimental work carried out by the Committee to date

EDITED BY

S. M. DIXON, M.A., B.A.I., M.Inst.C.E.,
Secretary to the Committee,

AND

H. J. GROSE, M.C., B.Sc.

LONDON
PUBLISHED BY HIS MAJESTY'S STATIONERY OFFICE
To be purchased directly from H.M. STATIONERY OFFICE at the following addresses:
Adastral House, Kingsway, London, W.C.2; 120 George Street, Edinburgh 2;
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The Council of the Institution also wish it to be understood that they must not be taken as endorsing the statements made, or the opinions expressed in those parts of the Report which are the work of the contributors whose names appear therein.

DEPARTMENT OF SCIENTIFIC AND INDUSTRIAL RESEARCH,
16 Old Queen Street,
Westminster, S.W.1.
December, 1935.

MUSEUM

ATTENTION is directed to the Sea Action Museum, which, by the courtesy of the Council, has been housed in the Institution of Civil Engineers, Great George Street, London, and in which will be found specimens (duly catalogued) which have been received from various bodies and individuals in different parts of the world, who have assisted the Sea Action Committee in their investigations.

The collection contains numerous examples illustrating the ravages of marine borers upon timbers, the effects of corrosion, under differing conditions, upon steels and irons and their alloys, and the deterioration of paints and other preservatives, and of reinforced concrete, and many other matters of interest in connection with the work of the Committee; also a valuable collection of photographs.

All who are interested in the work of the Committee are invited to visit the Museum, to which access can be obtained upon making application to the Secretary of The Institution.

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THE DETERIORATION OF STRUCTURES IN SEA-WATER

Report of the Committee of The Institution of Civil Engineers, being a summary of the experimental work carried out since the issue of their First Report in 1920.

PREFATORY NOTE

THE Committee's First Report was issued in 1920, since when Interim Reports have been brought out describing in considerable detail the work of the Committee during each year, the Fourteenth Report having been published in 1934. Having regard to the number of years during which the investigations have continued, and the several reports dealing with various portions of these investigations which have been issued, the Committee feels that the time has come when it is desirable to issue a connected account of the whole of the investigations which have been carried out up to date, and the conclusions which, in the opinion of the Committee, may reasonably be drawn from the results so far obtained. When the Committee's work is completed, a final report will be issued.

In order that this account may be complete it is desirable to make brief reference to the First Report. This dealt mainly with the reports which had been invited and received from the port engineers of upwards of forty harbour authorities throughout the British Dominions, and which describe the nature and condition of the structures under their charge. That Report also contained an abstract of references to the deterioration of structures due to sea action, which had appeared from time to time in the Minutes of Proceedings of The Institution of Civil Engineers, and also notes on the value of timber as a material for sea structures, and on marine borers and corrosion of steel and iron. The First Report may, therefore, be considered as an introduction to the actual experimental work subsequently carried out by the Committee and forming the subject of the present Report.

Since the formation of the Committee many changes due to deaths and resignations have taken place in its composition. A complete list of all those who have, at one time or another, served upon the Committee is here given, the names of deceased members being printed in italics.

Names of Members who have served upon the Committee.

Sir William Matthews, K.C.M.G. (First Chairman).
M. F.-G. Wilson (Chairman).
A. L. Anderson.
Sir John A. F. Aspinall, D.Eng.
Sir John Wolfe Barry, K.C.B.
Raymond Carpmael, O.B.E.
Sir Robert Elliott-Cooper, K.C.B.
Sir Archibald Denny, Bart.
Sir John Purser Griffith, M.A.I.
Sir Robert A. Hadfield, Bart., D.Sc., D.Met., F.R.S.
W. T. Halcrow.
Sir George W. Humphreys, K.B.E.
T. B. Hunter, C.B., O.B.E.
Sir Cyril R. S. Kirkpatrick.
A. G. Lyster, M.Eng.
C. S. Meik.
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H. A. Reed.
Sir Alexander Ross.
Sir Leopold H. Savile, K.C.B.
Sir Thomas Sims, C.B.
E. F. C. Trench, C.B.E., M.A., B.A.I.
W. C. Unwin, B.Sc., LL.D., F.R.S.
F. E. Wentworth-Sheilds, O.B.E.
W. B. Worthington, D.Sc.

The late Mr. P. M. Crosthwaite, B.A.I., the first Secretary, who resigned in 1926, was succeeded by Professor J. Purser, M.A., B.A.I., M.Sc. Professor Purser resigned in 1933, and was succeeded by the present Secretary, Professor S. M. Dixon, M.A., B.A.I.

Having obtained the necessary preliminary information as dealt with in the First Report, the Committee was in a position to pursue the main objects for which it was appointed, namely, experimental investigations on :—

1. The Preservation of Timber.
2. The Corrosion of Steel and Iron.
3. The Preservation of Steel and Iron.
4. The Deterioration of Reinforced Concrete.

These matters are fully dealt with in this Report under their respective sections.

The Committee desires to convey its sincere thanks to the various Government Departments, public bodies and others who have taken an active interest in the work, and to express its hearty appreciation of the services and assistance rendered by them to the Committee during the course of the investigations.

For the financial support of the work it wishes to thank the Department of Scientific and Industrial Research, dock, harbour and other authorities in the United Kingdom, and the Crown Agents for the Colonies, and through them the Governments of Bermuda, Gold Coast, Hongkong, Jamaica, Mauritius and Nigeria. The funds required from the commencement of the work in 1916 until 1923 were granted by the Department of Scientific and Industrial Research, who also contributed half the cost from 1923 to 1928. Since 1923, therefore, the Committee's funds have been substantially, and since 1928 wholly, derived from other sources. A list of the subscribers is given at p. 125.

In addition, the thanks of the Committee are due to the Civil Engineer-in-Chief's Department of the Admiralty, to the harbour authorities of Auckland, Brisbane, Chatham, Colombo, Halifax, Kilindini, Lowestoft, Plymouth, Singapore, Southampton, Wellington, and Weston-super-Mare, and to the Governments of Bermuda, Gold Coast, Jamaica, Mauritius and Nigeria for arranging for the exposure, supervision, local examinations and return of specimens of timber, steel and iron, and reinforced concrete. The Committee desires to include in its thanks all those officers who have so kindly given valuable time and assistance in the carrying out of the experiments.

Sir Robert Hadfield has generally advised the Committee upon the experiments on steel and iron, and has been responsible for the preparation of the steel and iron specimens and for the mechanical tests and analyses of the metals tested.

The Committee has been fortunate in securing the advice and assistance of the following gentlemen on the arrangement and in the conduct of the experiments, and desires herewith to place on record its appreciation of the valuable services rendered by them throughout the investigations:—Professor George Barger, M.A., D.Sc., F.R.S., who has advised on the selection of various poisons for the preservation of timber, and the experiments to be carried out, and has undertaken the examination of the timbers after exposure. Professor Dixon, the present Secretary, who has prepared and treated timber specimens, conducted experiments on incising timber, and carried out mechanical tests upon treated and untreated timbers; J. Newton Friend, D.Sc., Ph.D., who has advised upon experiments on the preservative treatment of steel and iron, and has examined and reported on all the Committee's ferrous test-pieces; and R. E. Stradling, C.B., M.C., Ph.D., D.Sc., M.Inst.C.E., Director of the Building Research Board of the Department of Scientific and Industrial Research, who has advised upon the experiments on reinforced concrete, and has been responsible for the preparation of the experimental test-pieces and for the periodical examinations and reports.

The Committee also desires to acknowledge the assistance of Dr. E. J. Allen, Director of the Laboratory at Plymouth of the Marine Biological Association of the United Kingdom, for allowing the use of the laboratory, and also to thank Professors C. R. Harington, F.R.S., and C. M. Yonge, and Dr. F. D. White, for their assistance in the experiments carried out in this laboratory under the general direction of Professor Barger.

In the investigations described in this Report the Committee has constantly kept in view the practical aspect of the questions they had under consideration. Certain scientific considerations of necessity arose, but it was not thought desirable, nor would it have been practicable with the means at its disposal, for the Committee to undertake, say, a complete biological investigation into the life history of marine borers, or a chemical investigation into the structure and composition of steel and iron in relation to their liability to corrosion. The questions examined have consequently been dealt with in an entirely practical manner. The materials have been submitted to sea action under conditions exactly similar to those experienced by marine structures. Artificial acceleration of corrosion and the uncertainties it introduces have been avoided as far as practicable, while variations in the rapidity of deterioration have been studied over long periods in widely different climates. Many experiments and tests dealing with different portions or aspects of the subjects examined have no doubt been carried out before, but the Committee is not aware that any systematic and connected inquiry into the behaviour of the materials dealt with in this respect under such differing conditions of climate and exposure has previously been carried out, and it therefore trusts that the investigations and their results as described in this Report will prove of definite interest and value to engineers and others engaged in works subject to sea action.

The Committee's experimental investigations are dealt with under four main sections, as follows :—

I. The preservation of timber, including incising before impregnation, together with the results of mechanical tests carried out on certain timbers both treated and untreated.
II. The corrosion of steel and iron.
III. The protection of steel and iron by means of paints and other preservatives.
IV. Reinforced concrete.

Each section is preceded by an explanatory introduction, intended to make clear the full scope of the investigation. References (placed in brackets) are made to the Interim Reports, where, if desired, fuller details of the matter described may be found. Thus (VII-27) signifies the Seventh (Interim) Report, page 27. Then follows a tabulated statement setting forth such conclusions as the

Committee has considered might reasonably be drawn from the investigations as a whole. In preparing these statements, the Committee has endeavoured to give a brief description of what is considered to be the main or more important conclusions to be derived from a consideration of the results of the numerous experiments which have been carried out over a period of more than 10 years under its direction, and which are described in the various reports which follow. These conclusions represent no more than the opinion of the Committee as a whole, and it is hoped that those interested in the matters dealt with will study the reports for themselves so as to form their own opinions and draw their own conclusions.

Finally there will be found detailed reports of the experiments by the investigators under whose direction the experiments were carried out.

SECTION I

PRESERVATION OF TIMBER

INTRODUCTION

IT was decided that a number of timber specimens treated in different ways with various preservatives should be exposed to the action of the sea. It was desirable that the specimens should be fairly numerous in order that fair average results should be obtained from the experiments. For this reason and for convenience in fixing, the test-pieces were of small size, usually about 12 in. by 8 in. by 2½ in., though in some cases pieces 4 ft. by 4 in. by 4 in. were adopted. The specimens were usually fixed near the level of low water. In order to attract *Teredo* or other pests the faces of a number of the test-pieces were covered with slabs of untreated timber or " appetisers " about ¼ in. thick, which were very effective for the purpose intended. In all cases a number of untreated specimens were simultaneously exposed to act as " controls."

In some of the experiments Baltic fir was used, but owing to difficulty in obtaining it, Swedish fir, Archangel pine and British Columbia fir were at times substituted. As a general rule the specimens were artificially dried before being treated. The apparatus used for this purpose has been described (IV-47).

As will be seen from the detailed report which follows, a large number of poisons were experimented with and also a number of oils and other vehicles by means of which the poisons could be introduced into the timber. As a result of many trials it was finally concluded that the most generally effective and suitable poison was the arsenical compound chloro-dihydrophenarsazine, usually known as D.M., and that the most satisfactory vehicle was ordinary creosote, which, as will be seen later in the Report, proved to be itself a very excellent deterrent.

For the actual impregnation of the specimens, four methods were adopted according to circumstances, namely :—

1. The " Griffith " process wherein the specimens were placed in a boiler filled with creosote or other oil, and the temperature was gradually raised to 110° C. or 150° C. (III-38.)
2. The ordinary " Bethell " process wherein the specimens after being placed in the boiler were first subjected to a vacuum, the creosote or other oil being then forced into the timber under pressure, and the temperature was raised to about 48° C. (III-38.)
3. The " tanking " process, the specimens being simply boiled in a bath of alcohol containing the necessary poison.

4. The "vacuum" process wherein the vehicle containing the poison was sucked by means of a vacuum through a tube applied to one end of the specimen. The solution, passing into the timber through the end grain, formed a poisoned core surrounded by non-toxic wood which acted as an "appetiser." (IV-26.)

It was rather difficult to find a place for the exposure of the specimens, which was sufficiently sheltered and where at the same time *Teredo* was vigorous. For the first exposures Lowestoft was selected and seemed fairly satisfactory, but it was soon found that, while *Teredo* was fairly active outside the harbour, the specimens were exposed to such heavy seas as to be constantly washed away, and that, when placed inside the harbour, they were soon covered with mud which prevented *Teredo* attack. Plymouth was then tried, with more success, and experiments were carried out there by Professors Harington and Yonge and Dr. White, as described by Professor Barger at p. 18.

It was, however, soon clear to the Committee that stations should, if possible, be selected where *Teredo* is far more active than in home waters, and ultimately specimens were sent for exposure to Colombo, Singapore (tropical), and Auckland, New Zealand (sub-tropical). At later dates specimens were also sent to the Gold Coast, Jamaica, Bermuda and Mauritius.

The general results of the experiments are described in Professor Barger's report which follows, whilst more detailed particulars will be found in the Interim Reports. Table I gives a concise list of the timber specimens prepared by Professors Barger and Dixon and despatched for exposure. In all about two thousand specimens were prepared, including the untreated specimens which were used as controls.

When the specimens had been exposed long enough they were returned to Professor Barger for examination and report. Professor Barger's report (which follows) does not deal with all the specimens exposed, a large number of the tests being of a preliminary nature only.

The penetration into the timber of the oil or other vehicle conveying the poison is a matter of great importance. Irregularities and inconsistencies in the results obtained from the experiments were frequently noticeable; many of these were due to irregularities in the nature of the timber itself, but some were no doubt due to the chemical nature of the poison (VII-20). In tests made by Professor Dixon, portions of whole timbers, 12 in. by 12 in. in section, whose ends had been sealed to prevent entry of the solution by the end grain, were impregnated with creosote containing 2 per cent. of D.M. Subsequent analysis showed that only 0·5 to 0·7 per cent. of the poison had penetrated to a depth of ¼ in. below the surface and only half that quantity as much as ½ in. Beyond 1 in. no D.M. could be detected nor was much creosote visible (XII-11). Professor

TABLE I.—*Timber Specimens prepared and despatched for Exposure.* Baltic, Swedish or British Columbia Fir, or Archangel Pine.*

Series	Port of Exposure	Number of Specimens	Treatment	Year of Exposure	Vehicle	Process	Approximate Size
I	Lowestoft	60	Various poisons	1921	Alcohol	Tanking	12″ × 8″ × 2″
II	Lowestoft	107	Various poisons	1922, 1923	Alcohol	Tanking	12″ × 8″ × 2″
IIA	Lowestoft	30	Various poisons	1923	Alcohol	Vacuum	12″ × 8″ × 2½″
III	Colombo	72	D.M. 0·3% to 0·01%. Creosote only	1923	Creosote	Griffith	12″ × 8″ × 2½″
IV	Colombo	72	D.M. 0·3% to 0·01%. Creosote only	1924	Creosote	Bethell	12″ × 8″ × 2″
V	Colombo	36	D.M. 0·3%; 0·1% to 0·01%. Carbazole 5·3%, 3·5%, 2·3%. Creosote only. Painted with 1·0% D.M. and creosote.	1925	Creosote	Bethell	4′ × 4″ × 4″
V	Singapore	36	Same as (V) Colombo	1925			
V	Brisbane	36	Do.	1925			
V	Wellington	36	Do.	1925			
V	Auckland	36	Do.	1925			
V Ratts 1, 2 and 3.	Plymouth	118	D.M. 0·3% to 0·01% Carbazole 5·3%, 3·5% and 2·3%	1924	Creosote	Bethell	4′ × 4″ × 4″
			Painted with D.M. 1·0% and creosote.	1924	—	—	4′ × 4″ × 4″
			D.M. 0·1% to 0·01%	1924	Alcohol	Tanking	12″ × 8″ × 2½″
			Acridine 0·3%, 0·07%	1924	Alcohol	Tanking	12″ × 8″ × 2½″
			D.M. 0·3% to 0·01%	1924	Alcohol	Vacuum	12″ × 8″ × 2½″
VI	Colombo	303	D.M. 2·0% to 0·06% D.A. do. D.A. Oxide do. B.D.C. do.	1926–28	Alcohol	Tanking Vacuum	8″ × 4″ × 2½″
VI	Singapore	160	D.M. 2·0% to 0·06% D.A. 1·0% to 0·03% D.A. Oxide do. B.D.C. do.	1926	Fuel-oil	Bethell	12″ × 8″ × 2″
	Singapore	28	Fuel-oil only D.A. 0·2%	1926	Fuel-oil	Bethell	4′ × 4″ × 4″
			Creosote only D.A. 0·2%	1926	Creosote	Bethell	4′ × 4″ × 4″
VII	Colombo	139	D.M. 5% B.D.C. 5%	1928	Creosote	Bethell	12″ × 8″ × 2½″
			Creosote only. Fuel-oil only. Pynkado untreated Satinwood untreated.	1928			
VIII	Gold Coast	120	D.M. 3% Creosote only.	1929	Creosote	Bethell	12″ × 7½″ × 2″
			D.M. 3% Fuel-oil only.		Fuel-oil		
VIII	Jamaica	120	Same as (VIII) Gold Coast	1930			
VIII	Bermuda	120	Do. do.	1929			
IX	Kilindini	120	Naphthalene only Naphthalene and creosote. Creosote only. D.M. 3% in naphthalene.	1930	—	Bethell	12″ × 7½″ × 2″
IX	Mauritius	120	Same as (IX) Kilindini	1930			
X	Gold Coast	84	*Replacing those lost* Creosote only. D.M. 3% in creosote. *Additional specimens.* Creosote followed by bath in naphthalene.	1931	Creosote	Bethell	12″ × 7½″ × 2″
XI	Colombo	48	Incised Unincised.	1934	Creosote	Bethell	3′ × 10″ × 6″

* In some Series the specimens prepared were not all exposed.

Note.—The letters used in the above Table refer to the arsenic compounds used.

D.M. denotes chloro-dihydrophenarsazine.
D.A. do. diphenyl chlor arsine.
D.A. oxide do. diphenyl arsenious oxide.
B.D.C. do. a mixture of phenyl arsenious chloride and phenyl arsenious oxide.

Dixon further noted that, while a specimen of the conifer larch increased only 3 per cent. in weight upon being creosoted, a specimen of the hardwood beech when similarly treated increased as much as 52 per cent. This result is attributed to the difference in the cellular structures of the two classes of timber.

The irregularities in penetration led the Committee to investigate the effect of making incisions with a chisel in the timber before impregnation—a method which had been used in Canada and the United States of America, and has been the subject of experiment at the Forest Products Research Laboratory at Princes Risborough. These experiments, which are fully described in Professor Dixon's report (p. 38), were entirely satisfactory and show that incising enables a very appreciable increase in the depth and uniformity of penetration of the creosote to be obtained.

In the course of these investigations, a limited number of specimens of timber from Australia, New Zealand and Ceylon were forwarded to the Committee at its request, in order that they might be subjected to a series of mechanical tests. The specimens were of well-selected straight-grained timber and may be considered as fair samples of the timbers available and in general use. Samples were creosoted by the Griffith and Bethell processes, so that the tests afford some indication of the effect of creosoting upon the strength of the timber. The results of these tests are included in Professor Dixon's report (p. 24).

CONCLUSIONS

1. Within the range of the experiments, no process for the preservation of timber was found more satisfactory than that of impregnation with creosote*; the efficacy of this process depended on the completeness with which the penetration of the creosote into the timber had been effected.

2. With the soft-wood timbers usually employed in dock and harbour engineering there was the well-known difficulty in obtaining penetration of creosote by the usual processes.

3. It was found that satisfactory penetration of the creosote into the timber was obtained when the timber had been previously incised. The depth of penetration was governed by the depth of the incisions.

4. In some cases it was found that there was a danger of injuring the timbers if the depth of the incisions exceeded $\frac{3}{4}$ in.

5. The best results were obtained when the incising immediately preceded the creosoting.

6. Some hardwood timbers used in marine constructions readily absorbed creosote when treated by the usual processes.

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* The creosote used in the experiments carried out by the Committee conformed to the British Standard specification current at the time the creosote was supplied.

7. Creosoting by the Bethell or similar processes was found a convenient and generally satisfactory method of impregnation.

8. It was not found that the process of creosoting by the methods described affected the strength of the timber to any material degree, though when a high temperature (150° C.) was adopted in the Griffith process some reduction in strength was observed.

9. The arsenical compound, chloro-dihydrophenarsazine, commonly known as " D.M.", proved very deadly to *Teredo* when in the state of free-swimming larvae. It was readily inserted into the timber by being added to the creosote during the ordinary process of creosoting. Although concentrations of this compound to the extent of 5 per cent. have been added to the creosote, no definite increase in the preservative qualities of the creosote became apparent, since the controls impregnated with creosote only were also fully protected during the course of the experiments.

10. Experiments with crude mineral oil as a vehicle for poison showed that the oil alone conferred no protection, but indicated that when D.M. was dissolved in it, it was efficient for such distance as the D.M. penetrated.

11. The experiments did not definitely show creosote to be efficient in the case of crustaceans such as *Limnoria*, though it appeared to have some useful effect against *Chelura*.

12. Merely painting the surface of the timber with the preservatives was found to be quite ineffectual.

13. Crude naphthalene proved less efficient than creosote. The activity of creosote seems to depend not on phenols but on hydrocarbons of high boiling point, less volatile than naphthalene.

EXPERIMENTS ON THE PROTECTION OF TIMBER AGAINST MARINE BORERS

By Professor George Barger, M.A., D.Sc., F.R.S.

MARINE BORERS

THE investigation was mainly concerned with the "shipworm" (*Teredo* or *Bankia*) a more or less cylindrical bivalve mollusc, of which many species have been described. They are all characterized by a much reduced shell, the two valves of which are about as long as they are broad, so that they cover only a very small (anterior) part of the soft body, instead of the whole as in mussels, oysters, etc. *Teredo* is, however, completely protected because it spends the whole of its adult life in the channels which it bores in wood and which it generally provides with a smooth calcareous lining. In *Teredo* the valves have lost their original protective function, and have become the chisels with which the burrow is excavated. The only other bivalve inhabiting wood is *Martesia*, in which the valves completely cover the body; the animal remains stationary, completely filling the burrow, one end of its body being in contact with the surface of the wood. *Martesia* and the similar rock-boring *Pholas* and *Saxicava* are intermediate between mussels and *Teredo*, but are more closely allied to the former. *Martesia* occurs only in tropical waters; it causes little damage to sea structures, but neither creosote nor any other poison experimented with prevents its entry into the wood. *Teredo*, on the other hand, is sensitive to poisons; the reason for this seems to be that it actually ingests the sawdust made by the sawing action of the teeth of the shell. There is even some evidence (III-26, 32), provided by a study of its digestive enzymes, that the sawdust may serve as a subsidiary food supply, although its main food consists of minute organisms (plankton) found in the sea-water, which is circulated by means of two siphons at the posterior end of the body; these siphons protrude from the burrow and are temporarily drawn back into it when adverse conditions supervene.

The ravages of the shipworm were known to the Ancients, and proved disastrous in the fourth voyage of Columbus whose ships were "pierced with worm-holes like a bee-hive." Later they became most obnoxious in stationary marine timbers of harbour works, etc. The Dutch name of the mollusc is not shipworm (*Teredo navalis* of Linnæus) but "paal worm" (pile worm). Protection was first attempted by mechanical means, such as covering the surface of the timber with flat-headed nails or copper sheathing, or simply charring of the surface. Later the method of impregnation with poisons, of which creosote is still the most widely used, was adopted.

Two other genera of marine borers infecting wood, *Limnoria* and *Chelura*, must be mentioned. Although sometimes these are also popularly called " worms " they are even less worm-like than *Teredo*, for they are crustaceans—members of a division characterized by an articulated exo-skeleton, of which shrimps and lobsters are well-known examples. *Limnoria* and the less common larger *Chelura* are minute in comparison with molluscan borers; like *Martesia*, they form numerous channels just below and usually parallel to the surface. By the disintegration of the interstitial wood fresh surfaces are exposed, and ultimately deep cavities may be formed in the timber. An examination of the numerous test-pieces exposed has shown that *Limnoria* prefers to bore circumferentially along the grain in the soft portions of the annual rings. The hard portions of these rings are then soon worn away (cf. Fig. 7, p. 33). If, in a rectangular test-block, the small inner rings are exposed in one of its faces, these rings are first attacked, which allows the core to fall out so that a cavity may be formed in the middle of the face. Similarly on the opposite face of the block the boring along the outer annual rings results in a wearing away of the angles. In a large pile containing the heart of the tree, the conditions are different and the ravages of *Limnoria* are not so rapid as small test-pieces would indicate. Large creosoted piles have occasionally been reduced to a mere outer shell at a certain level, which indicates some protection against *Limnoria*, but no really efficient poison is known, since the sea-water leaches poison out from the surface, to which the organism is restricted.

Since in marine structures of timber the ravages of *Teredo* are more serious than those of other borers, the investigation was mainly directed to finding substances deleterious to *Teredo*, and the question of testing such substances arose. The only really practical and decisive method of effecting this is the exposure of impregnated pieces of wood in the sea. The method is slow and the difficulties of impregnation on a laboratory scale have to be overcome. Moreover the extent of the damage done by *Teredo* is not evident on mere inspection—at least not in the early stages. It is necessary to saw or split the block into thin slices before the amount of infection can be determined. X-ray photography can also be employed, in which the calcareous linings of the channels cast a shadow; this method was, however, not used in the present investigations.

LABORATORY EXPERIMENTS ON BORERS

Since a preliminary selection of possible poisons to be used in the impregnation experiments might be made more rapidly in the laboratory, the following researches were carried out.

Adult specimens of *Teredo* were dissected out from timber and exposed. This method had already been used by investigators in the United States*. Much care is required to avoid damage to the organism, which in any case does not survive for many days after

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* L. F. Shackell, Proc. Am. Wood Pres. Assocn., 1915, p. 233. See also C. H. Teesdale, Engineering Record, vol. 70 (1914), p. 302.

removal from its burrow. Professor Harington (II-37) carried out a few preliminary experiments with adult *Teredo* and with a few related molluscs (the rock-boring *Saxicava*, mussels and *Pecten*). Professor C. M. Yonge (VII-28) found the method unsatisfactory.

Living teredines were exposed *in situ* by immersing blocks containing specimens in sea-water containing a known concentration of poison. The blocks were first kept in normal sea-water until the number of extruded siphons was at a maximum; this gave the number of live specimens. In poisoned sea-water the siphons were immediately retracted. After some days the blocks were returned to the normal sea-water and again observed until the number of extruded siphons was again at a maximum—this gave the number of surviving specimens. This method was used by Professor Yonge at Plymouth (VII-27).

Exposure of free-swimming larvæ to a known concentration of the poison in sea-water hardly gives direct information about the susceptibility of the adult, but it nevertheless indicates which substances are likely to be toxic. This method was extensively used by Professors Harington (III-27) and Yonge (IV-19, VII-28) in the summers of 1921 and 1922, at the Plymouth laboratory of the Marine Biological Association, for a preliminary survey of poisons.

As will be shown, the last two methods are of only limited value since the results they yield do not agree closely with those obtained from tests of impregnated blocks, which also take into account the degree of penetration of the poison into the wood and the rate at which it is dissolved out by sea-water.

Free-swimming larvæ are easily obtained by mixing spawn (ova and sperm) extruded from adult teredines. They can live for a fortnight on their own reserve food supplies, during which time they increase somewhat in size to 81μ by 65μ* or roughly 1/300 in. by 1/400 in. (IV-13). They may survive on strips of wood for about 5 weeks, and grow a little more, but the transformation from the free-swimming into the burrowing state could not be observed, probably on account of the lack of suitable micro-organisms serving as food under natural conditions. Professor Harington (III-28, 31) made the interesting observation that the larvæ are attracted by a chemical substance, extractable from sawdust by alcohol and by ether. The cause of this chemotropism was not identified, though it is possibly malic acid. Professor Harington stated " In view of the natural conditions which prevail in the sea it is not possible to imagine that the larvæ can be attracted towards wood by a chemical mechanism, since they must be at the mercy of the wash of the water. It would, however, obviously be of advantage to them if they possessed some means of recognising when they come into contact with it." (III-32.)

The effect of keeping the larvæ in sea-water containing a known amount of poison was studied by Professors Harington and Yonge.

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* $1\mu = 0{\cdot}001$ mm. or approximately $0{\cdot}00004$ in.

Mercuric chloride (corrosive sublimate) was the most active soluble salt, being several times as active as white arsenic (arsenious acid). It is evident, however, that in the sea insoluble substances only can be used, or such as dissolve so slowly that they leave a deposit of the poison in the wood. A substance of this kind was found in D.M. (chloro dihydrophenarsazine) used in the later stages of the Great War. On *Teredo* larvæ it was even more active than mercuric chloride (IV-21) and much more so than arsenious acid, although it contains a much smaller proportion of arsenic. Moreover, this substance is practically insoluble in water, and can be manufactured at a relatively low cost.

Other benzene derivatives, such as chloro-dinitro-benzene, dinitronaphthalene, trichlorophenol, and carbazole, were also found to be harmful to adult *Saxicava* (II-41) and to *Teredo* larvæ, so that it was decided to expose test-pieces impregnated with them.

Exposure of Treated Test-Blocks

During his visit to Plymouth in 1920 Professor Harington prepared some test-pieces by treating them with creosote, to which poisons had been added (II-39). Since the creosote itself is an excellent preservative, any possible difference between creosote and creosote plus poison could not be expected to show itself quickly. For a more rapid survey a vehicle was required having no permanent toxic effect, and alcohol was used as fulfilling this requirement (III-24). It mixes with water in all proportions so that it even enters moist wood, and in the sea it is readily washed out, leaving in the wood only the poison which it is desired to investigate. The technical use of alcohol was never contemplated, it having been early recognized that in all probability creosote would ultimately prove to be the most suitable vehicle. The purely experimental impregnation with alcohol as a solvent was carried out by the tanking process already described at p. 7 (VII-20). The degree of penetration of the poison secured in this fashion was not very great, at least not with the dilute solutions of the early experiments. An alternative method of impregnation consists in poisoning a core of the block by sucking a solution through it ("vacuum" method). Blocks of Baltic fir were employed, 12 in. by 8 in. by 2 in. Most of the later experiments were carried out with creosote, on blocks of about the same size. In some cases pieces 4 ft. by 4 in. by 4 in. were employed.

In order to facilitate the entry of *Teredo* into the wood, one face of the block was partly covered with a thin strip of untreated wood, which acted as an "appetizer" to attract *Teredo*, and also as a control. The use of appetizers has been criticized, inasmuch as *Teredo* was said not to pass across a crack or parting between two faces. Experience with some thousands of test-pieces, however, has proved the utility of appetizers. When two planed surfaces are in close contact, *Teredo* channels pass across them, as has been frequently observed in blocks in which the appetizers were only partly destroyed. In creosoted blocks, owing to the " sweating " of the creosote, the appetizer itself may occasionally become protected. In the tropics the appetizer is soon destroyed completely, and this affords proof that the block has been properly exposed to *Teredo* action. The most conclusive proof that *Teredo* passes from one piece of wood into the other was afforded by certain blocks which were exposed at Lowestoft for 1½ year. They were then sent to Edinburgh, sawn into slices, which were again bolted together, and sent to Colombo for further exposure. After 8 months exposure there they were found to contain numerous teredines whose burrows passed across the sawn surfaces.

The first series of sixty specimens (Series I) were exposed at Lowestoft in June and July, 1921, on the outside of the harbour pier. They were impregnated by boiling in dilute alcoholic solutions of various substances, including D.M., chlorodinitrobenzene, dinitronaphthalene, dichlorocresol, trichlorophenol, and carbazole. They became rapidly infected; after 8 months exposure a number were removed and were found to have an average of about six teredines in the " appetizer "; untreated controls had twice that number, and all treated blocks a few, except those poisoned with 1 per cent. and 0·1 per cent. of D.M. and 1 per cent. of chlorodinitrobenzene. This result led to the exposure of a further group of 107 blocks (Series II–Lowestoft) in August, 1922 (IV-24); they were impregnated with D.M. and other arsenical poisons in concentrations of 0·3, 0·1, 0·03 and 0·01 per cent. in alcohol. The untreated controls of this second group were found in April, 1923, to be hardly, if at all, infected, in contrast to those of the first group, which contained a dozen teredines. It was considered that possibly the second group were fixed too late in the breeding season, which might account for their immunity from attack. In July, 1933, a further group of thirty blocks (Series IIa) was added; these blocks were impregnated, by the vacuum method, with alcoholic solutions of D.M. or with aqueous solutions of metallic salts (mercury, zinc, copper and arsenic). Loss of specimens by wave action led to the removal of the remainder to the inside of the pier in November, 1923. In March, 1924, controls which had been exposed for 10 months were unattacked and covered with mud; hence the specimens were again moved to the outside of the pier. After further losses all those remaining were removed for examination in November, 1925. Out of a total of 197 blocks 80 were lost and 117 were examined. The results showed that after the first summer very little attack had occurred, even in untreated blocks, which made the later exposures practically valueless. Owing to the slight attack inside the pier, and the losses by storms outside, and since other places gave promise of better results, this station was abandoned.

In experiments of this nature within the British Isles it is not very easy to find a sheltered position where *Teredo* is vigorous.

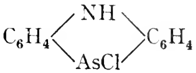
Thus, in his first visit to Plymouth, Professor Harington could find *Teredo* only outside the harbour, several miles to the south-west (II-35, 36). In 1920 he again visited Plymouth, and after investigation exposed some specimens at Pier Cellars outside the Breakwater near Penlee Point, and some further specimens from a raft immediately inside the Breakwater (II–39). During the next summer it was found that only those exposed at the former station had been attacked (III–27). In November, 1923, the raft, which had meanwhile become submerged to a depth of about 6 ft., was heavily infected, and was brought ashore. The results of the experiments at Lowestoft and Plymouth show that the activity of *Teredo* in English waters is very erratic, and the Committee, therefore, decided to send specimens to Colombo where *Teredo* is known to be very destructive.

So far as conclusions could be drawn, these early experiments pointed to arsenical compounds of the D.M. type as the most promising.

Series III was, therefore, prepared for exposure at Colombo. This series consisted of seventy-two blocks, half of which were treated with plain creosote, and half with creosote containing quantities of D.M. ranging from 0·3 to 0·01 per cent. They were impregnated by the Griffith process, and after exposure from September, 1923, onwards, for various periods up to 2½ years, only about 40 per cent. of the blocks remained quite free from *Teredo*. Many blocks were severely attacked by *Limnoria*, especially in the heartwood. The resistance to *Teredo* was slight, owing most probably to the method of impregnation. Series IV (Colombo) followed, and was identical with Series III, except that impregnation took place by the Bethell process. Practically all blocks remained intact, some for 5 years; the last were removed in 1929 owing to the failure from *Teredo* attack of the satinwood supports. This series demonstrated the superiority of the Bethell process as giving more complete impregnation than the Griffith process. Series V (Colombo) consisted of thirty-six pieces 4 ft. by 4 in. by 4 in., which were exposed from March, 1925, up to December, 1929. Some of these test-pieces were merely painted with 1 per cent. of D.M. in creosote, the others being impregnated by the Bethell process. The impregnation proved less complete with the larger pieces than with the smaller blocks. The pieces were treated (Table I) with various percentages of D.M. and carbazole in creosote and with plain creosote. Although little damage was done by *Teredo*, *Limnoria* severely attacked the middle portion of the pieces, eating right across in some cases. The small addition of carbazole in the creosote appeared actually to attract *Limnoria* (XII-7). Painting the surface with 1 per cent. of D.M. in creosote, without impregnation, was quite ineffective against *Teredo;* some pieces treated in this fashion became riddled and friable after an exposure of 1 year.

Series VI (Colombo) was designed to differentiate between four closely related arsenical poisons, and since in the previous series the effect of D.M. in creosote could not well be distinguished from that of creosote alone, recourse was once more had to alcohol as the solvent.

The chemicals experimented with were :—

D.M. 10-chloro-5 : 10 dihydrophenarsazine 

$$C_6H_4\begin{matrix}NH\\ AsCl\end{matrix}C_6H_4$$

D.A. Diphenyl chlor-arsine $(C_6H_5)_2AsCl$.

D.A. oxide $[(C_6H_5)_2As]_2O$.

B.D.C. "Mixed oil," a mixture of phenyl arsenious oxide C_6H_5AsO and phenyl arsenious chloride $C_6H_5AsCl_2$, which occurs as an intermediate product in the manufacture of the substance D.A., which latter was employed extensively in the World War.

These four related substances were chosen as the result of a preliminary selection by laboratory experiments at Plymouth by Professor Yonge. He used living *Teredo in situ* and also larvæ, and they both furnished evidence that B.D.C. and D.A. oxide might prove to be more active than D.M. and D.A. (VII–27). D.A. oxide was also more active on *Chelura*. With *Limnoria* little difference had been shown.

The alcoholic solutions of each of the four poisons for impregnation of the blocks in this series were in the four concentrations of 2·0, 0·6, 0·2 and 0·06 per cent. With the exception of the first, and possibly the second, these concentrations proved to be too low, and it was evident that the much more severe attack in the tropical, as compared with British waters, had not been sufficiently allowed for.

The impregnation of some of the specimens was effected by the tanking method, and of others by the vacuum method, both of which have already been described. A few blocks treated by the vacuum method had already been exposed at Lowestoft; at Colombo the tanking and vacuum methods were represented equally (in so far as concerns alcoholic solutions). The vacuum method proved rather disappointing, although occasionally it yielded good results. The tanking method also yielded rather irregular results ; the quantity of solution taken up ranged from 22·5 to 140 per cent. of the original weight of the block.

To obtain an idea of the extent to which the poison penetrated into the wood, certain blocks were analysed after boiling for various periods, and samples were taken from various depths below the surface of the timber. It was found, for instance, that, when a block was boiled for 40 hours in a 2 per cent. alcoholic solution of D.M., the concentration of the poison amounted to only 1 per cent., *i.e.*, one-half of the original concentration, at a distance of ¾ in. from the surface. The penetration of D.A. oxide and B.D.C. was better than that of D.A. and D.M. (VII–21, 22).

Under this series 255 blocks, 8 in. by 4 in. by 2½ in., impregnated with alcoholic solutions of arsenical poisons by the tanking and by the vacuum methods, and twenty-one untreated controls, were exposed at Colombo at various times from 1926 onwards. The superiority of the tropics over Lowestoft for testing purposes was soon evident. After 6 months exposure the untreated controls were riddled by *Teredo* and had lost half their weight. In 10–16 months they all disappeared. It also soon became evident that the lower concentrations of the poisons (0·2 and 0·06 per cent.) were ineffective, and that D.A. oxide, in spite of its superior penetration, was useless for protecting timber. In 1927 the conclusion was reached that D.A. was inferior to D.M. and B.D.C., and in 1929 D.M. was judged to be the most effective of the four poisons under test. As to the absolute effect of D.M., blocks boiled in a 2 per cent. alcoholic solution remained practically free from *Teredo* for 3½ years, the few *Teredo* channels observed being limited to those parts of the block which were inadequately impregnated. D.M., after exposure to sea-water, reveals itself by a steel blue colouring of the wood, and *Teredo* was never found where this colouring was present. Analyses of such a region in an exposed block, originally boiled in a 2 per cent. alcoholic D.M. solution, showed D.M. to be present to the extent of 0·6 per cent. of the wood (XII–7). Since, as has been stated above, the untreated controls entirely disappeared in about a year, the protective effect of D.M., first observed at Lowestoft, was confirmed under much more severe conditions. This conclusion is mainly based on the blocks treated by the tanking process. The results of those treated by the vacuum process were less conclusive, but they often showed an unaffected core surrounded by *Teredo* channels.

Further sets of Series V test-pieces exactly similar to the Colombo Series V, viz., 4 ft. by 4 in. by 4 in., and similarly impregnated, were prepared and sent in 1925 for exposure at Singapore, Brisbane, Auckland and Wellington. Generally speaking, the results were in all cases similar to those of the Colombo Series V, described at p. 16. It would appear, however, that *Teredo* is somewhat less active at Wellington than at Colombo and Singapore. This might be expected owing to the temperate latitude of Wellington in contrast to the tropical situations of Colombo and Singapore.

Whilst these experiments were going on abroad, further experiments were being carried out in home waters. As mentioned at p. 14, Professor Harington (II–39) had already prepared test-pieces by heating them in creosote containing various poisons. These were fixed to a raft anchored inside Plymouth breakwater. In 3 years time the untreated battens of the raft were almost completely destroyed by *Teredo* (V–14). From an examination of the test-pieces Professor Harington was led to consider that the addition of about 2 per cent. of carbazole, dinitronaphthalene, or chlorodinitrobenzene, increased the protection afforded by creosote, the order of effectiveness being that named. This led to further experiments with carbazole (Series V, Colombo, referred to at p. 16) which did not confirm the protective action of this substance. Professor Harington's experiments, however, showed that Plymouth breakwater was a suitable station, and three rafts, Nos. I, II and III, were put out there in July and September, 1924. These rafts were constructed of untreated timber and attached to them were (*a*) thirty-six pieces 4 ft. by 4 in. by 4 in., treated with creosote and with various percentages of D.M. and carbazole in combination with creosote; (*b*) nineteen blocks, 12 in. by 8 in. by 2½ in., impregnated with 0·01 to 0·1 per cent. of D.M. in alcohol by the tanking process; (*c*) thirty-one similar blocks impregnated with 0·01 to 0·3 per cent. of D.M. in alcohol by the vacuum process; (*d*) twenty such blocks impregnated with 0·3 to 0·07 per cent. of acridine in alcohol by the tanking process, and (*e*) twelve untreated blocks as controls.

The rafts were inspected at intervals by Professors Harington and Yonge. After 2½ years those pieces which had been merely painted with 1 per cent. of D.M. had perished. In June, 1926, some of the blocks, and in March, 1927, the remainder were removed by Professor Yonge, as nearly all of them had been severely attacked. Since the structural timber of rafts Nos. I and II had suffered severely from *Teredo* these rafts were broken up in 1927, and the creosoted pieces attached to them were made into a new raft, No. IV. This, and the original raft No. III, were inspected by Professor Harington in August, 1933, when he judged it best to break them up for examination, and twenty-nine pieces which had survived for 9 years were sent to Edinburgh for examination. Outwardly, the attack (by *Limnoria*) for the most part was slight, and the pieces treated with creosote only, or with the 0·3 per cent. concentration of D.M. were found free from *Teredo*; but those which contained, in addition to creosote, such small amounts of D.M. as 0·01 to 0·1 per cent., or contained 3·5 to 5·3 per cent. of carbazole, showed a few unusually wide *Teredo* channels, some of which attained a diameter of ¾ in. It would seem that carbazole and small amounts of D.M. had acted as a stimulus to the growth of a few *Teredo* individuals which had succeeded in establishing themselves in spite of the creosote.

COMPARISON BETWEEN CREOSOTE AND OTHER VEHICLES FOR POISON

In 1926 experiments (Series VI—Singapore) were begun at Singapore, in which crude fuel-oil was used as a vehicle for D.M., D.A., D.A. oxide and B.D.C. Most blocks were being returned and examined within 3 years. While fuel-oil is a cheap and sufficiently good solvent, it was found, upon examination of the returned blocks, that the penetration had been very incomplete. Generally, a cross section of a block showed one or two sharply defined black areas where the oil had penetrated, whilst the greater part remained unaffected by the oil. In blocks treated with fuel-oil only, both the affected and unaffected portions were equally riddled by *Teredo*, showing that oil is in no sense a deterrent. When the fuel-oil contained a sufficient concentration of D.M., the black portions were quite free from teredines, although they had bored into the unaffected portion right up to the line of demarcation. The addition to the fuel-oil of 2 per cent. of D.M. was quite effective in the black portions, and 0·6 per cent. of D.M. gave almost complete protection. As mentioned at p. 17, the quantity of D.M. actually present in the wood (expressed as a percentage of the weight of the wood) was found by analysis to be much smaller than would be due to the original concentration. Thus, with an original 2 per cent. solution of D.M. in fuel-oil, the black portions of the wood contained, in one case an average of only 0·12 per cent., and in another about 0·3 per cent. (XII–8). Yet these small concentrations of D.M., when actually in the wood, had completely stopped the attack of *Teredo*. Unfortunately, the penetration of fuel-oil and its consequent protection were very local. Owing to imperfect impregnation, Series VI (Singapore) did not throw any fresh light on the relative efficiency of the four arsenical poisons employed.

In 1926 Series VII was prepared and these specimens were sent to Colombo to be exposed. This series consisted of blocks treated with creosote and fuel-oil, either alone or containing 5 per cent. of D.M., or 5 per cent. of B.D.C., since experience had shown that these might be considered to be the most promising two arsenical compounds. The principal object of this series was to determine whether the efficacy of creosote could be increased by the addition of these poisons. The results with the fuel-oil were very similar to those obtained with Series VI (Singapore) referred to above. The creosote afforded practically complete protection against *Teredo* during the 4 to 5 years of exposure. No difference could be established between plain creosote, creosote plus 5 per cent. of D.M., and creosote plus 5 per cent. of B.D.C.

In 1929 three sets of specimens, constituting Series VIII, were exposed at Takoradi (Gold Coast), Kingston (Jamaica), and Bermuda; they consisted of pieces impregnated some with creosote and others with fuel-oil, with 3 per cent. of D.M., and without D.M. Many of the blocks were lost at the first two stations. At Bermuda the attack seemed to be relatively slow.

In 1930 some experiments were put in hand on blocks treated with naphthalene. These had been suggested by the consideration that the phenols (tar acids) of creosote might be unimportant in structures exposed to sea action, since phenols are somewhat soluble in water. It was further thought that a solid like naphthalene might block the pores of the wood, and so prevent the dissolving action of the water upon the poison from taking effect (XII-9). Series IX, consisting of two similar sets of 120 blocks each, was exposed at Kilindini (Kenya Colony) and Mauritius. The blocks were impregnated as follows :—

1. Crude naphthalene ;
2. A mixture of two-thirds crude naphthalene and one-third creosote ;
3. A mixture of one-third crude naphthalene and two-thirds creosote ;
4. Creosote ;
5. Creosote followed by a bath in naphthalene ;
6. Crude naphthalene plus 3 per cent. of D.M.

Naphthalene penetrated well and its crystals could be seen in the interior of blocks when split for examination after exposure (XIII-42). Naphthalene in itself confers some protection, but, judging from the blocks examined so far, it appears to be distinctly inferior to creosote. The mixtures of creosote and naphthalene penetrated less well than either of these materials alone, and the mixtures were also less efficient. This agrees with experience in the United States, (XII-25). Naphthalene plus 3 per cent. of D.M., and also plain creosote, gave complete protection for 12 to 18 months. This experiment is still proceeding.

INCISING

In the experiments so far described most of the test-pieces consisted of small blocks whose smallest dimension was only $2\frac{1}{2}$ in., so that the impregnation was complete; but larger pieces 4 in. by 4 in. in section were sometimes attacked by *Teredo* owing to less complete penetration of creosote. Hence it was decided to investigate the penetration of creosote under conditions more approximating to those of actual practice. Further experiments on larger specimens confirmed the fact that the penetration of creosote was very irregular, and this led to the carrying out of a series of incising experiments, described in Professor Dixon's report (p. 38).

In October, 1933, Series XI, consisting of forty-eight pieces of British Columbia fir, 6 in. by 10 in. by 3 ft. long, some incised and others not incised, were sent to Colombo for exposure. All have been impregnated with creosote by the Bethell process, the pressure being maintained for 2 hours instead of 1 hour. A description of these experiments is given at p 39.

SUBSIDIARY EXPERIMENTS

In addition to the main investigation, outlined above, a few subsidiary experiments were also carried out, which will be briefly referred to. The resistance of greenheart (*Nectandra rodioei*) to *Teredo* attack seems to be due to a chemical constituent of the wood, possibly the alkaloid bebeerine (II-34, IV-25). Baltic fir impregnated with an alcoholic extract of greenheart sawdust was found to be more resistant than untreated controls.

In the Interim Reports of the Committee a good deal of information is given by correspondents and others about extra-European timbers. Greenheart piles were resistant to *Limnoria* for 30 years at Plymouth (II-35) and fairly sound at Panama after 7 years (XII-23), but this timber failed in the locks of the Panama Canal (VII-40) and was not entirely satisfactory at Auckland, N.Z. (III-67). In New Zealand and Australia turpentine (*Syncarpia laurifolia*) enjoys a considerable reputation, which is borne out by experiments (III-68, IV-55, V-56). At Wellington several native timbers were exposed along with the Committee's test-pieces. Their descending order of merit would seem to be: brush box (*Tristania conferta*), totara, turpentine, white cedar (*Melia azedarach*) (XII-9). Brush box was attacked only very slightly in 6 years.

At Colombo untreated pynkado (*Xylia dolabriformis*) and satinwood were exposed along with the poisoned specimens of the Committee. Pynkado proved much superior to satinwood, and nearly as good as creosoted Baltic fir (XII-9). In the Rangoon river, Burma teak and pynkado were severely attacked within a year, but other native timbers were even less resistant (XIII-56). Native timbers have further been tested at Auckland (V-56) and in Kilindini harbour, Kenya Colony (XII-14). Information about South American and other tropical timbers exposed in the Panama Canal zone has been published in bulletins of the American Railway Engineering Association (VII-40, IX-68, XI-23, XII-23, XIII-54, XIV-53).

Mr. J. Marchbanks, formerly Engineer to the Wellington Harbour Board, exposed white pine impregnated with Pintsch gas tar which is obtained in the manufacture of gas from kerosene, used formerly for lighting on the New Zealand Railways. It differs considerably from creosote, containing no phenols or naphthalene, and seems to consist largely of aliphatic hydrocarbons. Yet it penetrated the timber well—much better than the crude oil used in the Committee's experiments—and its protective powers against *Teredo* appear to be considerable (XI-15).

There seems to be some evidence that substances which are toxic when in large concentrations, may actually attract marine borers when the concentration is low. Thus creosote containing 0·1 per cent. of D.M. or less sometimes appeared to be less protective than creosote alone. Results obtained in the United States indicate that treatment with creosote containing 1 per cent. of D.M. generally rendered timber immune, but that fuel-oil containing arsenical poisons (probably in smaller quantity owing to inferior solubility) appeared to render the blocks actually attractive to *Limnoria*, and afforded uncertain protection against *Teredo*. The most marked attraction seems to be exercised by carbazole, with which, using 2·3 per cent. in creosote, the Committee impregnated a number of specimens, and these have almost invariably suffered much more from *Limnoria* and *Teredo* than have similar pieces treated with plain creosote (XII-7).

In experiments in the United States (XII-26) similar test-pieces containing creosote plus carbazole resisted attack for 4 years, but there the extent of the impregnation was exceptionally high, being 20 to 30 lb. per cu. ft. Again, blocks of Douglas fir, impregnated with 5 per cent. of cresylic acid in crude oil, were destroyed in 16 months at Seattle, and appeared to be more heavily attacked than untreated timber (VII-41).

Such so-called oligodynamic effects are well known in biology: for instance, minute quantities of zinc and copper salts favour the growth of fungi which are killed by larger concentrations.

In some situations *Limnoria* causes more damage than *Teredo*, or may be harmful in opening the way to the latter organism. No really effective protection against *Limnoria* has been revealed by the Committee's experiments, although this organism may be repelled to some extent by good creosoting. This was notably shown by certain piles at Southampton where an outer creosoted shell remained immune and the inner portion had partly disappeared owing to severe attack by *Limnoria*. The creosote remaining in the outer layer was extracted by alcohol, and found to consist almost wholly of hydrocarbons of high boiling-point (anthracene oil). The more volatile naphthalene and phenols were hardly present; they may have been extracted by sea-water in the course of about 40 years, or the creosote employed at the time may have differed considerably from that used to-day. It may be that the really toxic constituents of creosote are complicated hydrocarbons of the type now known to produce cancer. The specific toxicity of organic substances was also shown in laboratory experiments at Edinburgh by Dr. White (V-12, 17) on adult isolated *Limnoria*. This crustacean is relatively resistant to arsenic compounds and metallic salts, but specially susceptible to fluorenone, a benzene derivative containing only carbon, hydrogen and oxygen. *Limnoria* constitutes a separate problem, rendered the more difficult by the fact that it only bores on the surface, where the poison is most readily dissolved out. Professor Yonge (VIII-69) failed to find any evidence that *Limnoria* digests the food which it ingests. This borer has been found in the insulation of a telegraph cable.

MECHANICAL TESTS OF FOREIGN TIMBERS UNTREATED AND CREOSOTED AND NOTE ON INCISING

By Professor S. M. Dixon, M.A., B.A.I., M.Inst.C.E.

THE Committee, having received a number of specimens of various timbers from Australia, New Zealand and Ceylon (Table II) decided that mechanical tests (bending, compression and shearing) should be made both on the timber as received and on pieces after creosoting, to determine the effects of creosoting processes on the strength and elasticity of the timbers. It was realized that the specimens, being chosen from merchantable timber and not being specially selected, could give only approximate values of the average mechanical properties of the timbers. The specimens received were well selected timber, straight grained and free from knots and shakes, and about 8 in. by 8 in. by 4 to 6 ft. long. Each of these was sawn into four pieces 4 in. by 4 in. in cross section, and three of the pieces from each specimen were creosoted before any tests were carried out, one piece being treated by the Bethell process (III-38), and two by the Griffith process (III-38) at different temperatures. The amount of moisture in the timber at the time of creosoting was approximately the same as the amount present in the uncreosoted timber at the time of testing, ranging from 7·8 to 13·9 per cent.

The specimens were weighed before and after creosoting; but this does not necessarily give the weight of creosote absorbed. The timber when placed in the creosote contained on an average 10 per cent. of moisture, and one of the first effects of raising the temperature of the creosote was to drive off some of the moisture which is normally distributed all through the wood. But it is difficult for the creosote to enter into the timber, on account of the air imprisoned in the small cavities and the moisture imbibed in the walls of these cavities. Very small quantities of water prevent the walls from taking up greasy substances like creosote. The blocking of imprisoned air is quite fortuitous in air-dried wood, and when there is only very little water in the substance of the walls its location will be quite fortuitous also. Without raising the water to boiling point it is very difficult to abstract it from the walls, as once its surface retreats into the substance of the walls among the micellae (submicroscopic particles) it forms such fine meniscuses that it practically ceases to give off water-vapour. If, however, the temperature of the creosote bath is kept at 150° C. for 1 hour and then allowed to fall slowly to the atmospheric temperature, it is reasonable to suppose that all or nearly all the moisture is driven off; and the advocates of the Griffith process urge that, since the moisture is driven off and much of the air is expelled from the minute cavities, the creosote is able to enter the timber and completely saturate it. Most of the creosote only enters the cavities in the timber, where they exist, and so in some cases only small quantities of creosote find their way into the stick. The specific gravity of the creosote used was only 1·17, so that even when the creosote replaced the moisture driven off the increase in weight was very small, and it was possible for the weight of creosote absorbed to be less than that of the moisture driven out. Again, in some dense hardwoods, the quantity of air in the dry timber is small and only a fraction of this is expelled by the rise in temperature due to the creosoting process; thus the quantity of creosote replacing this air may be very small. In such cases the process of creosoting might again actually lead to a diminution in the weight of the specimen. With several of the timbers treated there was very little penetration of the creosote, and the final result of creosoting such timbers by any of the processes employed was practically the same as would be obtained by painting over the surface with creosote. The absence of penetration was specially noticeable near the middle of the specimen since the creosote generally enters the timber easily only where the grain is cut transversely. The penetration of the creosote in every piece under test was therefore noted, and the irregular extent of the area of the cross section visibly affected by the creosote is recorded as a percentage of the cross section (Table IV). It will be seen, therefore, that the results obtained are very complicated and difficult to interpret correctly. There is a wide variation in the strength of pieces cut from the same stick of timber, whether tested in bending, compression or shearing, according to the direction of the grain or of the annual rings with regard to the applied forces or according as the test-piece is nearer to or farther from the centre of the tree. In the present series of tests, besides these factors, there are at least two other possible causes of variations in the resistance of the timbers, namely, the quantity of creosote present in the specimen at the time of the test, and the effect on the timber of the process of creosoting, that is, chiefly the effect of the temperature to which the timber was raised during the operation (48°, 110°, or 150° C. according to the process employed).

CREOSOTING PROCESSES EMPLOYED

(A) *Griffith process at* 110° *and* 150° *C.*—Creosoting by the Griffith process was carried out in the apparatus shown in Fig. 1. The boiler was a vertical flanged steel tube, 2 ft. in diameter and 5 ft. high. The bottom plate, 1 in. thick, was reinforced by two angles and bolted on, being packed by a rubber ring. This boiler was supported on a base of hollow concrete blocks, containing a space for a gas burner. A top plate, similar to the bottom, was furnished with a lifting ring by means of which it could be raised by a small block and tackle supported on the ridge piece of the frame supporting the shelter of corrugated iron enclosing the plant. The boiler was lagged with asbestos fibre about 1½ in. thick, and the temperature of the creosote was observed by a thermometer in a steel tube screwed into the boiler near the middle. The boiler could be emptied and filled by means of pressure and air pumps. The timber charge for the boiler consisted of seven of the 4-in. by 4-in. by 4-ft. 3-in. specimens.

These specimens, air dried, and containing on an average 10 per cent. of moisture, were placed in the boiler, being held vertical and separated from one another by a light iron frame with seven radial arms carrying caps which loosely fitted the tops of the specimens. By means of this arrangement they were depressed below the surface of the creosote and kept steady when the cover of the boiler was placed in position. The creosote was then pumped into the boiler.

The specimens were numbered with lead labels and weighed before being placed in the boiler. The creosote was then heated by the gas burner to the required temperature, 110° or 150° C., as the case might be, and held at this for 1 hour. In some cases this time was increased to 2 hours. The specimens were then left in the creosote to cool for 18 hours, after which they were removed and allowed to drain. They were then weighed. No further attempt was made to extract any of the creosote from the specimens. Their weights, before and after creosoting, are summarized in Table III, which shows that, contrary to expectation, many of them lost in weight as explained above. When this was first noted a number of specimens were treated a second time in a similar manner except that they were kept at the higher temperature, 110° or 150° C., for 5 hours before cooling. Similar effects were observed, as shown in Table III.

(B) *Bethell process.*—The method adopted was that in use on the London, Midland and Scottish Railway, the sequence of operations being as follows. The timber, having been weighed, was placed in the boiler shown in Fig. 1, and the cover was bolted down, the joint being made with a rubber ring. The air in the boiler was now exhausted and the pressure reduced to 10 in. of mercury, and kept at this for ½ hour; the creosote was then run in, and the temperature was raised to 48° C., and the pressure to 190 lb. per sq. in., this state being maintained for 1 hour. The creosote was then run off, and the pressure reduced to 15 in., and kept thus for ½ hour. At the end of this time the specimens were removed and weighed. The percentage changes in weight are given in Table III. The changes in weight obtained by the Griffith and Bethell processes cannot be strictly compared, as in the latter process an attempt was made as usual to drain the superfluous creosote from the specimens.

In Table IV the penetrations of the creosote are recorded in terms of the percentage of the area of the cross section stained by the creosote. Column (A) refers to the section at the middle of the specimen, and (B) is a mean value for the two sections 8 in. from each end respectively.

A further note on penetration of creosote appears at p. 35

CREOSOTING BOILER

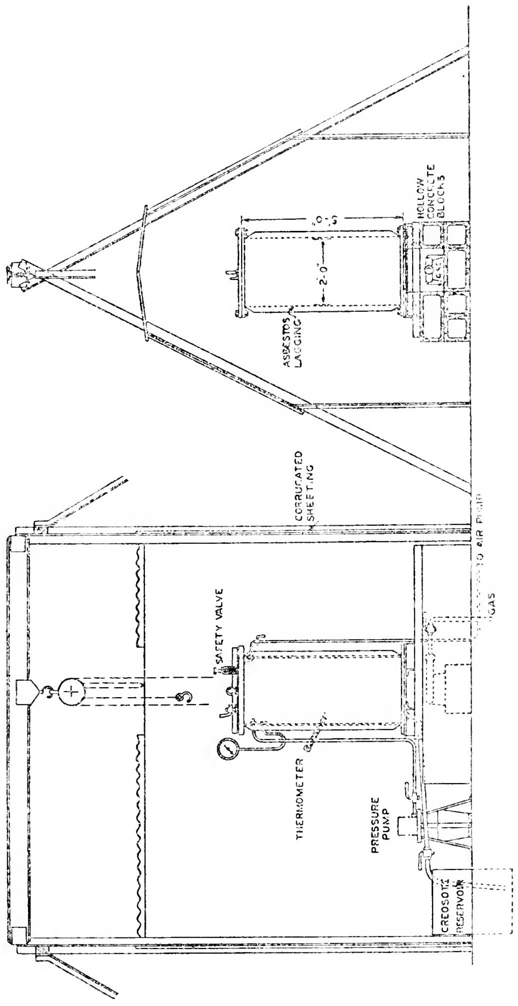


FIG. 1.

MECHANICAL TESTS

The only tests systematically carried out were: (1) bending made on a span of 4 ft. with the load at the centre, local crushing being guarded against; (2) compression on short columns endwise to the fibre and also on blocks on which the load was applied across the fibre; (3) shearing on slotted double-ended specimens. The test-pieces for compression and shearing tests were cut from the uninjured ends of the pieces broken in the bending tests. No pieces were available for satisfactory tests on long struts in compression, and comparative tensile tests were impossible since the timber, though roughly straight-grained, could not furnish a sufficient number of fair size test-pieces with uniform grain and free from evident defects. And, further, very few of the specimens broken in bending would supply tension test-pieces as well as pieces for testing in compression and shearing. Tensile tests were, therefore, made only on uncreosoted specimens of some of the timbers furnished from some smaller pieces supplied to the Committee. In practice the tensile strength of timber has not often to be considered in the design of marine structures, since timbers are generally stronger in tension than in compression or shear. Professor W. H. Warren has given* the following figures for the tensile and compressive strengths of specimens of three of the timbers tested in the present series :—

	Strength : Lb. per sq. in.	
	Tensile.	*Crushing. Short Columns*
Tallow wood ..	21,000	11,000
Blue gum	16,000	9,400
Turpentine ..	15,000	9,600

The densites recorded in Table V of the timbers tested were those found at the time of test of the uncreosoted specimens, and include the moisture as then determined. The specimens, after being cut in pieces, roughly 4 in. by 4 in. in section, were stacked for 1 year under cover in open, well-ventilated piles on the floor of the laboratory, where the temperature varied from 40° to 90° F. The timber, being protected from the sun and being in a very dry atmosphere for at least 6 months, was seasoned very slowly so that practically none of the specimens was cracked or shaken. The average moisture-content at the time of test, as shown in Table V, was about 10 per cent. In the United States a standard moisture-content of 12 per cent. is regarded as that of dry timber, out of doors, and it has been shown that the average strength of several timbers tested with 12 per cent. of moisture was 75 per cent. greater than that of the same timbers green or thoroughly wet after seasoning.

(1) *Bending Tests.*—These tests were carried out on specimens 4 ft. 3 in. long supported on a span of 4 ft. in a 100-ton Riehlé machine. As is usual with short sticks, the load was centrally

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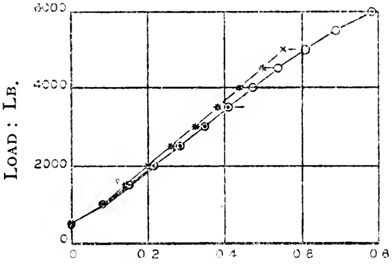
* "The Strength, Elasticity, and Other Properties of New South Wales Hardwood Timbers," Sydney, 1911.

applied. The sticks were all approximately 4 in. by 4 in. in cross section, and local crushing of the specimens was avoided by supporting the piece on two steel plates, 4 in. by 3 in., resting on the end cylindrical supports, the load being applied through a similar plate at the centre of the beam. The load was applied continuously at such a rate as to produce a deflection of $\frac{1}{8}$ in. per minute, and the deflections produced were read at each increment of 250 lb. until the beam failed. The load-deflection curves were then plotted for each beam, as shown in Figs. 2, 3 and 4, and the maximum fibre stresses at the elastic limit were calculated in each case. After fracture the penetration of creosote at the break was noted and recorded. The results of these tests are given in Tables VI and VII.



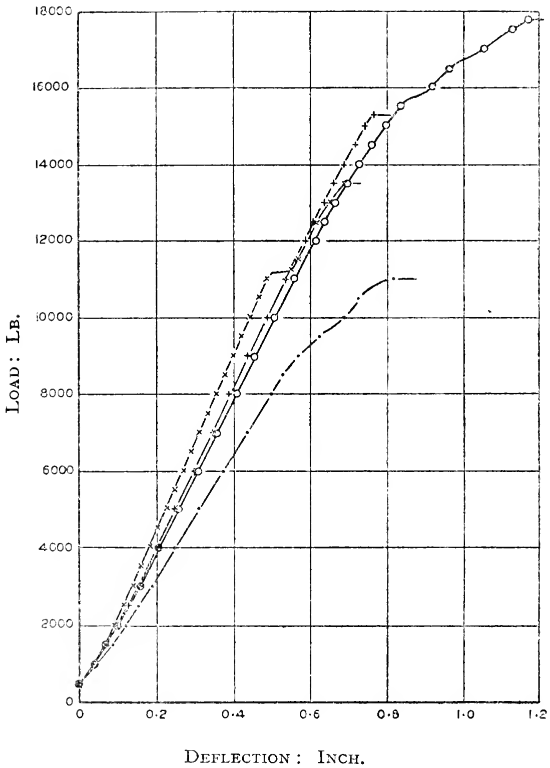
	Beam No.	Size. Wide. Deep.	Modulus Lb./Sq. in. Range.
o Untreated ..	47·01	4′ 0″ × 3·85″ × 3·85″	E (1,000–4,500) = 970,000
· Griffith at 150° C. ..	47·711	4′ 0″ × 3·80″ × 3·80″	E (1,000–3,500) = 1,060,000
+ Griffith at 110° C. ..	47·712	4′ 0″ × 3·85″ × 3·90″	E (1,000–4,000) = 1,020,000
× Bethell ..	47·11	4′ 0″ × 3·90″ × 3·90″	E (1,000–5,000) = 1,000,000

FIG. 2.

LOAD-DEFLECTION DIAGRAMS OF TOTARA.

The figures are the averages from tests on four specimens except in the case of the four Australian timbers when only one test-piece of each was available. The value of the modulus of elasticity obtained by tests on timber creosoted by the Griffith process at 150° C. is generally lower than the value obtained for timber either untreated or creosoted by the Bethell process or the Griffith process at 110° C. Table IV shows that of the timbers treated by the Griffith process at 150° C., in all except four a considerable part of the area of the cross section, broken in the test, was impregnated with creosote.

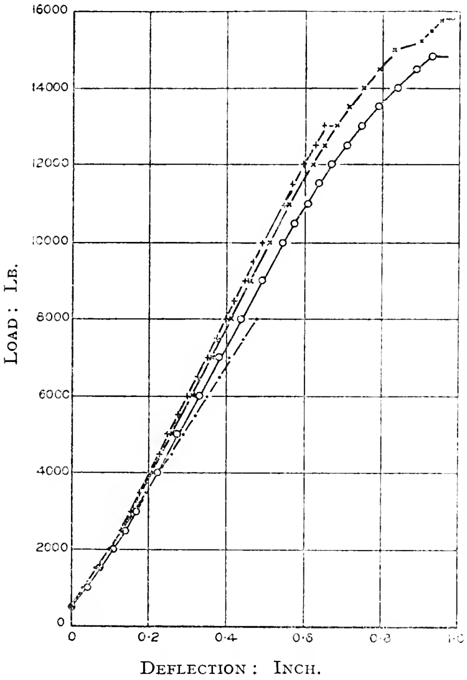
The diminution in the value of the modulus of elasticity may, therefore, be due to the presence of this creosote, or to the high temperature of 150° C. to which the timber was raised in the process of creosoting. It is apparent that the other two processes of



	Beam No.	Size. Wide. Deep.	Modulus Lb./Sq. In. Range.
o Untreated ..	55·01	4′ 0″ × 3·80″ × 3·70″	*E* (3,000–11,000) = 2,880,000
· Griffith at 150° C. ..	55·711	4′ 0″ × 3·75″ × 4·00″	*E* (2,500–8,500) = 1,830,000
+ Griffith at 110° C. ..	55·712	4′ 0″ × 3·72″ × 3·80″	*E* (3,000–12,000) = 2,840,000
× Bethell ..	55·11	4′ 0″ × 3·82″ × 3·85″	*E* (2,500–11,000) = 2,890,000

Fig. 3.

Load-Deflection Diagrams of Nah.



	Beam No.	Size.	Wide.	Deep.	Modulus Lb./Sq. In. Range.
o Untreated ..	37·01	4′ 0″	× 3·85″	× 3·90″	E (3,000–10,000) = 2,240,000
· Griffith at 150° C. ..	37·711	4′ 0″	× 3·75″	× 3·85″	E (500–7,500) = 2,070,000
+ Griffith at 110° C. ..	37·712	4′ 0″	× 3·85″	× 3·95″	E (3,000–11,000) = 2,420,000
× Bethell ..	37·11	4′ 0″	× 3·75″	× 3·90″	E (3,000–11,000) = 2,490,000

FIG. 4.

LOAD-DEFLECTION DIAGRAMS OF IRONBARK.

creosoting employed have little or no effect on the value of this modulus. Corresponding results are seen in Table VII, where the stress on the extreme outer fibre at the limit of proportionality, as determined from the load-deflection curve, is given. Generally, the effect of creosoting by the Griffith process at the higher temperature of 150° C. was to lower the value of this stress even where the area of the cross section showed little or no impregnation by creosote, as shown in Table IV. Typical fractures are shown in Fig. 5.

(2). (*a*) *Crushing* (*endwise*) *Tests.*—This is the most important of all timber tests. It is also the easiest to make, and Professor J. B. Johnson has stated* that for commercial purposes this test alone is sufficient. Pieces 8 in. long, with carefully squared ends, were cut from the uninjured ends of the pieces already tested for bending. The average cross-sectional area of these pieces was 15 sq. in. The compression of the piece under test was read for increments in the load varying from 4,000 lb. to 6,000 lb., the rate of increase of the load being kept as uniform as possible until failure took place. The maximum load recorded was not far from the limit of the machine, being 188,570 lb. on a piece of Ceylon timber named nah, equivalent to a stress of 13,960 lb. per sq. in. The creosoted specimens in these tests, being cut from the ends of the timber sticks, showed a much larger area of impregnated surface than was shown by the middle parts ruptured by bending. Table VIII shows the results obtained and Fig. 6 illustrates typical fractures.

(2). (*b*) *Crushing* (*across grain*) *Tests.*—Failure by crushing across the grain is fairly common in practice because the strength of timber loaded in this way is much less than when loaded endwise. As is well known, failures from crushing across grain are very erratic, some test-pieces failing suddenly, whereas many crush gradually, presenting an ever-increasing area to the load so that it is practically impossible to determine the exact crushing strength. These differences, when they occur in test-pieces cut from the same timber, may, in some cases, be due to the angle which the direction of the applied force makes with the annual rings in the specimen. How this direction may vary is seen in Fig. 7, where A, B and C represent 4-in. by 4-in. sticks cut from the same tree; in A the horizontal faces are approximately parallel to the annual rings, while in B the horizontal faces are at right angles to them. In many of the hardwood timbers tested no annual rings are visible. The crushing strength of some timbers is greater in the tangential than in the radial direction, whereas in other timbers the reverse holds. In the series of tests here described most of the timbers experimented on showed a very definite though erratic crushing strength, and the intensities of these ultimate stresses have been tabulated in Table IX. At the same time Professor Johnson's method* was also used, in which the intensity of stress producing a compression of 3 per cent. of the thickness of the test-piece is regarded as the "safe '

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* "Materials of Construction," pp. 467-8, New York, 1897.

[To face p. 32

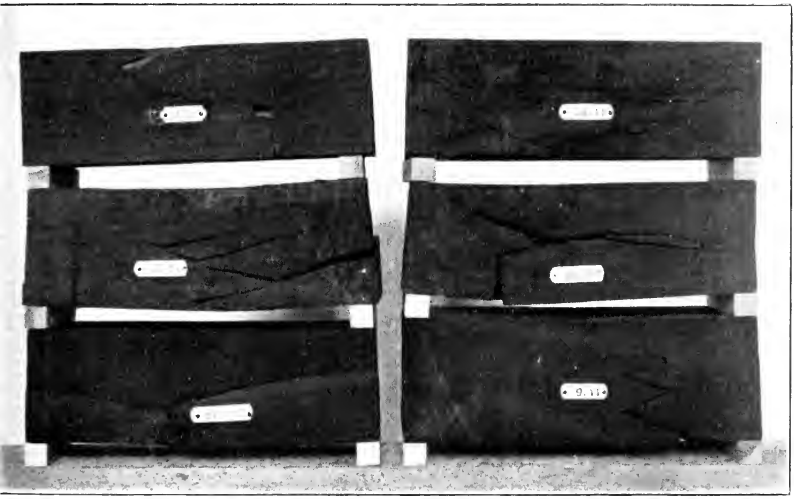

Fig. 5.

Typical Bending Fractures.

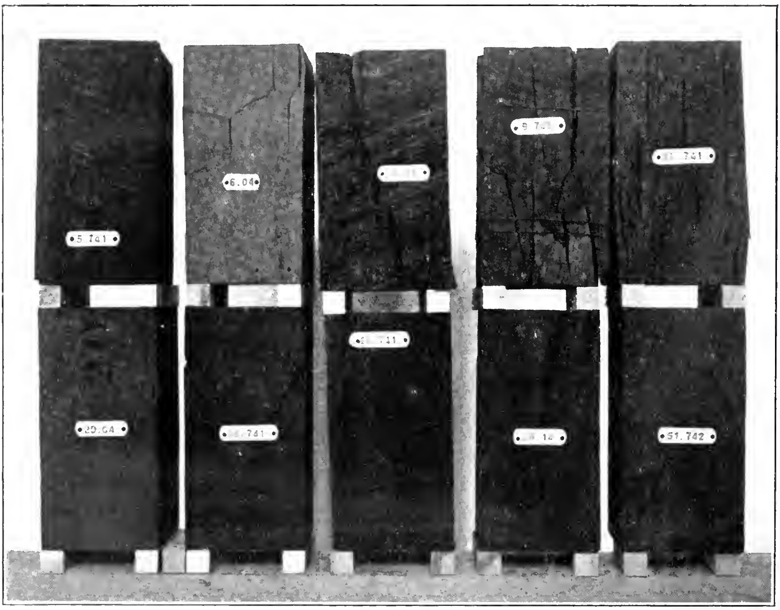

FIG. 6.

TYPICAL CRUSHING (ENDWISE) FRACTURES.

stress (Table X), and 15 per cent. compression denotes a "failure" (Table XI). Of the sixteen timbers, when tested in the uncreosoted condition, three—spotted gum, iron bark and tallow wood—failed before a compression of 15 per cent. was reached, the maximum compressions being 8, 9 and 13 per cent. respectively. Five of the timbers when creosoted by the Bethell process failed before a compression of 15 per cent. was reached, and ten of the timbers when creosoted by the Griffith process at 150° C. failed before 15 per cent. compression was reached. On the other hand several of the timbers showed high degrees of compression, ranging up to 83·7 per cent.; one specimen exhibited this compression at the maximum load (200,000 lb.) of the testing-machine, the intensity of stress being 13,500 lb. per sq. in. The kinds of failure are illustrated in Fig. 8.

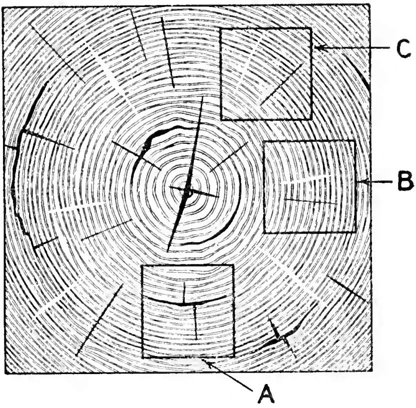

FIG. 7.

SECTION OF LOG SHOWING VARIOUS DIRECTIONS OF PLANES OF CRUSHING ACROSS GRAIN.

(3) *Shearing Tests.*—These tests are of practical importance because shearing is a common kind of failure in framed work. The slotted specimen used in these tests is shown in Fig. 9, where its dimensions are given. A shackle holding a pin passing through the central hole was held in the upper jaw of the testing machine, and a 1-in. by 1-in. bar was passed through one of the end slots and held in a lower shackle in the lower jaw. One end having been tested, the piece was swung round and the other end was tested. Each specimen, therefore, gave two tests in double shear over an area of 1 in. by 2½ in. Table XII indicates that in most of the pieces in this test the sheared area showed either no creosote or nearly 100 per cent. This is because these test-pieces were cut from the middle of the sticks where, unless the timber readily absorbed the creosote,

there was practically no penetration. The effects of complete impregnation by creosote are clearly shown in Table XII by the lowered average values of shearing strength. The bad effect of the Griffith process at a high temperature is also apparent. The fractures were generally regular as is seen in Fig. 10.

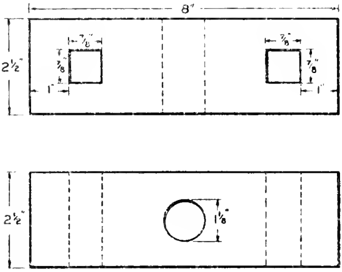

FIG. 9.

SHEARING TEST-PIECE.

(4) *Tension Tests.*—As already explained, owing to the unequal distribution of creosote in any cross section available after the other test-pieces had been cut, tension tests were made only on uncreosoted specimens. It was impossible to arrange in every case for the test-piece to be cut so as to give a uniform pull along the grain at the smallest cross section. Some of the specimens, therefore, show irregular effects which might have been avoided if the timber had been specially selected for these tests, but on the whole they show the well-known fact that the tensile strength of timber is roughly twice the compressive strength. The form of specimen used is shown in Fig. 11. The area at the smallest cross section, approximately 3 in. by $\frac{3}{8}$ in., was measured exactly for each specimen. The results of these tests are shown in Table XIII, and typical fractures in Fig. 12.

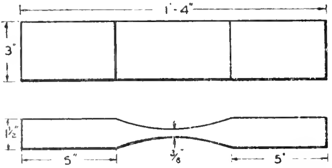

FIG. 11.

TENSION TEST-PIECE.

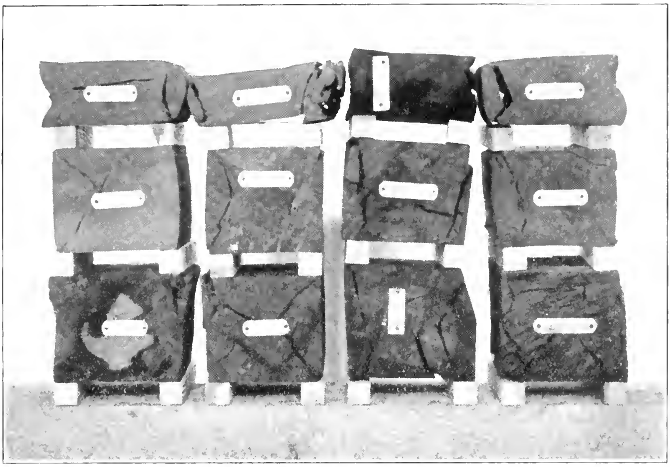

Fig. 8.

Typical Fractures in Crushing Across Grain.

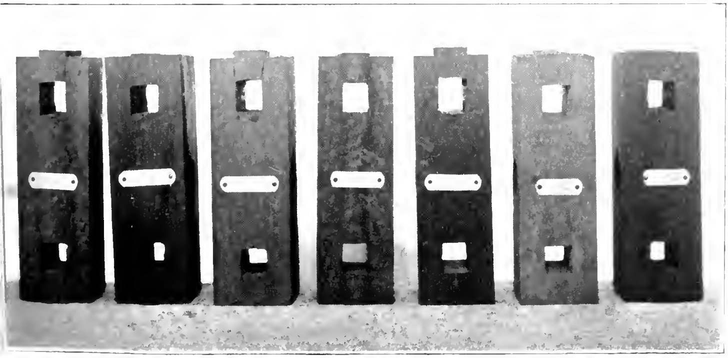

Fig. 10.

Typical Fractures in Shearing.

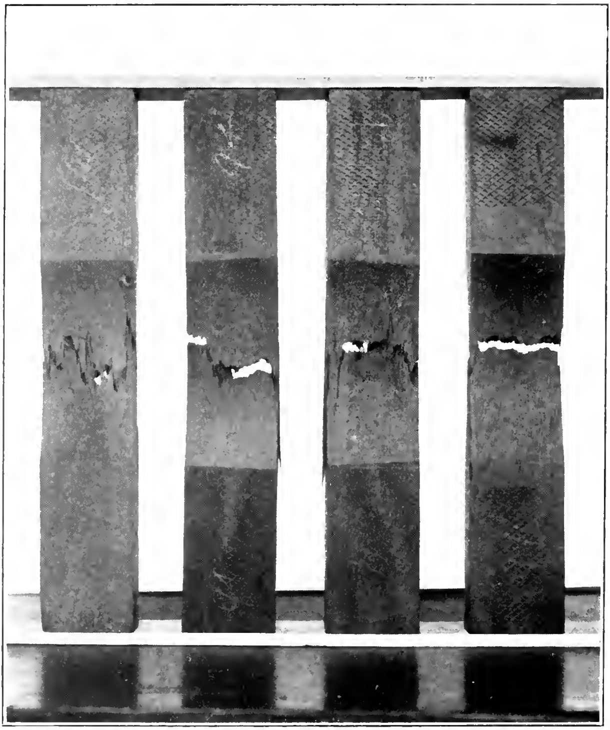

FIG. 12.

TYPICAL TENSION FRACTURES.

NOTE ON CREOSOTING

The denser species of timbers generally absorbed more creosote than the lighter timbers, and, as already pointed out, weighing timber before and after creosoting is of little value as indicating the penetration of the creosote. Of course, there are exceptions to this, and some of the lighter timbers absorbed considerable quantities of creosote. These facts are well known to those who have studied the physical structures of various timbers, but they may not be generally appreciated by engineers.

The structure of the timber determines the penetration of the creosote. Many of the lighter timbers are conifers, and in these trees the wood is composed of short prismatic chambers (tracheids) about 2 mm. long by 0·02 mm. The walls of these chambers have no perforations and the chambers in dry timber are filled with air. Under the conditions generally obtaining in the creosoting processes employed the creosote penetrates with difficulty into the cavities filled with air to any considerable distance from the cut surface of the stick. Since the larger dimensions of these chambers are disposed longitudinally in the timber, soakage of the creosote would be easier in the longitudinal than in the transverse direction of the grain. This is often noticed: the ends of the specimens show considerable penetration, whereas at the middle of the stick the timber has merely a thin coating, a section showing little or no creosote except at the edge. In heavy timbers usually obtained from hardwood trees (dicotyledons), besides the small, prismatic chambers, long tubules (vessels) run longitudinally in the wood. These vessels may be 6 ft. long and up to $\frac{1}{32}$ in. in diameter. They might be completely filled with creosote in the different processes and so there would be complete penetration to every part of the stick from the points in the surface where the vessels might be cut. These general conditions may be illustrated by the behaviour of two timbers much used in structural work, namely, larch, a conifer, and beech, a dicotyledon. A number of sticks of these timbers were creosoted by the Griffith and Bethell processes, with the following results. Four sticks of larch with an average density of 34 lb. per cu. ft., on being treated by the Griffith process, increased in weight by only 3 per cent., while four sticks of beech, with an average density of 43 lb. per cu. ft., on the same treatment increased in weight by 52 per cent.

Unfortunately, however, the matter is not at all so simple as outlined and illustrated above. As pointed out by Laslett*, merely weighing a cubic foot of timber does not yield its specific gravity. On account of its structure no two single cubic feet of a timber would have exactly the same weight except by chance. And so with creosoting, the creosote may pass into the tracheids, existing in all timbers, or it may be absorbed more or less by the walls of these cavities, and in the case of hardwoods it may pass into the vessels.

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* "Timber and Timber Trees," p. 16, London, 1894.

Then the sizes and volumes of the various cavities may differ widely, not only when various timbers are compared, but even in sticks of the same timber. The density of a timber depends on the number of air chambers in it, and also on the specific gravity of the fibre. In specifying the increase in weight desired on creosoting any timber, average values for a large number of samples will be required, and the penetration of the creosote at the middle of the logs should be examined. Increase in weight may indicate very little when one timber is compared with another, but ascertaining increase in weight will always be a convenient test to carry out once the conditions for any particular timber have been determined.

It has already been pointed out that in some cases the sticks, contrary to expectation, lost weight in one of the creosoting processes employed, since increase in weight is only possible when the weight of creosote absorbed exceeds that of the moisture expelled, and whether an increase will occur depends on the structure of the timber, as explained above. The sticks of timber used were only commercially dry, containing at the time of creosoting about 10 per cent. of moisture, and the presence of any moisture has a very serious effect on the penetration of the creosote.

Typical penetration of creosote in a stick of timber cut from a conifier (Archangel pine) is shown in Fig. 13, where sketches of the cross sections cut every 6 in. in the length of the piece, after creosoting by the Bethell process, are reproduced. The penetration is much more effective longitudinally than transversely, the inner sections being stained with creosote only round the edges, while the end sections show complete penetration where creosote must have travelled a considerable distance longitudinally.

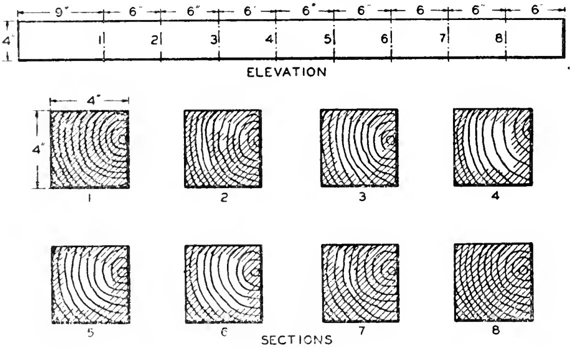

Fig. 13.

Penetration of Creosote.

To show the wide variation in change of weight obtaining when different sticks of the same timber are creosoted the following results are cited. In the course of the experiments 224 sticks of Archangel pine were creosoted by the Bethell process for exposure at overseas ports. They were treated in groups of twenty-eight sticks each, seven sticks being creosoted at the same time, and the following figures show the results obtained in the first eight groups of these sticks, the absorption being expressed as a percentage of the weight of the timber—

Group No.	1.	2.	3.	4.	5.	6.	7.	8.
Absorption of creosote	40	38	31	45	45	30	41	33

The average absorption was 38 per cent., but the extreme values in group 2 were 75 per cent. and 14 per cent., and in group 4, 102 and 22 per cent. Only a microscopical examination of the timber would enable the quantity of creosote which could be absorbed by any dried stick of timber to be predicted with any accuracy, though, as is seen, the measured values of, say, twenty-five sticks will give a fair average. While the densities of these sticks ranged from 40·5 lb. to 28·1 lb. per cu. ft. (the weights ranged from 18 lb. to 12·5 lb. respectively), the average density of the sticks in any of the eight groups mentioned above was very close to the average of the whole number. Actually, it happened that each group of twenty-eight sticks contained one very heavy and one very light stick, and the averages obtained were as follows :—

Group No.	1.	2.	3.	4.	5.	6.	7.	8.
Average density.	35·1	32·6	32·1	30·1	30·6	33·0	33·3	31·3

giving an average for the whole number of 32·3 lb. per cu. ft. It might, therefore, be considered that for this timber (Archangel pine) a close value of the average density could be obtained by finding the average value of about twenty-eight sticks taken at random.

Some of the effects of the structure of timber are exhibited when a creosoted specimen is being crushed in the testing machine. A hard dense timber which has, perhaps, absorbed only a small percentage of creosote will " bleed " freely when compressed, the creosote flowing over the platten of the testing machine, while often, when a light timber, which may have absorbed a considerable weight of creosote and showing the area well stained, is considerably compressed, no creosote will be pressed out. Some interesting points are seen from Table XIV, where the densities of the timbers, the percentage increases in weight, and the penetrations of the creosote at the middle of the stick, as shown by the percentages of cross section stained, are tabulated. Firstly, the lightest conifer tested, totara (30·5 lb. per cu. ft.), while it increased considerably in weight on being creosoted, showed hardly any penetration near the middle of the stick. The gain in weight is due solely to the creosote absorbed at the end of the stick. The lightest Ceylon timber, jak (40·7 lb. per cu. ft.) showed no penetration at the middle of the stick.

Secondly, the various specimens of eucalyptus treated, although their increases in weight were very small, showed great penetration at every point of the stick. Iron bark, one of the densest timbers examined (71·9 lb. per cu. ft.), has very minute pores and these were apparently filled with creosote which thus penetrated to all parts of the timber, though the actual increase in weight was almost negligible. Thirdly, of the New Zealand conifers, kauri absorbed the least creosote, as shown by the average increases in weight and by the penetration near the middle of the sticks which was only 15 per cent. This agrees with what might be expected from the structure of the timber. Kauri, though light (33·7 lb. per cu. ft.), is an extremely close grained solid timber, being one of the slowest growing conifers. Laslett has referred to a tree 72 ft. in circumference whose age he estimated as 2,000 years. The general conclusions to be drawn from Table XIV are that, while generally larger percentages of creosote may be absorbed by conifers, the passage of the creosote longitudinally in the dicotyledons is much easier. This should be remembered when long sticks have to be creosoted.

Incising Timber Before Creosoting

It was noticed by the earliest workers in creosoting that there was great difficulty in obtaining penetration of creosote in large sticks of soft wood, but the cause of this was not well understood. H. P. Burt stated* in 1853 that, when it was desirable to expedite the process of saturation, by essential oils, it was necessary to remove the external ring of the timber or to puncture it with numerous small holes. It would seem that he thought the outer timber was more resistant to penetration—a view not shared by Bethell who, in the discussion on Burt's Paper, said that it was desirable to use round timber with the outer layer intact, and that the outer soft wood, being creosoted, would protect the heart wood since the latter was very resistant to creosoting. However, Burt's suggested method of puncturing or incising does not seem to have been practised, and little work was done in this direction until about 1906 when the Haltenberger process was developed in Austria for the treatment of telegraph poles. In this process punctures are made by a number of smooth drills which have no cutting edge and which force aside the fibres so that no wood is removed. The holes are arranged in spirals round the pole, these spirals being about $\frac{3}{8}$ in. apart, and the distance between holes being 8 in. In 1907 a Patent was applied for in England by A. R. Whitehead for a process of incising, involving staggered incisions across the grain of the timber, but the method does not seem to have been adopted to any great extent—perhaps because engineers did not share the inventor's belief that the cross-grain cuts would not impair the strength of the timber. In the following years considerable experimental work

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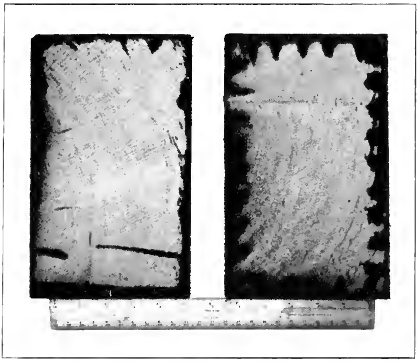
* Minutes of Proceedings Inst. C.E., vol. XII (1853), p. 223.



NOT INCISED. INCISED.

FIG. 14.

CROSS SECTIONS OF TIMBER AFTER CREOSOTING.

was carried out, and the method generally adopted was to use the simpler incising knives making incisions parallel to the grain of the timber, the method being regulated so as to give a depth of penetration of about 1 in. into the timber. A different process, in which the incising chisel was perforated with a small hole through which a special antiseptic could be forced, has also been tried for telegraph poles (XI-17). Since 1912 in the United States of America and 1919 in Canada much progress has been made in developing machines for incising sleepers of Douglas fir, and in 1929 the Committee decided that experiments should be made to determine the penetration of creosote into incised timber. Douglas fir was used in sticks about 6 in. by 10 in. in section. This timber contains very little sapwood, and so it is difficult to obtain penetration by ordinary creosoting processes. In the first tests the incisions were $\frac{3}{4}$ in. deep, parallel to the grain in rows $1\frac{1}{2}$ in. apart and staggered with respect to those in the adjoining rows, the distance between incisions in each row being $1\frac{1}{2}$ in. The ends of the timbers were covered with rubber packing clamped in position to prevent the entry of the creosote through the end grain. The ratio of gain in weight during creosoting of the incised timber to that of unincised timber was 2·41 to 1 in these preliminary experiments (XI-17). Further experiments (XII-12) were made in which the depth of incisions and the distance apart of the rows of incisions were varied. The depth of the incisions ranged from $\frac{3}{4}$ in. to 1 in. and, though more creosote was absorbed with the deeper incisions, the increase was not very great.

Although in these tests the weight of creosote absorbed is a direct indication of the depth of penetration, some further experiments were made so that direct observations of the depth of penetration might be obtained. This was done by cutting the test-piece in two midway between two rows of incisions and photographing the section immediatly after cutting before the creosote could creep over the fresh cut surface. Typical photographs showing the cross sections of blocks incised and not incised are reproduced in Fig. 14.

Further tests (XIII-44) on twelve specimens 2 ft. long and all cut from the same log of Douglas fir, which was sawn up the middle, were made with incisions 1 in. apart in rows 2 in. between centres, the staggering being $\frac{1}{3}$ in., as shown in Fig. 15. Nine of the specimens were incised and three were not incised. The average weight of these sticks was 25·16 lb., and on creosoting the average gain in weight of the incised sticks was 9·06 lb. as compared with 3·17 for the unincised sticks. These tests were checked by a further series (XIV-44) in which six incised and six unincised sticks, cut from the same log, were creosoted in pairs, consisting of one incised and one unincised stick, so as to secure identical treatment for comparison. The average weight of the specimens was 27·15 lb. and the gains in weight on creosoting were 9·15 lb. and 4·05 lb. for the incised and unincised sticks respectively. Two further sets of experiments were then made with sticks 3 ft. long, five different planks being used in each case. In the first set of these the planks were cut into five lengths, the centre length being unincised and the other lengths incised as before, and the incisions being 1 in. apart in rows 2 in. between centres. In the second set the incisions were $\frac{3}{4}$ in. apart in rows $2\frac{1}{4}$ in. between centres. Two pieces from each plank were not incised, the remaining three being incised.

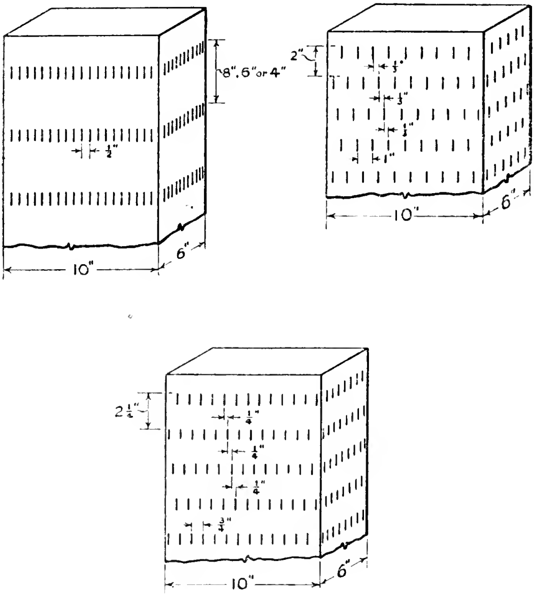


Fig. 15.

Arrangements of Incisions.

The planks for these two sets were from different consignments. The densities of the timber were very different in the two cases and varied considerably from plank to plank. In the first set the average weight per piece of the twenty-five pieces, 6 in. by 10 in. by 3 ft., was 47·8 lb., the extremes being 56·1 lb. and 42·1 lb; while in the second set the average weight was 42·6 lb., the extremes being 46 lb. and 37·5 lb. The lighter timber absorbed more creosote than the heavier, as occurred in the tests on creosoting Archangel pine, though, of course, with both Douglas fir and Archangel pine the quantity of creosote absorbed depends on other factors as well as on the density.

All these results are summarized in Table XVI, and the difference in the gain in weight during creosoting between the incised and unincised specimens may be taken as a measure of the value of the incising. The factor obtained by dividing the gain in weight of the incised specimens by that of the unincised is given in the Table under the heading "Gain Factor." The factor determined by these experiments is only directly applicable to specimens of approximately the same cross section as those tested, and would, of course, also vary with different kinds of timber.

The experiments show considerable variation in the results as indicated by the gain factor, owing probably to the nature and condition of the timber from which the test-specimens were cut. The gain factor was 2·6 in set V and 2·5 in set VI, and it is of interest that, while the average gain in weight during creosoting was far greater in set VI than in set V, the gain factor was nearly the same in the two cases.

In regard to set II, when the area per incision was increased from 2 sq. in. to 3 sq. in., the gain factor did not alter materially, but it dropped appreciably when the area per incision was increased to more than 3 sq. in.

Large incising machines are now available and a certain amount of work has been done in this direction on large engineering timbers for marine work. Quite recently a method has been developed in Germany for treating railway sleepers. Saw cuts at right angles to the grain are made by circular saws, the cuts being 1⅛ in. deep at the centre, 2½ in. long, and 7½ in. apart. It seems likely, however, that the mechanical properties of timber treated in this way will be inferior to those of timbers incised longitudinally.

TABLE II.—*List of Foreign Timbers received.*

Local Name	Origin	Botanical Name	Timber
Rimu ..	Auckland, N.Z.	*Dacrydium cupressinum*	Soft wood
Kauri ..	,, ,,	*Agathis australis* ..	,, ,,
Totara (1) ..	,, ,,	*Podocarpus totara* ..	,, ,,
Matai ..	,, ,,	*Podocarpus spicata* ..	,, ,,
Totara (2) ..	Wellington, ,,	*Podocarpus totara* ..	,, ,,
Turpentine ..	Auckland, ,,	*Syncarpia laurifolia* ..	Hardwood
Spotted Gum	Brisbane ..	*Eucalyptus maculata* ..	,, ,,
Iron Bark ..	,, ..	*Eucalyptus resinifera* ..	,, ,,
Blue Gum ..	,, ..	*Eucalyptus globulus* ..	,, ,,
Tallow Wood	,, ..	*Eucalyptus microcorys* ..	,, ,,
Nah ..	Colombo ..	*Lasiosiphon eriocephalus*	,, ,,
Palu	,, ..	*Mimusops hexandra* ..	,, ,,
Rani ..	,, ..	*Quercus lanuginosa* ..	,, ,,
Jak	,, ..	*Artocarpus integrifolia* ..	,, ,,
Kumbuk ..	,, ..	*Terminalia glabra* ..	,, ,,
Hora	,, ..	*Dipterocarpus zeylanicus*	,, ,,

TABLE III.—*Percentage Changes in Weight of Commercially Dry (Seasoned) Timbers when Creosoted by Different Processes.*

Timber	Number of sticks for each treatment	Percentage change in weight* when treated by		
		Griffith process		Bethell process
		at 110° C.	at 150° C.	
Turpentine	4	0·7	1	1
Rimu	4	45	34	60
Kauri	4	21	21	19
Totara (Auckland) (1) ..	4	4	8	42
Matai	4	16	18	27
Totara (Wellington) (2) ..	4	4	1	33
Spotted Gum	1	−3	−2	3
Iron Bark	1	−2	−7	1
Blue Gum	1	−2	−3	2
Tallow Wood	1	−2	−10	2
Nah	4	−1	−5	1
Palu	4	0	−7	1
Rani	4	0	−5	2
Jak	4	0	−2	3
Kumbuk	4	1	−4	5
Hora	4	21	8	12

Eleven timbers were treated by the Griffith process a second time for 5 hours and showed the following further percentage changes in weight.

Timber	Number of sticks for each treatment	at 110° C.	at 150° C.	Bethell process
Totara (Wellington) (2) ..		3	4	
Spotted Gum		0	−5	
Iron Bark		0	−9	
Blue Gum		0	−5	
Tallow Wood		0	−1	
Nah		0	−6	
Palu		−1	−6	
Rani		0	−11	
Jak		1	−4	
Kumbuk		−1	−1	
Hora		−3	6	

* Minus sign denotes loss.

TABLE IV.—*Average Percentage of Area of Cross Section Stained when the Stick was Creosoted by the Different Processes used.*

(A) Cross section at the middle of the 4 ft. 3 in. stick.
(B) Mean value for cross sections 8 in. from each end of the stick.

Timber	(A) Creosoting process			(B) Creosoting process		
	Griffith at 110° C.	Griffith at 150° C.	Bethell	Griffith at 110° C.	Griffith at 150° C.	Bethell
Turpentine ..	0	0	0	50	50	0
Rimu	40	45	70	90	90	90
Kauri	15	15	22	55	65	60
Totara (1) ..	0	0	0	5	5	5
Matai	40	50	35	75	75	75
Totara (2) ..	0	35	0	0	36	10
Spotted Gum ..	0	0	0	25	60	0
Iron Bark ..	0	80	0	40	80	50
Blue Gum ..	0	80	0	10	100	0
Tallow Wood ..	0	100	0	0	100	0
Nah	8	75	0	45	90	0
Palu	0	85	5	5	85	6
Rani	7	45	0	10	60	0
Jak	0	0	0	0	0	0
Kumbuk	7	45	7	10	45	14
Hora	100	100	100	100	100	100

TABLE V.—*Density and Moisture at Time of Creosoting and also at Time of Test of Uncreosoted Specimens.*

Timber	Weight	Moisture
	Lb. per cu. ft.	Per cent.
Turpentine	60·7	13·9
Rimu	40·9	11·2
Kauri	33·7	9·9
Totara (1)	30·5	10·8
Matai	44·3	7·8
Totara (2)	31·2	10·0
Spotted Gum	65·5	9·0
Iron Bark	71·9	10·7
Blue Gum	60·9	10·6
Tallow Wood	62·7	9·4
Nah	73·6	9·3
Palu	74·4	10·2
Rani	51·5	9·0
Jak	40·7	9·0
Kumbuk	58·1	9·2
Hora	53·4	9·9

TABLE VIII.—*Compression Endwise*

Maximum Stress: lb. per sq. in.

Timber	Untreated	Creosoted		
		Griffith at 110° C.	Griffith at 150° C.	Bethell
Turpentine	9,235	9,270	8,414	10,890
Rimu	7,840	7,612	7,805	8,280
Kauri	5,407	5,307	5,347	5,582
Totara (1)	5,475	4,857	4,670	5,112
Totara (2)	5,704	5,137	4,812	5,340
Matai	8,412	7,520	6,370	8,945
Spotted Gum	10,820	8,050	5,210	11,520
Iron Bark	10,560	11,370	9,060	9,900
Blue Gum	9,770	9,450	5,825	10,050
Tallow Wood	10,640	8,650	5,830	9,825
Nah	13,207	11,352	7,504	13,227
Palu	11,337	10,390	5,772	11,352
Rani	8,516	7,085	7,675	7,142
Jak	7,430	7,512	5,601	8,059
Kumbuk	7,657	7,339	8,262	8,139
Hora	9,565	9,936	10,010	8,590

TABLE IX.—*Compression Across the Grain*

Maximum values from each group of ultimate intensity (lb. per sq. in.) and maximum compression (per cent.)

Timber	Untreated		Creosoted					
			Griffith at 110° C.		Griffith at 150° C.		Bethell	
	Stress	Comp.	Stress	Comp.	Stress	Comp.	Stress	Comp.
Turpentine	3,860	18·3	2,890	2·5	2,770	12·5	3,660	16·1
Rimu	6,890	56·3	2,160	7·0	2,540	35·6	2,860	8·4
Kauri	12,820	71·3	2,870	41·3	6,330	64·9	2,200	16·5
Totara (1)	13,500	83·7	1,340	3·3	2,730	53·5	1,560	16·8
Matai	11,650	57·5	2,035	10·6	2,790	7·5	3,325	10·7
Totara (2)	13,000	73·0	1,633	25·9	1,082	7·3	1,775	16·4
Spotted Gum	2,530	8·2	2,125	14·9	1,674	2·5	2,610	11·8
Iron Bark	3,455	9·0	3,590	4·9	1,538	3·0	3,890	7·9
Blue Gum	12,830	70·0	2,595	3·8	1,360	3·4	2,555	11·7
Tallow Wood	2,465	13·0	2,360	5·3	1,580	3·3	2,430	5·8
Nah	6,930	17·1	5,720	22·4	2,880	5·3	7,580	15·2
Palu	8,300	17·4	6,460	19·2	3,810	15·0	9,200	19·3
Rani	5,270	43·1	3,360	39·8	839	5·4	4,460	42·8
Jak	2,975	17·4	5,125	51·3	2,535	10·1	3,510	17·2
Kumbuk	10,540	54·6	3,580	9·5	1,537	4·0	4,510	20·8
Hora	2,740	16·9	2,150	7·4	2,110	6·7	2,626	16·3

TABLE X.—*Compression Across Grain*

Average intensity of stress (lb. per sq. in.) at the arbitrary "safe" load causing 3 per cent. compression

Timber	Number for each treatment	Untreated	Creosoted		
			Griffith at 110° C.	Griffith at 150° C.	Bethell
Turpentine ..	4	1,631	1,275 (50)	1,094 (50)	1,450 (0)
Rimu ..	4	1,218	919 (100)	862 (100)	987 (100)
Kauri ..	4	858	957 (80)	1,049 (70)	1,243 (40)
Totara (1) ..	4	801	1,147 (0)	989 (0)	981 (85)
Totara (2) ..	4	1,081	719 (0)	411 (40)	1,048 (26)
Matai ..	4	1,653	877 (70)	1,500 (85)	1,803 (75)
Spotted Gum	1	1,460	1,385 (0)	—	2,070 (0)
Iron Bark ..	1	2,215	2,405 (0)	1,538 (0)	2,860 (0)
Blue Gum ..	1	2,135	2,265 (5)	1,322 (100)	1,627 (5)
Tallow Wood	1	1,973	1,853 (0)	1,480 (100)	1,773 (0)
Nah	4	2,795	2,352 (0)	442 (70)	2,625 (0)
Palu	4	2,800	2,100 (4)	246 (56)	2,870 (6)
Rani ..	4	1,780	1,176 (2)	427 (60)	1,153 (0)
Jak ..	4	1,672	1,988 (0)	1,090 (0)	1,956 (0)
Kumbuk ..	4	2,050	1,611 (10)	858 (26)	2,160 (24)
Hora ..	4	1,370	1,402 (100)	933 (100)	1,136 (100)

Note.—The numbers in brackets indicate the percentage of the cross-sectional area stained by the creosote, and are each the average of four test-pieces. Owing to the variation in penetration of the creosote into different parts of any stick, there is some variation in these numbers from those given for the test-pieces in Tables IV and XI.

TABLE XI.—*Compression Across Grain* (2)

Average intensity of stress (lb. per sq. in.) at the arbitrary "failure" load causing 15 per cent. compression

Timber	Number of pieces of each treatment	Untreated	Creosoted		
			Griffith at 110° C.	Griffith at 150° C.	Bethell
Turpentine ..	4	3,296	2,397 (50)	2,130 (50)	3,387 (0)
Rimu ..	4	1,623	—	1,780 (100)	1,940 (100)
Kauri ..	4	1,492	1,685 (80)	1,655 (70)	1,652 (40)
Totara (1) ..	4	1,031	1,157 (0)	1,123 (0)	1,212 (85)
Totara (2) ..	4	1,329	1,153 (0)	—	1,360 (26)
Matai ..	4	2,811	—	—	—
Nah	4	6,297	5,720 (0)	—	7,580 (0)
Palu	4	6,716	5,770 (4)	3,810 (56)	7,450 (6)
Rani ..	4	2,246	1,895 (2)	—	1,851 (0)
Jak	4	2,375	2,955 (0)	1,563 (0)	2,528 (0)
Kumbuk ..	4	3,335	3,050 (10)	—	3,547 (24)
Hora ..	4	2,185	—	—	2,227 (100)
Blue Gum ..	1	12,830	2,595 (5)	1,360 (100)	2,555 (5)
		70%	3·8%	3·4%	11·7%
Tallow Wood	1	2,465	2,360 (0)	1,580 (100)	2,430 (0)
		13%	5·3%	3·3%	5·8%
Spotted Gum	1	2,530	2,125 (1)	1,674 (10)	2,610 (0)
		8·2%	14·9%	2·5%	11·8%
Iron Bark ..	1	3,455	3,590 (0)	1,538 (0)	3,890 (0)
		9·0%	4·9%	3·0%	7·9%

The numbers in brackets indicate the average percentage of the area stained by creosote.

In the upper part of the Table the blanks indicate that the specimen collapsed before 15 per cent. compression was reached.

All the eucalyptus hardwoods, except one untreated piece of blue gum, failed before 15 per cent. compression was reached. The ultimate stresses and total compressions for these timbers are recorded in the lower part of the Table.

TABLE XII.—*Average Shearing Stress : lb. per sq. in.*

Timber	Number for each treatment	Untreated	Creosoted		
			Griffith at 110° C.	Griffith at 150° C.	Bethell
Turpentine ..	8	1,066	570 (10)	653 (10)	763 (0)
Rimu ..	8	580	375 (75)	392 (75)	430 (100)
Kauri ..	8	456	468 (15)	403 (20)	424 (14)
Totara (1) ..	8	426	420 (0)	550 (0)	326 (30)
Totara (2) ..	8	335	393 (5)	270 (40)	493 (12)
Matai ..	8	543	673 (40)	483 (30)	677 (80)
Spotted Gum	2	998	725 (0)	438 (30)	970 (100)
Iron Bark ..	2	1,175	735 (0)	330 (100)	891 (0)
Blue Gum ..	2	694	640 (0)	276 (100)	763 (0)
Tallow Wood	2	870	591 (10)	442 (100)	917 (10)
Nah	8	1,283	805 (2)	321 (100)	1,165 (0)
Palu	8	1,577	1,262 (0)	421 (60)	1,305 (0)
Rani ..	8	825	651 (0)	427 (55)	632 (0)
Jak	8	672	639 (0)	422 (0)	699 (0)
Kumbuk ..	8	882	883 (20)	766 (50)	982 (10)
Hora ..	8	787	707 (100)	544 (100)	832 (100)

Percentage of the sheared area stained by creosote is shown by the numbers in brackets.

TABLE XIII.—*Tensile Strength of Untreated Timbers : lb. per sq. in.*

Average values from tests on three pieces of each timber

Timber	Tensile strength
Turpentine	18,280
Rimu	12,360
Kauri	16,370
Totara	8,240
Matai	7,310
Nah	26,510
Palu	19,290
Rani	20,600
Jak	7,590
Kumbuk	16,400
Hora	21,810

TABLE XIV.

Timber (1)	Hard or Soft (2)	Density (3) Lb. per cu. ft.	Increase in weight on creosoting (4) Per cent.	Area stained by creosote at middle of stick (5) Per cent.
Rimu	Soft	40·9	60	45
Kauri	,,	33·7	19	15
Totara (1) ..	,,	30·5	42	0
Totara (2) ..	,,	31·2	33	35
Matai	,,	44·3	27	50
Turpentine ..	Hard	60·7	1	0
Spotted Gum ..	,,	65·5	3	0
Iron Bark ..	,,	71·9	1	80
Blue Gum ..	,,	60·9	2	80
Tallow Wood ..	,,	62·7	2	100
Nah	,,	73·6	1	75
Rani	,,	51·5	2	45
Palu	,,	74·4	1	85
Jak	,,	40·7	3	0
Kumbuk ..	,,	58·1	5	45
Hora	,,	53·4	12	100

The percentages of stained section shown in column (5) are those given by the Griffith process at 150° C., and the percentage increases in weight in column (4) are those due to the Bethell process, since maximum effects were generally obtained by these processes respectively.

TABLE XV.

Average Results of All Tests on Untreated Timber.

Timber	Density	Bending		Compression		Tension	Shearing
		Young's Modulus	Stress at elastic limit	Endwise	Sideways at 3% compression		
	Lb. per cu. ft.	Lb. per sq. in.	Lb. per sq. in.	Lb. per sq. in.	Lb. per sq. in.	Lb. per sq. in.	Lb. per sq. in.
Totara (1) ..	30·5	1,295,000	6,495	5,475	801	—	426
Totara (2) ..	31·2	988,000	6,103	5,704	1,081	8,240	335
Kauri ..	33·7	1,012,000	5,925	5,407	858	16,370	456
Jak	40·7	1,155,000	6,575	7,430	1,672	7,590	672
Rimu ..	40·9	1,632,000	8,515	7,840	1,218	12,360	580
Matai ..	44·3	1,612,000	10,687	8,412	1,653	7,310	543
Rani ..	51·5	2,129,000	9,912	8,516	1,780	20,600	825
Hora ..	53·4	2,095,000	11,370	9,565	1,379	21,810	787
Kumbuk ..	58·1	1,543,000	8,893	7,657	2,050	16,400	882
Turpentine ..	60·7	1,670,000	8,270	9,235	1,631	18,280	1,066
Blue Gum ..	60·9	1,870,000	9,230	9,770	2,135	—	694
Tallow Wood	62·7	2,310,000	12,300	10,640	1,973	—	870
Spotted Gum	65·5	2,570,000	13,500	10,820	1,460	—	998
Iron Bark ..	71·9	2,240,000	12,900	10,560	2,215	—	1,175
Nah ..	73·6	2,419,000	13,050	13,207	2,795	26,510	1,283
Palu ..	74·4	1,995,000	12,283	11,337	2,800	19,290	1,577

TABLE XVI.

Comparative Results in Creosoting Incised and Unincised Timber.

All incisions $\frac{3}{4}$ in. deep.

Set of Experiments	Report	Distance between rows of incisions	Distance between incisions	Area covered by each incision	Av. weight of incised specimens before creosoting	Av. gain in weight during creosoting		Gain Factor
						Incised	Not incised	
		In.	In.	Sq. in.	Lb.	Lb.	Lb.	
I	(XI-17)	$1\frac{1}{2}$	$1\frac{1}{2}$	2·25	31·29	7·32	3·03	2·41
II	(XII-12)	4	$\frac{1}{2}$	2·0	27·5	6·78	2·51	2·70
		6	$\frac{1}{2}$	3·0	26·0	6·76	2·51	2·69
		8	$\frac{1}{2}$	4·0	27·2	4·77	2·51	1·90
III	(XIII-44)	2	1	2·0	25·16	9·06	3·17	2·86
IV	(XIV-44)	2	1	2·0	27·15	9·15	4·05	2·26
V	*see* p.40	2	1	2·0	47·8	7·55	2·88	2·62
VI	*see* p.40	$2\frac{1}{4}$	$\frac{3}{4}$	1·69	42·6	21·75	8·75	2·49

SECTION II

CORROSION OF STEEL AND IRON

INTRODUCTION

Selection of Materials for the Research.—In the choice of materials for this research the Committee was guided by the necessity for including a selection as representative as possible of the materials—wrought irons, ordinary steels and cast irons—ordinarily employed by engineers in constructional work. At the same time it was desired to ascertain, by the inclusion of suitable special steels, how far the use of these might be expected to reduce the wastage by corrosion now experienced.

In view of the extensive range of conditions covered by the Committee's programme the possible selection was necessarily restricted, particularly as regards the range of special steels investigated, otherwise the work entailed in carrying out the research would have been more than the Committee could undertake, and it would have been too costly. Nevertheless, it was found practicable to include three representative rolled irons, four ordinary steels, two types of cast iron, and five special steels, making a total of fourteen different materials, the behaviour of which under the wide variety of circumstances planned in the research should provide a considerable amount of useful information about the respective merits of the materials ordinarily used, and what might be possible in the way of reduction in the corrosion wastage now experienced.

The Rolled Irons.—In view of many remarkable instances of the resistance to corrosion shown by wrought iron, it was particularly necessary to include this material. For this purpose, therefore, Low Moor iron was chosen as a good representative of British manufacture, and Swedish charcoal iron was also chosen on account of its special purity. The latter material used in the present research gave the following analysis :—99·82 per cent. of iron, 0·03 per cent. of carbon, 0·03 per cent. of silicon, 0·019 per cent. of sulphur, 0·022 per cent. of phosphorus, 0·01 to 0·03 per cent. of manganese, and 0·06 per cent. of copper. It was possible, therefore, to compare a typically commercial wrought iron with the higher grade metal, Swedish charcoal iron.

The selection of irons was completed by the inclusion of a special ingot iron, the composition of which closely resembles that of Swedish iron. It had, however, during its manufacture, been in a fluid condition, and in this respect differs from both the wrought iron and Swedish charcoal iron just described, which were produced by the puddling process, and have, therefore, not been liquid, except in the form of the original cast iron from which they were prepared.

The Ordinary Steels.—The compositions of the ordinary steels were so chosen that as far as possible, within the limits of the four representatives allocated to this class of material, the effects of the ordinary variations in carbon and manganese contents, and of purity, as measured by the contents of sulphur and phosphorus, could be investigated. The manner in which this has been achieved will best be seen from an inspection of the respective analyses, the range of carbon covered being from 0·215 to 0·40 per cent., of manganese from 0·34 to 0·85 per cent., of sulphur from 0·025 to 0·10 per cent., and of phosphorus from 0·027 to 0·067 per cent.

The Special Steels.—These included two steels containing copper, two nickel steels, and chromium steel of the type ordinarily known as "stainless." The amount of copper to be added received special consideration in view of the facts known at the time regarding the effect of this element on the resistance of steel to corrosion. By numerous experiments made in America and elsewhere it had been proved that the addition of about 0·2 to 0·3 per cent. of copper had not conferred the advantages which some had claimed for it, so it was not thought that the absence of specimens containing such small percentages of copper would be felt. It seemed likely that if in this research a steel of such small percentage had been used there would probably have been no clear proof of any superiority or inferiority compared with ordinary steel. By increasing the content to 0·6 per cent., such steel was, so to speak, really hall-marked as being copper steel; therefore, any superiority or inferiority could be taken as due to the copper present. From this it can be gathered whether the addition of lower or higher percentages of copper would be of service. In view also of the lack of knowledge about the full extent to which copper might be added so as to produce beneficial results it was thought desirable to include a steel with an appreciably higher precentage than 0·6, namely, 2 per cent.

Whilst it is true that such materials as nickel steel containing 36 per cent. of nickel, or "non-rusting" steel containing high percentages of chromium, may not be generally useful in practice owing to their exceedingly high price, yet the Committee thought that the information which it was hoped would be obtained by testing them might prove of considerable value. There are, for example, parts of dock gates and other structures in which the first cost of the steel is hardly a consideration if greater resistance to corrosion can be obtained. In addition to the 36 per cent. nickel alloy, an alloy containing 3·75 per cent. of nickel was also included among the special steels.

All the wrought iron and steel specimens, except the chromium steel, were prepared in the condition "as rolled," that is, without further heat treatment.

The Cast Irons.—It was thought by the Committee, in view of the large employment of cast iron in harbour, dock and other works subject to marine corrosion, that it would be desirable to include samples of this material. Specimens were therefore selected of cold-blast cast iron and hot-blast cast iron, as representing the two principal types. Cold-blast cast iron was included as probably representing the cast iron used a generation or more ago, which, in the opinion of several members of the Committee, who have had opportunities of observing its behaviour, resists corrosion better than the cast iron produced to-day.

Additional Specimens of Low-Carbon Chromium Steel.—Subsequent to the planning of the research a modified type of chromium steel of a softer and more ductile kind was manufactured. This material was generally known as "stainless iron," which, however, is rather a misnomer, as it is essentially a steel and differs from stainless steel only in its carbon content. Whereas the "steel" may contain 0·20 to 0·40 per cent., or even as much as 0·60 per cent. of carbon, it is endeavoured in the "iron" to keep the carbon as low as possible. Usually it does not amount to more than 0·15 per cent. For convenience in this research the two types are distinguished as hard and soft grades of the non-rusting chromium steel containing from 12 to 14 per cent. of chromium. As the lower tenacity and greater ductility of the soft grade material renders it, from the mechanical point of view, more suited to the structures concerned in harbour works, the Committee considered it desirable to include specimens of this material in the research. The effect of heat treatment on the corrosion-resisting properties of these specimens of soft-grade non-rusting chromium steel was examined, and the specimens include, besides those in the "as rolled" condition, others treated by annealing, and quenching and tempering respectively.

Complete List of Materials Tested.—In the Table on p. 46 is given a complete list of all the materials tested together with the identification letters by which they have been known throughout the investigations (III-14). The whole of these materials, except the specimens M, N, P, Q and R, were prepared at the works of Messrs. Hadfields, Ltd., Sheffield, under the supervision of Sir Robert Hadfield.

Materials specially prepared for the Committee and from which the Specimens were made

Carbon Steels ...	*A and E : Medium carbon steel, low sulphur and phosphorus.
	B : Mild steel with low manganese and high sulphur and phosphorus.
	*C and F : Mild steel with 0·7 per cent. of manganese.
	D : Steel with 0·4 per cent. of carbon.
Special Steels ...	G : Mild steel with 0·6 per cent. of copper.
	H : Mild steel with 2·2 per cent. of copper.
	J : Steel with 13·5 per cent. of chromium.
	K : Steel with 3·75 per cent. of nickel.
	L : Steel with 36 per cent. of nickel.
	S T U V W X } Special soft-grade chromium steel.
Irons	M : Ingot iron.
	N : Low Moor iron.
	P : Swedish charcoal iron.
Cast Irons	Q : Hot-blast cast iron.
	R : Cold-blast cast iron.

Form of Specimens and Conditions of Exposure : (i) *Plain Bars.*—Test-specimens were prepared in the form of bars 24 in. by 3 in. by ½ in. from all the materials in the Table except the soft-grade chromium steel. The wrought-iron specimens were all cleaned of mill-scale by grinding, as also were the carbon steels A and C. All these specimens and those of the special steels except the chromium steel, J, were prepared in the "as rolled" condition without further heat treatment. The chromium steel J before machining required to be softened by a low-temperature treatment. Bars of each material were prepared for exposure for 5, 10 and 15 years as follows :—

Aerial	Above the level of high water.
Half-tide	Between the levels of high and low water.
Complete immersion...	Below the level of low water.

In order to obtain climatic variation complete sets were sent to Auckland, N.Z., Colombo, Halifax, N.S., and Plymouth.

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* Identification letters A and C were used for bars exposed with the mill-scale removed, while letters E and F were used for bars with the mill-scale attached. The thickness of metal removed by grinding did not exceed 0·0025 in. per side.

Table XVII contains a list of all the bars sent for exposure for 5, 10 and 15 years at these four stations.

Eighteen test-bars were made of the special soft-grade chromium steel (S to X). These were exposed only at Plymouth for 5 years, and were treated as follows :—

(S) as rolled, scale not removed.
(T) annealed ,, ,,
(U) annealed and pickled.
(V) annealed and polished.
(W) quenched and tempered, scale not removed.
(X) quenched, tempered and polished.

Three sets of these bars were made for exposure under aerial, half-tide and complete-immersion conditions.

(ii) *Bars in Combination.*—In order to examine the effects of corrosion on (*a*) bars when riveted or bolted together; (*b*) bars with edges in contact, and (*c*) combinations of bars of various metals in close metallic contact, the following series of specimens were sent to each of the above-mentioned four ports for exposure for 5 years :—

(1) Three sets each of bars E-L, B-Q and C-N to be placed edge to edge.

(2) Three sets of bars B and J, with rivets inserted, and of bars D, L, Q and R, with bolts inserted.

(3) Six frames riveted together, each consisting of four bars. The combinations were: two C bars with two P bars, and two J bars with two N bars.

(iii) *Special Tests.*—For exposure at Plymouth only a number of test-bars were prepared to determine (*a*) the loss of tensile strength due to corrosion in sea-water; (*b*) the amount of corrosion when exposed to fresh water; (*c*) the corrosion of chromium steel in fresh water compared with that in salt water. A number of bent bars were also exposed at this port in both fresh water and sea-water. This series consisted of :—

(1) Fourteen tensile test-bars, B, D, E, F, G, H, J, K, L, M, N, P, Q, R, for 5 years exposure in sea-water.

(2) Three sets of bars of all the materials except S to X in the Table on page 46, for exposure in fresh water for 5, 10 and 15 years.

(3) Four bars of 13·5 per cent. chromium steel, all polished, for exposure in aerial and half-tide positions, and for complete immersion in sea-water and in fresh water. These bars were exposed for 5 years (X-9).

(4)—(*a*) Twenty-seven bent bars, E, L, M, for exposure in aerial and half-tide positions and for complete immersion in sea-water.

(*b*) Nine bent bars, E, L, M, for complete immersion in fresh water.

Removal of Specimens.—After exposure for the required periods the bars were removed from their supports, freed from loosely adherent material and dried. They were then packed, protected with slaked lime, in cases, and sent to Dr. J. Newton Friend, whose complete report upon the results of the 5- and 10-year exposures follows.

CONCLUSIONS

1. The maximum differences in resistance to corrosion by the various metals were shown in the aerial and fresh-water tests. In the half-tide, and more particularly in the complete-immersion tests in sea-water, the metals behaved more alike.

2. On the whole there appeared little to choose between the wrought irons and the ordinary carbon steels used in this research in their mean resistance to the various types of corrosion studied. The carbon steels proved superior to the wrought irons in their resistance to aerial corrosion, whilst in fresh water there was nothing to choose. In the half-tide tests the wrought irons were slightly superior and in the complete-immersion tests in sea-water the wrought irons were decidedly superior to the steels.

Steel high in sulphur and phosphorus but low in manganese (0·22 per cent. C, 0·10 per cent. S, 0·07 per cent. P, 0·34 per cent. Mn) proved erratic in its resistance to corrosion.

4. Increasing the carbon content of ordinary steel from about 0·24 to 0·40 per cent. did not appear appreciably to affect the resistance of the metal against corrosion.

5. The presence of mill-scale accentuated in a marked manner the tendency to localized corrosion and pitting. This was evident under all the conditions of exposure to which the metals were exposed.

6. The cast irons resisted aerial corrosion exceedingly well, comparing favourably with the best of the alloy steels tested in this research. They also resisted fresh water reasonably well. In the half-tide and complete-immersion tests in sea-water corrosion frequently penetrated to the middle of the bars through pores and casting flaws. The extent of penetration was only ascertainable by fracture of the bars.

7. The addition of 0·6 and 2·2 per cent. of copper to mild carbon steel markedly increased the resistance of the metal to aerial and fresh-water corrosion. This advantage, however, did not appear to be maintained in the half-tide and complete-immersion tests in sea-water.

TABLE XVII.—*List of Bars Exposed to Marine Corrosion at Auckland, Colombo, Halifax and Plymouth, and additional Bars exposed at Plymouth to Marine and Fresh Water Corrosion*

Materials		Number of Bars at each Station					Number of Additional Bars at Plymouth only.					
Identification letter	Condition.	Single bars	Bars in pairs	Riveted and bolted	Frames	Total	Single bars	Tensile test-pieces	Bent Bars	Bolted Bars with asbestos washers	Frames with asbestos washers	Total
		Aerial, half-tide and complete immersion					Fresh water immersion	Marine immersion	Aerial, half-tide and marine and fresh water immersion	Aerial, half-tide and complete marine immersion		
		5, 10, 15 yr.	5 yr.	5 yr.	5 yr.		5, 10, 15 yr.	5 yr.	5, 10, 15 yr.	5 yr.	5 yr.	
A	Cleaned	3 3 3	—	—	—	9	1 1 1	1	—	—	—	4
B	As rolled	3 3 3	3	3	—	15	1 1 1	1	—	—	—	4
C	Cleaned	3 3 3	3	—	6	18	1 1 1	1	—	—	—	4
D	As rolled	3 3 3	—	3	—	12	1 1 1	1	—	—	—	4
E	,,	3 3 3	3	—	—	12	1 1 1	—	4 4 4	—	—	15
F	,,	3 3 3	—	—	—	9	1 1 1	—	—	—	—	3
G	,,	3 3 3	—	—	—	9	1 1 1	1	—	—	—	4
H	,,	3 3 3	—	—	—	9	1 1 1	1	—	—	—	4
J	Softened	3 3 3	—	3	6	18	1 1 1	1	—	3	6	13
K	As rolled	3 3 3	—	—	—	9	1 1 1	1	—	—	—	4
L	,,	3 3 3	3	3	—	15	1 1 1	1	4 4 4	—	—	16
M	Cleaned	3 3 3	—	—	—	9	1 1 1	1	4 4 4	—	—	16
N	,,	3 3 3	3	—	6	18	1 1 1	1	—	—	6	10
P	,,	3 3 3	—	—	6	15	1 1 1	1	—	—	—	4
Q	As cast	3 3 3	3	3	—	15	1 1 1	1	—	—	—	4
R	,,	3 3 3	—	3	—	12	1 1 1	1	—	—	—	4
Special Chromium Steel bars	—	—	—	—	—	—	—	—	—	—	—	22
						204						135

GRAND TOTAL
4 × 204 + 135 = 951

8. High-chromium steel of the type containing about 13·6 per cent. of chromium satisfactorily resisted atmospheric and fresh-water corrosion. In the half-tide and complete-immersion tests in sea-water the test-bars suffered serious localized corrosion with frequent perforation. This refers to bars tested both with their mill-scale on and when ground and polished.

9. The addition of 3·75 per cent. of nickel to 0·31 per cent. carbon steel enhanced markedly its resistance to aerial and fresh-water corrosion. In the half-tide and complete-immersion tests the nickel steel, however, whilst losing decidedly less in weight, manifested a tendency to deeper localized corrosion which reduced the advantage of the nickel content.

10. Steel containing 36·6 per cent. of nickel proved highly resistant to all forms of corrosion. It was the most resistant of all the materials tested. Steel of this composition also showed comparative freedom from pitting.

11. Placing dissimilar metals in contact did not lead to any pronounced results in the aerial tests. In all the other tests it was found that :—

(*a*) Ordinary mild steel in contact with wrought iron was partially preserved at the expense of the wrought iron.

(*b*) Chromium steel and high nickel steel in contact with ordinary carbon steel were protected from corrosion at the expense of the latter.

12. Cold working of the bars by bending did not lead generally to any appreciable increase in their total corrosion.

RESULTS OF THE CORROSION TESTS CARRIED OUT WITH FERROUS SPECIMENS FOR 5 AND 10 YEARS AT AUCKLAND (NEW ZEALAND), COLOMBO (CEYLON), HALIFAX (CANADA), AND PLYMOUTH (ENGLAND)

By J. Newton Friend, D.Sc., Ph.D.

THIS report co-ordinates the data obtained from the corrosion tests carried out for 5 and 10 years respectively with the ferrous metals listed in Table XVIII, at Auckland (New Zealand), Colombo (Ceylon), Halifax (Canada), and Plymouth (England). Detailed reports on the bars exposed at each of the stations, together with photographs, have already been published in the Interim Reports.* Most of the test-pieces were in the form of flat bars which were exposed separately, and which are referred to as "single bars"; in addition test-pieces were prepared of a selection of the materials, in which different metals were in contact. In general the single bars were exposed in triplicate under each of several different conditions at each station; up to the present two specimens of each metal have been dismantled after exposures of 5 and 10 years respectively. It is intended to dismantle the remainder after a total exposure of 15 years.

In comparing the results at different stations, and the results of the 5- and 10-year tests at any one station, care must be taken not to emphasize unduly minor differences in the behaviour of the metals. The rate of corrosion depends upon a wide variety of factors, not the least of which is variations in the metals themselves. This is particularly the case with cast iron (Figs. 115, 116, 117 and 118) which may, on superficial examination, appear very perfect, but which upon fracture show cavities and other internal discontinuities.

Furthermore, the possibility of mechanical damage to the bars *in situ* must not be overlooked. Such damage may stimulate localized corrosion to such an extent that all sign of the original cause may be obliterated, and the investigator may be led to attribute the behaviour to the erratic nature of the bar. This is illustrated by Figs. 52, 55, 78 and 80. Whilst the channelling on the first three bars might have been due either to corrosion pursuing a line of fault in the metal or to mechanical injury, that on the fourth bar would appear to be due to the latter cause only.

GENERAL RESULTS

Although small specimens of ferrous metals exposed to corrosion in a laboratory for short periods may show considerable divergence

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* VIII–10, 33; IX–7, 37; X–9; XIII–7, 21; XIV–8, 27.

in their rates of corrosion, even when subjected to what appear to be identical external conditions, yet any eccentricities in the metals are more likely to average themselves out in large specimens such as those now dealt with, particularly over protracted periods such as 5 and 10 years. The present results may thus be expected to have a better average value.

The results obtained with the corresponding 5- and 10-year bars at any one station show a satisfactory agreement, and indicate not only that the conditions of exposure have remained uniform throughout, but also that the specimens themselves have been well and uniformly prepared. This is evident from the curves in Figs. 16, 17 and 18, each pair showing the same general form, and in many cases showing a remarkable similarity in detail. This is particularly true for the completely immersed bars (Fig. 18), the corrosion conditions being, in these cases, probably somewhat more uniform.

At Plymouth, in addition to the ordinary single-bar tests, a single set of cleaned tensile test-bars was exposed for 5 years to complete immersion in the sea. Although the area of each test-bar was only 360 sq. cm. (56 sq. in.), compared with 823 sq. cm. (128 sq. in.) for each of the ordinary bars, the relative losses in weight of the specimens exposed in each case in a cleaned condition, the Low Moor iron being taken in each series as standard, are very similar, as the following figures taken from Table XXVI clearly show :—

	N	P	M	A	C
Single bars	100	124	132	130	157
Tensile test-bars	100	122	147	120	158

These results are very close indeed for this kind of work. The corrosion of these bars was not complicated by the presence of marine growths.

Comparison of the behaviour of similar bars at the various stations under analogous conditions shows that, apart from the eccentricities characteristic of this type of work, the bars have behaved with great uniformity.

Where comparison is possible with the results of either practical experience or other reliable researches, good general agreement occurs.

EXPERIMENTAL CONDITIONS AT THE STATIONS

The chemical analyses of the materials used in these researches are given in Table XVIII. The bars measured 60 cm. (2 ft.) in length, 7·5 cm. (3 in.) across, and 1·25 cm. (0·5 in.) in thickness. Their weights ranged from about 4·3 to 5·6 kg. (9·5 to 12·5 lb.). They were embedded in concrete at both ends to a depth of approximately 5 cm. (2 in.), the exposed area being on an average 850 sq. cm. (132 sq. in.). As this area varied slightly in the different sets of experiments, all the losses in weight have been calculated for an area of 1,000 sq. cm. (155 sq. in.), and are thus strictly comparable.

Before despatch for exposure the wrought and ingot irons, N, P, and M, mild steels A and C, and the tensile test-bars had been ground free from mill-scale; in all the other steels the mill-scale was undisturbed, and the casting " skin " was left on the cast irons.

The concrete, in which the ends of the bars were embedded for support, proved an ideal medium for the purpose; it was well made and carefully punned into position and no air holes or porous sections were left round the metals. It is very important to observe this precaution. In a few isolated cases the concrete had cracked, as at Halifax through the action of frost in March, 1926, and the bars had corroded where water had gained access. Since rust is of greater bulk than the amount of iron or steel from which it is derived, and which it replaces, considerable pressure is set up where corrosion occurs in a restricted space, as inside a crack. There is a tendency, therefore, for small cracks to widen continuously once water gains access to the metal. In every case where cracks did not develop the condition of the metal embedded in the concrete was excellent in both the 5-year and the 10-year tests. The original scratches, machine marks, and stamped letters remained as clearly and sharply defined as at the beginning of the experiments. In most cases there were clearly marked lines or channels where the metal bars had emerged from the concrete, showing that corrosion had not penetrated between the metal and the concrete. It was particularly noticeable that the cast irons had undergone no deterioration beneath the concrete levels.

Auckland (*New Zealand*).—The bars were exposed in Calliope dock, being fixed in reinforced-concrete frames made of 4 parts of graded shingle and sand to 1 part of cement. The aerial bars were exposed 9 ft. above H.W.O.S.T., the level referring to the middle of the specimens. The frames (Fig. 20) were straight and lay in an east-to-west direction so that the eastern and western faces of the bars were fully exposed to the morning and afternoon sun respectively. The upper ends of the bars were somewhat sheltered from rain and weather generally by the top member of the frame, which was 15 in. wide, a circumstance that probably accounts for the heavy scale adhering near the upper ends of many of the bars when dismantled. The bars were not appeciably wetted by spray. The mean temperature of the air is 68° F. in summer, and 60° F. in winter. The annual rainfall approximates to 44 in.

The half-tide bars were fixed at mean sea-level, namely, 6 ft. 2 in. above L.W.O.S.T., measured from the middle of the bars, and 5 ft. distant from the wharf. The spring rise and fall is 12 ft., the neap range being 6 ft. The bars were completely immersed for 42·2 per cent., and completely above water for 45 per cent. of the total time of exposure. Within a few months of exposure the bars were observed to be covered with small shell fauna, mainly small white barnacles (Fig. 27); upon dismantling after 10 years exposure the bars appeared externally to be almost entirely covered with barnacles and a very few oysters; but examination after the bars were cleaned showed that there were barnacles between the oysters and the metal, and in no case were oysters in direct contact with a bar. As the barnacles retained much moisture the half-tide bars were probably never really dry. There was a clear circulation of clean sea-water all round the frames, and no pollution occurred in the vicinity, despite the fact that fuel-oil for the Navy is discharged into tanks and naval vessels are bunkered at the wharf. Spillage is very little, any that does occur being rapidly carried away by tidal flow. Upon examination in Birmingham at the conclusion of both the 5- and 10-year tests no trace of oily or bituminous material was detected on the bars.

In the complete-immersion tests the bars were fixed with their top ends 4 ft. below L.W.O.S.T. They were exposed in the shelter of the wharf where the tidal current is very slight, probably not exceeding ¼ knot. They were 5 ft. distant from the wharf, equally exposed to corrosion, and generally not subject to erosion. The mean summer temperature of the sea is 65·5° F., the winter mean being 57° F. The salinity of the water averaged 3·46 per cent. Soon after exposure the bars became covered with shell fauna, and the dense accumulation that collected round the frames in the course of 10 years is shown in Fig. 22. It consisted of a heavy growth of oysters, large mussels, sea anemones, sponges, etc., but very little seaweed. The outstanding feature was the protection afforded by oyster-shells where these were attached with their flat side direct to the surface of the bars. Over the remaining surface of the bars marine growth was separated from the metal by a layer of soft black oxide, and broke away freely in large sections. Fig. 28 shows a group of shells removed from some of the bars after 5 years exposure.

Colombo (*Ceylon*).—All the bars were fixed in rectangular concrete frames and placed in such positions that the various specimens in each set were exposed to identical corrosion conditions. (Figs. 25 and 26.)

The aerial bars were exposed to spray from the sea. The temperature of the air ranged from 63·4° to 92·3° F., and the humidity from 75 to 81 per cent.; the rainfall averages 90 in. per annum. The conditions were such as to favour exceptional corrosion, and this is evidenced by the relatively severe losses in weight shown in Table XIX for both the 5- and 10-year sets; the losses of the wrought irons and steels are approximately ten times as great as those of the corresponding Halifax set. It is not surprising, therefore, that these bars, upon cleaning, were found to resemble those exposed to half-tide conditions more closely than was the case at any of the other stations.

In the half-tide tests, and in the complete-immersion tests, the bars were exposed to what was practically open sea, nearly free from all currents, but subject to waves and heavy swell, particularly during the south-west monsoon. There was no scouring action by sand.

No temperature data for the harbour water at Colombo are available; but in the Gulf of Manar the sea temperature ranges in the north-east monsoon from 79° to 86° F., and in the south-west monsoon from 77° to 84° F., and Colombo water temperatures are stated to be similar to these.

The salinity of the sea-water in Colombo harbour varies from 3·44 to 2·69 per cent., the higher figure prevailing from March to September, and the lower during November and December in consequence of dilution by flood water of the river Kelani. The mean salinity for the year is 3·23 per cent.

The tidal rise and fall is about 2 ft. 6 in. for ordinary spring tides, and about 1 ft. for neap tides, mean sea-water level being taken as 1 ft. 5 in. above datum, L.W.O.S.T. The bottom of the exposed portions of the bars in the half-tide tests was 3½ in. above L.W.O.S.T., and the top 1 ft. 11 in. above L.W.O.S.T. From a tidal diagram it has been calculated that, theoretically, the bars were "dry" for about 0·5 per cent. of the total time of exposure, and completely immersed for about 22 per cent. In consequence of wave-action, however, the bars were continuously wet, a condition conducive to heavy corrosion.

The bars in the complete-immersion tests were so fixed that the tops of the exposed portions were 1 ft. 6 in. below L.W.O.S.T.; they were subjected only to such currents and eddies as were initiated by wave-action on the frames and bars themselves. The marine growths on the half-tide specimens were as heavy as on those completely immersed, and the shelly material adhered tenaciously, proving exceptionally difficult to remove when the bars reached Birmingham several months after dismantling. Although traces of fuel-oil had been observed in the water from time to time they were not sufficient to affect the marine growth appreciably, and no trace of oily or bituminous material was found on the bars during cleaning and examination at Birmingham.

Halifax (*Canada*).—The aerial bars were exposed in the dockyard in rectangular concrete frames 7½ ft. (as measured from the middle of the bars) above H.W.O.S.T., in such a position that they were rarely, and then only slightly, moistened by sea spray. The air temperature ranges from — 10° to + 90° F., although these extremes are seldom reached. The rainfall is about 54 in. per annum.

The half-tide bars were placed at a mean level (as measured from the middle of the bars) of 3 ft. 6 in. above L.W.O.S.T., the neap tide rise and fall being 4½ ft., and the spring 6 ft. The bars were thus almost always wet, though possibly on a warm fine day they may have been dry for an hour or so. The salinity of the water was approximately 3 per cent. Some oil was present in the water, several of the half-tide bars being coated in patches with bituminous material. This was the only station where oil was present in the water to an appreciable extent. In 1925 the late Mr. C. E. W. Dodwell, M.Inst.C.E., directed attention to a dark-coloured incrustation on these bars which yielded on analysis the following result :—

	Per cent.
Oil easily extracted with petroleum ether	45
Oil not easily extracted as above, but readily combustible	26
Silica and iron oxide	29
	100

The possible effect of this oily incrustation on the general corrosion of the bars is discussed later in this report.

Some barnacles were found on most of the bars, but did not appear to have affected them to any appreciable extent. Some small mussels were noticed growing round the bottoms of the bars; these would help to hold moisture at those particular parts, and would thus stimulate pitting.

The completely-immersed bars were fixed at a mean level (as measured from the middle of the bars) of about 4 ft. below L.W.O.S.T., the frames containing them being so placed that the various bars would be equally exposed to eddies and currents, the speed of which never exceeded 1 knot, and was usually very much less. All the bars were subject to the same erosive action of sand. The sea temperature ranges from a rare winter minimum of 34° F. to a summer maximum of about 70° F.

During the first few years all the bars in the submerged frames were reported to have been partly covered with vegetable and animal growth, but as time progressed this growth gradually lessened. After 10 years no marine fauna was found attached to the bars although some starfish and different kinds of snails were crawling over them; they did not in general, however, remain in the same place for more than a few minutes at a time.

Plymouth (*England*).—The bars were exposed in cylindrical concrete frames (Figs. 23 and 24) at the breakwater pier. This site was chosen as being very free from fuel-oil which contaminates the ordinary harbour water, but which appears to be swept out to sea by tidal action, and does not collect near the breakwater, even at low water. Examination of the bars at Birmingham revealed no trace of oil or bituminous deposit upon them.

No data of air-temperature at the breakwater are available, but the mean summer and winter temperatures at Plymouth are given, over a period of 35 years, as 59° F. and 42° F. respectively. The rainfall is about 45 in. per annum. The breakwater lies 2 miles southwards from the shore at West Hoe, and is exposed to heavy seas, so that the aerial bars were, during heavy gales at spring tides, sprayed with sea-water, their position being exceptionally bleak, and not protected in any way from the elements. This is reflected by the generally high losses in weight of the wrought iron and carbon steel bars, as compared with the aerial specimens at Halifax and Auckland, and with the half-tide specimens at the breakwater itself. The average height of the bars, as measured from the middle of the cradle, was 6 ft. 7 in. above high-water level.

The half-tide bars were placed on the landward side of the breakwater, and were thus protected to a certain extent from the open sea. The sea at the site is exceptionally clean. Except during a short period when dredging was in progress near the pier and a small deposit of mud was found on the cradles, the latter have always been found quite clean. The tidal rise and fall is 15 ft. 7 in. for ordinary spring tides and 7 ft. 8 in. for neap tides, mean sea-level being 8 in. below Ordnance datum. The cradles rested on a concrete base 2 ft. 3 in. below Ordnance datum. From the tidal diagram it has been calculated that theoretically the single bars were " dry " for about 25 per cent. of the total time of exposure and completely immersed for about 57 per cent. of the time. In consequence of wave action all the bars were continuously wet. A few limpets collected from time to time on the bars, and probably encouraged localized corrosion, for it was observed, in the case of a special set of 11·9 per cent. chromium steels, exposed during 1924 to 1929, that, if the adhering limpets were obviously fresh, the metal beneath was either apparently uninjured or at most slightly stained, but the metal below very old shells was found to be more or less deeply pitted, the pits being filled with a black, slimy substance, presumably a hydrated oxide of iron, doubtless contaminated with other substances. It would appear, therefore, that the presence of isolated shelly growths stimulates localized corrosion much in the same way as does that of isolated patches of scale, etc.

In the complete-immersion tests in sea-water the conditions of exposure were the same for all the bars; the cradles rested on the sea-bottom, 21 ft. 7 in. below Ordnance datum. There was no erosion by sand during the exposure. Barnacles had collected on the 5-year bars intermittently, and had possibly initiated some of the pits. When dismantled the 10-year bars were thickly coated with barnacles (Fig. 70). The mean summer and winter temperatures of the sea-water are 56° F. and 50° F. respectively. The salinity of the sea-water ranges from 2·5 per cent. at the surface to 3·0–3·5 per cent. at the bottom.

The specimens exposed to complete immersion in fresh water lay at the bottom of an Admiralty concrete reservoir consisting of two chambers each 33 ft. 5 in. by 33 ft. 8 in., with a depth of water averaging 10 ft. 4 in. They were practically free from growths and fauna, and all the bars appeared to occupy equivalent positions. The reservoirs are emptied for inspection and cleaning twice a year, and the water is constantly changing as the supply is governed by a ball-valve which admits water automatically after any draw-off.

Types of Corrosion

Probably all the types of corrosion to which ferrous metals are subjected when exposed to sea action have been encountered in this research. By *corrosion* is understood the destruction of the metals through oxidation, the hydrated oxide of iron thus produced being known as *rust*. This is a porous, friable material of composition represented approximately by the chemical formula Fe_2O_3 Aq., where Aq. represents a fluctuating amount of more or less combined water. Owing to its porous nature rust offers but little, if any, protection to the underlying metal from further attack, and thus differs very materially from the mill-scale on wrought iron and steel and from the " skin " on cast iron. Mill-scale, in particular, if it could be retained intact, would afford a very efficient protection against corrosion. Actually in the case of steel it very readily becomes cracked or chipped and the steel thus exposed is rapidly attacked. As the corrosion may proceed underneath the mill-scale its extent may not be evident on a merely superficial examination of the bar, so that this type of corrosion is particularly insidious.

In describing the condition of the specimens it is convenient to give a somewhat specialized meaning to certain phrases in order to avoid repetition or lengthy explanations. The following expressions will be used strictly in accordance with the definitions given.

Corrosion is termed *widespread* when it is fairly evenly distributed over the surface considered (Figs. 30 and 44), and *localized* when it occurs in isolated patches (Figs. 91, 92 and 108), the metal being eaten out in cavities or pits. Such *pitting* assumes many forms. In the majority of the aerial tests other than those at Colombo, the entire surfaces of the metals were roughened with innumerable *pocks* (Figs. 29 and 44). These pocks may be regarded as incipient pits. A type of pitting common to specimens exposed at half-tide level or to complete immersion in the sea is shown in Figs. 56, 57, 68, 73 and 74, the cavities being circular and of various diameters and depths. When first starting pits may be no larger than the pinholes shown in Fig. 85.

The depth of pits is an extremely important feature, and the nature of the pitting is defined as follows :—

Negligible ...	Less than 0·1 mm. deep.
Shallow ...	Between 0·1 and 0·5 mm. deep.
Medium ...	Between 0·5 and 2 mm. deep.
Deep	Between 2 and 5 mm. deep.
Very deep ...	More than 5 mm. deep.

Sometimes the bar is *perforated* (Figs. 46, 79, 98 and 101), the special steels being specially subject to this form of corrosion. Usually in these cases pitting had begun at opposite points on both faces, and in due course the hollows met resulting in perforation.

Corrosion may follow the direction of the rolling of the bar during manufacture, leading to well-defined *channelling* as shown in Figs. 102 and 106.

The channels on the wrought irons and some of the carbon steels were narrow, giving rise to a *furrowed* (Fig. 31) or *fibrous* appearance (Figs. 30 and 35). In the fresh-water tests the channels followed varying directions reminiscent of worm-eaten wood. Figs. 42 and 43 illustrate this type of *vermiform* corrosion.

Cast iron is particularly susceptible to what is known as *graphitization*, being converted by oxidation into a soft greyish mass consisting of oxide of iron and graphite, the whole of which is readily cut with a penknife and feels graphitic to the touch.

METHODS OF DETERMINING THE EXTENT OF CORROSION

In order to determine quantitatively the extent to which corrosion has taken place, four different methods have been used in this research.

Loss in weight.—This is a very usual method in experimental work, though clearly incapable of use in most cases in practice, because it not only means that the specimens must be sufficiently small to be capable of being weighed accurately, but it also presupposes a knowledge of the initial weight before exposure. The results for the single bars used in this research are given in Tables XIX, XX and XXI, and are shown graphically in Figs. 16 to 19.

Dimensional Changes.—When corrosion has proceeded uniformly over the whole surfaces of the specimens, measurement of the reduction of width or thickness may give a rough idea of the relative extents to which corrosion has proceeded. This is illustrated by the results obtained with the wrought and ingot irons and carbon steels exposed for 5 years to aerial corrosion at Colombo. They had been uniformly attacked and their relative losses in weight and relative losses in thickness were as follows :—

Bar	N	P	M	B	F	C	E	A	D
Relative loss in weight ..	100	116	164	133	138	150	143	158	133
Relative loss in thickness ..	100	102	166	127	119	135	128	116	124

The two sets of figures are not identical, but they exhibit a relationship that is remarkably close for this type of work.

Depth of Pitting.—If corrosion normally proceeded uniformly over the whole area of the specimens, the losses in weight and, to a less extent, the dimensional changes, would each give most of the information required. But, unfortunately, owing to the almost universal tendency to localized corrosion these results rarely give the extent of the deterioration of the specimen sufficiently for practical purposes. Thus the 3·75 per cent. nickel steel bar K 13 lost only half as much in weight as the mild steel bar A 13 after 5 years exposure to half-tide conditions at Colombo, but it was perforated with a hole 3 cm. in diameter (Fig. 97) which would ruin it for practical purposes. Again the test-bar J (Figs. 90 and 92) lost less in weight than test-bar A, but it had suffered such severe localized corrosion as to be commercially "destroyed." It is important, therefore, to determine the extent of localized corrosion. Pits in the bars were carefully scraped clean, and their depths were determined with a spherometer reading to 0·005 mm. (0·0002 in.). After a little practice consistent results could be obtained with ease of an accuracy of the order of 0·02 mm. (0·001 in.). The advantage of this method is that it can be applied at any time, often without dismantling the specimen, and it is thus capable of use in practice. A knowledge of the previous weight or dimensions of the specimens is not necessary. The results obtained in the single-bar tests are given in Tables XXII and XXIII, while in Table XXIV the mean relative losses in weight are compared with the mean relative depths of pitting. The two sets of results have not been calculated in quite the same way. Thus the relative losses in weight are the means of the relative losses (R.L.) as given in Tables XIX, XX and XXI, and not the means of the total losses of the bars, expressed relatively to that of Low Moor iron taken as 100. In this way equal weight is given to the relative losses at all four stations, whereas by comparing the absolute losses in weight the overwhelming losses suffered by the bars exposed to aerial corrosion at Colombo would completely swamp the corresponding data for Halifax and Auckland. On the other hand the relative depths of pitting could not be satisfactorily compared for each station as in some instances (Table XXII) the standard bar N was not pitted. In Table XXIV, therefore, the details for relative depths of pitting have been taken direct from the R.P. columns in Tables XXII and XXIII.

Except in a few isolated cases which are more or less fortuitous it will be observed that the two sets of data show little or no agreement. This was to be expected and illustrates very forcibly the need for taking as many factors as possible into consideration before deciding whether or not one specimen is to be regarded as more corrodible than another.

Tensile Strength.—A mere statement of the depth of pitting, however, may not itself be sufficient. The longitudinal strength of a bar, for example, would be more seriously reduced by a series of pits running transversely than by a similar series strictly longitudinal in direction, such as, for example, the fibrous pittings of the wrought irons or the longitudinal furrows on the special steels. It is useful, therefore, to determine the influence of corrosion upon the tensile strength. This, of course, implies a knowledge of the previous strength of the bars, which in practice may not be forthcoming. The method, however, has been tried in this research. It possesses an advantage over the previous three methods in that it is able to indicate any weakness in the bar due to internal corrosion, such as that caused by porosity, which may not be noticed or detectable by other means. This is particularly the case with cast irons, to which reference is made later. A comparison of the relative corrodibilities of the metals by three of the methods used is given in Table XXV which relates to the cleaned tensile test-bars totally immersed in sea-water. The bars were of the shape shown in Fig. 90 and measured 42 cm. (16·5 in.) in length and 5 cm. (2 in.) in width at the middle, the total area exposed to sea action being 360 sq. cm. (56 sq. in.) per bar.

The relative losses in strength are given by expressing the percentage losses in maximum stress as percentages of the loss of maximum stress suffered by the Low Moor wrought iron chosen as standard (18 per cent.). The actual stresses were given in terms of tons per square inch of the original uncorroded section of the bars, thus enabling the variation in strength due to corrosion to be directly observed.

The Table shows a fairly close proportionality between the losses in strength and in weight of the wrought irons N and P and of the ingot iron M. A rough proportionality also appears between the losses in strength and in weight of steels A, C and D, bar D losing least and bar C the most. Bars J and R, however, are excellent examples of the difference between loss in strength and loss in weight. The weakness of the bar J lay in its excessive localized corrosion as shown by the depth of pitting. The weakness of the bar R, which appeared to lose less in weight than the Low Moor iron, is probably explained by its internal corrosion, to which further reference is made hereafter. The order of merit of the special steels G, H, K, and L is the same in regard to both loss in strength and loss in weight.

As was observed in discussing the results in Table XXIV there is no connection other than fortuitous coincidence between the relative losses in weight and depths of the deepest pits.

AERIAL SINGLE-BAR TESTS

Although in the aerial tests the rates of corrosion were not affected by marine growths, the bars were subjected to varying atmospheric conditions; consequently they manifest wide differences in their absolute rates of corrosion although they show encouraging agreement in their relative corrosion (Table XIX). Thus in both the 5- and 10-year sets the wrought irons N and P at Colombo lost approximately twice as much in weight as those at Plymouth, 5 times as much as at Auckland, and 10 times as much as at Halifax. The reason for this is not difficult to understand in view of the varying conditions at the four stations. The conditions may be summarized as follows :—

Station	Approx. mean temp. of air	Rainfall	Position	Total loss in weight		Ratio $\frac{\text{10-year}}{\text{5-year}}$
				5 years	10 years	
	Deg. F.	In. per annum		Gm.	Gm.	
Halifax ..	50	54	Normal	1,016	2,108	2·07
Auckland ..	64	44	Normal	2,125	5,025	2·36
Plymouth ..	50	45	Very subject to spray.	6,598	13,153	1·99
Colombo ..	80	90	,,	17,781	29,583	1·66

In the Halifax and Plymouth tests the total loss in weight is directly proportional to the duration of exposure. The proportionality is less precise for the Auckland and Colombo bars. The mean ratio for the four stations, however, is 2·0 to 1. The combined influence of an elevated air temperature, heavy rainfall, and exposure to repeated drenchings by sea spray has resulted in an excessive corrosion of the Colombo bars. In so far as mean air temperature and rainfall are concerned the station at Plymouth compares favourably with Halifax and Auckland; but the exposed position of the bars on the breakwater at Plymouth has resulted in heavy corrosion. In consequence, the Plymouth aerial bars and, to an even greater extent, the Colombo aerial bars, after exposure, closely resembled the corresponding bars exposed at half-tide level at these stations.

The conditions to which the Halifax bars were exposed may be regarded as typically aerial; but in passing from the Auckland and Plymouth series to those of Colombo, the conditions and types of corrosion steadily merge into those characteristic of half-tide conditions. It is difficult, therefore,to enumerate any special features of the bars exposed to aerial corrosion which are characteristic of them all, but yet not shared by the bars exposed at half-tide level or to complete immersion. If this is borne in mind, the following general observations appear to be justified.

Nature of Aerial Corrosion.—The type of corrosion termed pocking occurred only amongst the aerial bars. It was shown by most of the Halifax bars and some of the Auckland bars, but by only a very few of the Plymouth bars. At Colombo only the chromium steel bars, J, showed appreciable pocking. The pocks occurred in various degrees of coarseness and fineness. Typical fine pocking is shown in Fig. 44, and coarse pocking in Fig. 29; in some cases slight channelling was apparent where the series of pocks had coalesced in lines running parallel with the length of the bar. Usually the pocks were of negligible depth. None of the bars exposed at half-tide level or to complete immersion in either fresh water or sea-water showed pocking.

The pocked bars were in general the more evenly corroded; but with few exceptions the aerial bars were more uniformly corroded than the others. Even the Colombo aerial bars corroded with considerable uniformity, as shown by the fact that the relative dimensional changes of the wrought irons and carbon steels bore a striking relationship to their relative weight losses, as indicated on page 58.

The Halifax aerial bars bore shallow pits only and were less deeply pitted than the corresponding bars exposed at half-tide level. This feature is probably characteristic of the typical aerial corrosion. The pitting on the aerial bars at the other three stations was more serious, as shown in Table XXII.

Deep circular pits occurred on several bars. Pitting was most severe on the Colombo bars, three of which, namely, ingot iron (Fig. 40) and the cleaned mild carbon steels A (Fig. 64) and C (Fig. 53) were found to be perforated after an exposure of 10 years. This further emphasizes the similarity of the aerial and half-tide sets at Colombo.

At both Plymouth and Colombo the 10-year aerial bars of wrought iron and carbon steel were thickly coated on each face with stratified layers of rust approximating to the thickness of the remaining unattacked metal, as shown in Figs. 45 and 76. This had not been encountered in any of the other sets. Analysis of the rust from several of the Plymouth bars showed that it was free from organic matter; it contained traces of chloride, undoubtedly from sea spray, and a trace of copper was detected in the rust from the copper steel G. The rust was thus very pure hydrated oxide of iron. Fig. 45 shows the edge of a bar of carbon steel B with sufficient of the rust removed to lay bare the metallic edge, thus indicating the thickness of the adherent rust and illustrating its stratified nature. In Fig. 76 the metal is completely hidden and a longitudinal crack runs along the thick layer of rust on the edge of the bar. The metal itself was not cracked.

Sometimes the bars were very seriously thinned at their bottom ends by corrosion. An example is afforded by the Swedish wrought iron P 2 (Fig. 34), the edge of which, after 10 years exposure, was reduced from 0·84 to 0·60 cm. (0·33 to 0·236 in.). This thinning occurred half way across the bar (Fig. 33).

No graphitization occurred with any of the cast-iron bars exposed to aerial corrosion, and their fractures showed that in no case had corrosion penetrated beneath the surface in the single-bar tests. (Fig. 115, bar R20; Fig. 116, bars Q2, R2; Fig. 117, bars Q29, R29; Fig. 118, bars Q11, R11.) In one isolated case, namely, that of the hot-blast cast iron Q43 carrying four steel bolts, internal corrosion had occurred. The bar broke in two during cleaning and the fracture revealed the corrosion. Elsewhere the bar appeared to be in excellent condition, as was also the cold-blast cast-iron bar R43 exposed under identical conditions. There can be little doubt that in this case the internal corrosion was due to a crack or fault in the original bar, and not to normal penetration of corrosion through the metal such as occurred under the more exacting conditions at half-tide level and with complete immersion.

Examples of extreme aerial corrosion comparable with much of the corrosion undergone by bars at half-tide level are illustrated in Figs. 33, 34, 53 and 64.

Comparison of the Individual Bars.—The various metals used in this research show a considerably wider variation in their resistance to aerial corrosion, as measured by loss in weight, than to any of the other types of corrosion studied. This is evident from the following data which give the total mean relative losses of all the 5- and 10-year bars that show the greatest and least losses in each series. The data are taken from Tables XIX, XX and XXI :—

Type of Exposure	Most and least corroded bars	Mean Relative Losses	Ratio of most/least Losses
Aerial	B (Mild steel) L (36% nickel steel)	145 2	72·5
Half-tide	M (Ingot iron) A (Mild steel) L (36% nickel steel)	134 22	6·1
Complete Immersion in sea	A (Mild steel) L (36% nickel steel)	135 51	2·6
Complete Immersion in fresh water.	M (Ingot iron) L (36% nickel steel)	104 4	26·0

The most corroded aerial bars lost 72·5 times as much in weight as the least corroded bars, whereas the corresponding figure for the bars exposed at half-tide level was only 6·1, and in the complete immersion tests in sea-water the figure was only 2·6, all the bars behaving very much more alike. This is clearly shown by the curves in Fig. 19. The Low Moor wrought iron, N, proved slightly superior to the Swedish charcoal iron, as regards both loss in weight and depth of pitting.

With the exception of the specimens at Colombo and one Plymouth bar the cleaned mild steels A and C lost appreciably less in weight than the Low Moor iron, which also was cleaned before exposure; they were not, in general, more deeply pitted. They lost much less in weight and were less deeply pitted than bars E and F respectively, of the same steels but exposed with adherent scale. The beneficial effect of removing scale prior to exposure to aerial corrosion is thus clearly demonstrated.

In all the tests, except those at Colombo, mild steel B, high in sulphur and phosphorus, proved, as was expected, to be easily the most corrodible steel. This is well illustrated by the peaks in the curves in Fig. 16.

Raising the carbon content of the steels from 0·24 per cent. (F) to 0·4 per cent. (D) had no apparent effect upon the corrodibility as regards either loss in weight or pitting.

The alloy steels resisted aerial corrosion remarkably well, especially the 36 per cent. nickel steel, L, which suffered a negligible loss in weight, and remained free from pits. The J bars of 13·5 per cent. chromium steel were almost as good as the L bars. The copper steels, G and H, and the 3·75 per cent. nickel steel, K, which are strictly comparable with the mild steels E and F, offered a high resistance to corrosion, the nickel steel in particular having lost less than half as much in weight as the carbon steels and suffered much less severe pitting.

The cast irons, Q and R, were extremely resistant to corrosion, as regards both loss in weight and depth of pitting, for only in the Colombo bars was pitting observed. As already mentioned, the fractures were perfect, showing that in no case had corrosion penetrated beneath the surface.

Half-Tide Single-Bar Tests

Except possibly at Plymouth, the corrosion of the bars was complicated by marine growths, including barnacles (Figs. 21, 26 and 27) and oysters. At Halifax a further complication arose through the presence of small quantities of oil in the water. Several of the bars when being cleaned in Birmingham were found to have patches of adherent bituminous material clinging tenaciously to their surface. It is evident that such incrustations would tend to reduce corrosion by preventing access of air and water. This tendency, however, cannot have been very great, for the Halifax bars are the only sets in which the half-tide specimens lost more in weight than those exposed to aerial corrosion.

The fact that the half-tide bars at Auckland and Colombo lost less in weight than those exposed to the air might have been attributed to the protective action of barnacles and other shell fauna which, particularly at Colombo, adhered with surprising tenacity But at Plymouth, although the half-tide bars were not subject to marine growths, they also lost less severely than the aerial bars, the ratios of the losses for the two sets of bars for 5 and 10 years respectively being practically identical with those for the corresponding Colombo sets, as shown in the following Table :—

Station	Exposure A=Aerial HT=Half-tide	Total 5-year loss* Gm.	Ratio A/HT	Total 10-year loss* Gm.	Ratio A/HT
Halifax.. ..	A	1,007	0·34	1,982	0·46
	HT	3,008		4,310	
Auckland ..	A	2,101	1·21	4,774	1·77
	HT	1,741		2,697	
Plymouth ..	A	6,592	1·62	13,107	1·72
	HT	4,062		7,612	
Colombo ..	A	17,304	1·63	27,938	1·64
	HT	10,635		17,067	

* The losses of the cast irons are omitted, since in the half-tide tests they corroded internally.

Whatever influence these shelly faunæ may have had, therefore, they do not appear to have been the deciding factor determining the relative losses in weight of the aerial and half-tide bars, although they probably do exert a certain amount of protective influence.

In the half-tide tests, as in the aerial tests, the bars at the Colombo station were the most severely attacked. Next in sequence are those from Plymouth and Halifax, the Auckland bars having suffered least. Although the relative rates of corrosion at the various stations are influenced by many factors, it appears very probable that the high temperature of the air and sea normally prevailing at Colombo has exerted an important influence upon the rapid corrosion observed at that station.

As in the aerial tests, the total losses in weight of the different sets greatly increased with the duration of the exposure. These losses are not directly proportional to the duration of the exposure, though the rate of increase is generally similar throughout the four stations :—

Halifax .. $\left\{\frac{\text{10-year loss}}{\text{5-year loss}}\right. = \frac{4{,}310}{3{,}008} = 1{\cdot}40$

Auckland .. do. $= \frac{2{,}697}{1{,}741} = 1{\cdot}55$

Plymouth .. do. $= \frac{7{,}612}{4{,}062} = 1{\cdot}87$

Colombo .. do. $= \frac{17{,}067}{10{,}635} = 1{\cdot}60$

Mean ratio $= 1{\cdot}61$

Nature of the Corrosion at Half-Tide Level.—There was no pocking such as characterized many of the aerial bars, and corrosion was in general more uneven and pitting more serious. The corrosion was particularly severe at the lower ends of the bars (Figs. 32, 77 and 111) which remained wet much longer than the upper, both because of the drainage of the water from above and because of their position nearer to low-water level. The levels where the bars entered the concrete were usually well defined (Figs. 32 and 57), although occasionally corrosion had penetrated for various distances under the concrete (Figs. 77, 82 and 95), sometimes resulting in an enlargement of an identification-hole and making it look like a perforating pit (Fig. 50). Occasionally the bars were very appreciably thinned near their bottom ends (Figs. 32, 37 and 41). Pitting varied enormously in character, from numerous shallow to large circular pits (Figs. 57, 59, 78 and 96), which were often very deep. Thus the large circular pit of bar G14 (Fig. 73) had penetrated three-quarters of the way through the bar. The pit shown in Fig. 74 occurred on the opposite side of the same bar and penetrated almost half way through the bar. Sometimes the pits were mere pinholes, thus representing incipient pitting. Some bars showed oval or elongated pitting (Fig. 58). With the wrought irons, N and P, corrosion proceeded in narrow furrows down the length of the bar following the direction of rolling (Fig. 36).

The Swedish charcoal iron bars after 5 years exposure at Halifax (Fig. 35) were sprinkled with large circular pits mostly congregated near the lower end and ranging in diameter from 1·35 to 3·4 cm. (0·53 to 1·3 in.). They were not deep, and their craters were flat and showed the fibrous structure of the metal. When two very deep pits occurred at corresponding points on opposite faces of the bar, their troughs frequently met and a perforation resulted. Examples are afforded by Figs. 46, 79, 83 and 97. Fig. 98 is unusual, showing the metal to be perforated in two places close together. The edges of the bars were very liable to special localized corrosion. (Figs. 72, 78, 83, 97 and 111), the metal, particularly in the case of the chromium steel, being left at times very sharp and jagged (Fig. 84).

Graphitization of several of the cast-iron bars occurred, particularly amongst the 10-year bars, and the fractures of the bars showed that corrosion had penetrated beneath the surface.

Comparison of the Individual Bars.—Reference to Fig. 19, the Table on p. 63 and Tables XIX and XX, shows that, although the various metals differ widely in their resistance to corrosion under half-tide conditions, as measured by loss in weight, this variation is not so pronounced as in the aerial tests, but is much greater than in the complete-immersion tests in sea-water. In the aerial tests the ratio of the mean losses in weight of the most and least corroded bars is 72·5 to 1, as against only 6·1 to 1 in the half-tide tests. In so far as loss in weight is concerned the Low Moor iron, N, proved superior to the Swedish wrought iron, the ingot iron and the ordinary steels.

On the whole there was little to choose between these irons as regards pitting.

Except for the 10-year bars at Halifax, the cleaned steels, A and C, lost appreciably more in weight than the Low Moor iron, N, which also was cleaned before exposure; on the whole they were pitted to much the same extent as the wrought iron. They sometimes lost more and sometimes less in weight than the corresponding bars E and F of the same steels respectively exposed with adherent mill-scale, but they were much less deeply pitted than these. The removal of scale before exposure at half-tide level is thus distinctly advantageous.

In the Halifax tests, mild steel B, high in sulphur and phosphorus, again proved the most corrodible steel in the set. At the other stations it compared very favourably with the ordinary steels E and F as regards both loss in weight and depth of pitting, except that at Colombo the 10-year bar was perforated in the centre (Figs. 46 and 48). The erratic behaviour of this material is shown by the curve in Fig. 17. Raising the carbon content of the bars from 0·24 per cent. (F) to 0·4 per cent. (D) showed no appreciable influence upon the loss in weight or depth of pitting.

Relatively to the others the alloy steels have not resisted corrosion quite as satisfactorily as in the aerial tests. As before, the best material was the 36 per cent. nickel steel L, which lost at the most only 27 per cent. of the amount lost by the wrought iron N, whilst pitting was usually of negligible depth (Fig. 107). The 13·5 per cent. chromium steel, J, lost, on the average, much less in weight than the Low Moor iron, but it was usually badly pitted. The pits were often more or less circular (Fig. 82), but at other places the metal was attacked at the edges, sharp, jagged surfaces being left (Fig. 84) and sometimes holes (Fig. 83). The 3·75 per cent. nickel steel, K, lost but little less in weight than the wrought iron, N, and was often seriously pitted both at the lower concrete level where it was eaten away (Fig. 95) and on the general surface of the bars where deep circular pits were found (Figs. 96 and 97); in two cases the bar was perforated, once with one hole (Fig. 97) and once with two holes lying close together (Fig. 98), both specimens having been exposed at Colombo. These were the only K bars showing perforation. The copper steels behaved in a similar manner, corrosion at the concrete levels being illustrated in Figs. 71 and 77, and deep circular pits in Figs. 72, 73, 74 and 78, culminating in actual perforation in a 10-year Colombo bar (Fig. 79).

The cast irons sometimes suffered severely (Figs. 109, 110 and 111) but their losses in weight do not give an adequate idea of the extent of corrosion, since, on fracture, many of the bars showed that corrosion had penetrated beneath the surface (Figs. 115, 116, 117 and 118). For exposure to half-tide conditions, therefore, cast iron must be viewed with suspicion, and the data are not included in Tables XX, XXII and XXIV, in the sections dealing with the half-tide bars, as they are misleading.

COMPLETE-IMMERSION TESTS IN SEA-WATER

At all the stations the corrosion of the bars was complicated by marine growths. At Halifax the growth lessened as time progressed and no fauna was found attached to the 10-year bars when these were dismantled. The shells were of the barnacle and oyster types as shown in Figs. 22, 28 and 48. The shells at Colombo adhered with great tenacity and proved difficult to remove when the bars reached Birmingham some months after dismantling. It is not easy to determine to what extent the accretions retarded corrosion by mere mechanical action, or stimulated localized corrosion resulting in pitting and perforation. The bars corroded, however, at comparable rates at all four stations, although during the first 5 years at Plymouth only a few barnacles had collected intermittently on the bars. This appears to suggest that, as was indicated in the half-tide tests, the faunæ do not very seriously influence the total losses in weight of the bars as compared with certain other factors.

As in the aerial and half-tide tests, the total losses in weight of the bars greatly increased with the duration of the exposure, as is shown in the following Table :—

Halifax ...	$\left\{\frac{\text{10-year loss}}{\text{5-year loss}}\right.$	$=\frac{11,403}{5,073}$	=	2·25
Auckland ...	do.	$=\frac{7,349}{4,443}$	=	1·65
Plymouth ...	do.	$=\frac{7,843}{4,844}$	=	1·62
Colombo ...	do.	$=\frac{9,697}{5,114}$	=	1·90
		Mean ratio	=	1·85

Except at Colombo, the complete-immersion bars lost more heavily in weight than those exposed at half-tide level. The popular idea that corrosion is most severe under half-tide conditions is thus not always in accordance with the facts. The ratios of the total losses for each set are as follows :—

Station	Exposure C = Complete-Immersion HT = Half-tide	5-year loss	Ratio C/HT	10-year loss	Ratio C/HT
Halifax.. ..	C	5,073	1·69	11,043	2·56
	HT	3,008		4,310	
Auckland ..	C	4,443	2·55	7,349	2·72
	HT	1,741		2,697	
Plymouth ..	C	4,844	1·19	7,843	1·03
	HT	4,062		7,612	
Colombo ..	C	5,114	0·48	9,697	0·57
	HT	10,635		17,067	

Nature of the Corrosion under Conditions of Complete Immersion.—As with the bars exposed at half-tide level, there was no pocking such as characterized many of the aerial bars; corrosion was more uneven, and the pitting was quite as serious as in the half-tide bars as is evident from a comparison of the results in Tables XXII and XXIII. A notable difference between the complete-immersion and half-tide bars lay in the tendency towards excessive corrosion of the latter at their lower ends due to the very obvious causes already explained, whereas the completely-immersed bars showed more uniform corrosion all over. The levels where the bars entered the concrete were usually well defined (Figs. 66, 67, 69 and 75). Pitting generally was similar to that observed in the half-tide bars, ranging from the pin-holes so frequently observed in the 13·5 per cent. chromium steel to large pits of various sizes, shapes and depths, of which typical illustrations are afforded in Figs. 47, 54, 60 and 86. Honeycombing leading to perforation is shown in Fig. 87.

As in the half-tide tests, the wrought irons showed their fibrous structure, this being etched out in long furrows parallel with the direction of rolling (Figs. 30 and 31). This furrowing was also shown in the 36 per cent. nickel steel, L, exposed for 5 years at Plymouth (Fig. 106). But this was one of the tensile test-bars and had been cleaned before exposure. Usually the high-nickel steel furrowed after the manner shown in Fig. 102.

A sharp, jagged fibrous structure was occasionally shown by ordinary carbon steels (Fig. 69). In many cases the edges of the bars were severely attacked (Figs. 62, 91, 92, 113 and 114), the chromium steel being left in a sharp and jagged condition. Graphitization occurred with the cast irons, and the fractures showed that corrosion had penetrated to a serious degree beneath the metal surface.

Comparison of the Individual Bars.—Reference to Fig. 19, to the Table on p. 63 and to Tables XIX, XX and XXI shows that, although the different metals vary considerably in their resistance to the corrosive action induced by complete immersion in the sea, as measured by loss in weight, this variation is not as pronounced as in the aerial and half-tide tests. The ratio of the mean losses in weight of the most and least corroded bars is 2·6 to 1 as compared with 6·1 to 1 and 72·5 to 1 in the half-tide and aerial tests respectively. In other words the bars behaved very much more alike. This similarity of behaviour is shown also in Fig. 18, the curves for the 5- and 10-year bars respectively at each station lying much closer to one another than the corresponding curves in Figs. 16 and 17.

The two wrought irons, N and P, behaved very much alike as regards loss in weight, but the Low Moor metal, N, was, on the average, slightly less deeply pitted. There was little to choose between the irons M and P.

The cleaned mild steels A and C lost appreciably more in weight than the Low Moor iron, and pitting was of comparable depth. They lost slightly more in weight than bars E and F respectively, of the same materials, but exposed with adherent scale; this very slight disadvantage, however, was more than counterbalanced by the freedom of the cleaned steels from serious pitting (Table XXIII). Corrosion was very much more uniform and quite distinct from that experienced by the bars exposed with mill-scale, as is evident from a comparison of Figs. 51 and 66, which are typical. As in the half-tide tests, the results clearly demonstrate the beneficial effect of removing scale before exposure.

Contrary to expectations, mild steel B, high in sulphur and phosphorus, behaved quite as well in these complete-immersion tests as steels E, F and D as regards both loss in weight and depth of pitting.

Raising the carbon content of the steel from 0·24 per cent. (F) to 0·4 per cent. (D) had no appreciable effect upon the resistance to corrosion as regards either loss in weight or depth of pitting.

The alloy steels did not show so marked a superiority over the carbon steels and wrought irons as in the half-tide and aerial tests. As before, the best metal in every way was the 36 per cent. nickel steel, L, but it lost, on the average, half as much in weight as the Low Moor iron, N. It was usually furrowed in the direction of rolling (Fig. 102), on one occasion presenting an appearance like wrought iron (Fig. 106); sometimes it bore small circular pits.

The chromium steel, J, was severely attacked locally, proving itself quite unsuitable for resisting sea action (Figs. 87, 90 and 92).

The 3·75 per cent. nickel steel, K, lost appreciably less in weight than the carbon steels E and F, its pitting being comparable. The copper steels, G and H, lay intermediately. The cast irons suffered severely, and corrosion penetrated into their interiors (Figs. 115, 116, 117 and 118) as shown by their appearance on fracture. As in the half-tide tests, therefore, their losses in weight do not give an adequate expression of the extent of their corrosion. The results, for this reason, are not included in Tables XXI and XXIV, nor particulars of their depths of pitting in Tables XXIII and XXIV.

Complete-Immersion Tests in Fresh Water

These tests were carried out at one station only, namely, Plymouth. There were no disturbing influences due to fauna, etc., as in the complete-immersion tests in the sea.

The total losses in weight of the bars greatly increased with the duration of the exposure, as in the sea-action tests, but the losses are not directly proportional to the duration. The ratio of the 10-year loss to the 5-year loss is 1·53 to 1, which is somewhat lower than the lowest ratio, namely, 1·62 to 1, also at Plymouth, for the bars completely immersed in sea-water.

Nature of the Corrosion in Fresh Water.—In several respects the types of corrosion observed were different from those met with in the bars exposed to sea action. There was no pocking of the bars, and pitting was by no means so severe. The deepest pit measured was only 2·47 mm. (0·09 in.) in depth; it occurred on the 10-year bar of copper steel H, the general appearance of which steel is shown in Fig. 81. No bar was perforated by pitting. Some of the localized corrosion resembled oyster-shells (Figs. 49 and 52). Sometimes the shallow pits were furrowed in their troughs (Figs. 63) with, perhaps, a central deeper pit within (Fig. 81). There was nothing quite corresponding to these in the sea-water tests. The wrought irons, N and P, showed their characteristic furrowing and, in common with the special iron, M, and the mild steels A and C, were scored with vermiform corrosion (Figs. 42 and 43). This type of corrosion only occurred with the cleaned bars and was never observed in the aërial and complete-immersion tests in sea-water, although in the 10-year half-tide tests at Colombo one bar was marked in a somewhat similar manner. This, however, was very unusual and was confined to a relatively small patch of the metal. The 36 per cent. nickel steel was not furrowed as in the other tests, but was locally attacked in more or less oval patches of medium depth (Fig. 108). The cast irons showed a certain amount of pitting (Fig. 112) and graphitization, and the fractures (Fig. 117) showed that corrosion had penetrated beneath the surface.

Comparison of the Individual Bars.—Reference to Fig. 19 and to the Table on p. 63 shows that the different metals exhibit a far greater variation in their resistance to fresh water than to sea-water as measured by loss in weight. The ratio of the mean losses of the most and least corroded bars is 26·0 to 1, as opposed to 2·6 to 1 in the sea-water tests. This is due to the very great resistance offered by the chromium and nickel steels.

The wrought irons and the two cleaned mild steels, A and C, behaved so much alike that there is nothing to choose between them. As in the complete-immersion tests in sea-water, the cleaned metals corroded in quite a different manner from the steels exposed with adherent mill-scale, as is evident from a comparison of Figs. 42 and 43 with Figs. 52, 63 and 81. The cleaned steels lost more heavily in weight but were in general much less deeply pitted.

Mild steel B, high in sulphur and phosphorus, behaved normally. Raising the carbon content of the ordinary steel from 0·24 per cent. (F) to 0·4 per cent. (D) had no appreciable effect upon the resistance to corrosion as regards either loss in weight or depth of pitting.

The chromium, nickel and copper steels show a pronounced superiority over the other metals. As usual the best material in every way was the 36 per cent. nickel steel, L, which lost on the average only 4 per cent. of the amount lost by the Low Moor iron, N. It was not furrowed, but bore a few oval pits (Fig. 108) the maximum depth of which, in the 10-year bar, was only 1·32 mm. (0·052 in.). The chromium steel, J, withstood corrosion exceedingly well also, its mean loss in weight being only 5 per cent. of that suffered by the Low Moor iron; pitting was rare and shallow except for one pit on the 10-year bar which measured 0·78 mm. (0·031 in.). The 3·75 per cent. nickel steel, K, lost only 25 per cent. as much as the Low Moor iron, whilst the two copper steels, G and H, behaved alike, losing about 44 per cent. The general appearance of copper steel is shown in Fig. 81. The cast irons were both pitted (Fig. 112) and graphitized. Fracture showed that, just as in the sea-water tests, corrosion had penetrated beneath the surface (Fig. 117), so that the observed losses in weight and depths of pitting do not give a correct idea of the extent of corrosion. The results obtained for these bars have therefore been omitted from Tables XXI, XXIII and XXIV.

Wrought Iron versus Steel

Consideration of the results obtained with the wrought irons, N and P, and with the mild carbon steels, A and C, all of which were cleaned free from scale before exposure and are, therefore, truly comparable, indicates that on the whole the two classes of metal behaved almost equally well. This is shown, in so far as loss of weight is concerned, by the grand mean of the relative losses of the bars in the last column of the following Table, the figures of which have been abstracted from Tables XIX, XX and XXI :—

Metal	Aerial	Half-tide	Immersion in sea	Immersion in fresh water	Grand mean
N	100	100	100	100	107
P	124	125	106	102	
A	86	134	135	103	113
C	94	126	121	101	

This Table also shows that the resistance of the metals to the different types of corroding influences was not the same throughout.

In regard to aerial corrosion the steels, except at Colombo, lost appreciably less in weight than the Low Moor iron, which latter almost invariably proved slightly superior to the Swedish charcoal iron. Except at Colombo, also, the pitting was of much the same order in both cases. As already explained, the conditions at Colombo closely approximated to half-tide tests, and the exceptional behaviour of the bars at this station under aerial conditions need not be regarded as invalidating the foregoing observation.

In the fresh-water tests there was nothing to choose between the wrought irons and steels as regards either loss of weight or depth of pitting.

In both the aerial and the fresh-water tests the bars were entirely free from the disturbing actions of fauna. In the half-tide tests the steels lost 26 and 34 per cent. more in weight than the Low Moor iron whilst the Swedish iron lost almost as much as the steels. The pitting was much the same in all cases. In the complete-immersion tests in sea-water the advantage again lay decidedly with the wrought irons in so far as loss in weight is concerned, whilst the pitting was generally of the same order (Table XXIII). In both the half-tide and complete-immersion tests the wrought irons showed their fibrous structure (Fig. 39), being eaten out in narrow longitudinal furrows, whereas the steels in general tended to corrode at disconnected centres (Fig. 56). Despite the greater loss in weight of the steels in the half-tide and complete-immersion tests, it was found that when mild steel and wrought iron were placed in contact, the steel was invariably partially protected at the expense of the wrought iron. It is therefore evident that the question whether wrought irons resist corrosion more efficiently than ordinary mild carbon steels cannot be answered unless particulars are given of the nature of the corroding influence to which the metals are to be subjected.

THE CARBON STEELS

The following conclusions appear to be justified by a comparison of steels B, E, F and D, all of which were exposed with adherent scale.

Steel B, high in sulphur and phosphorus, but low in manganese, has not in every test behaved as badly as was expected. From Table XIX and the curves in Figs. 16 and 19, it is obvious that on the average it was the worst steel in its resistance to aerial corrosion. In the half-tide tests it was sometimes the worst of the carbon steels, for instance at Halifax (Fig. 17), and sometimes, as at Auckland, it was one of the best. In the complete-immersion tests in both sea-water and fresh water, metal B compared very favourably with the other steels.

Increasing the carbon content from 0·24 per cent. (F) to 0·4 per cent. (D) did not appreciably affect the extent of corrosion. This is evident from the following figures abstracted from Tables XIX, XX and XXI giving the mean relative losses of the steels at the several stations under various conditions. The grand means for all the steels are practically identical :—

Steel	Carbon per cent.	Aerial	Half-tide	Complete-Immersion		Grand mean
				in sea	in fresh water	
F	0·24	114	111	110	67	101
E	0·345	106	115	113	71	101
D	0·40	110	107	110	80	102

INFLUENCE OF MILL-SCALE

The presence of mill-scale on the specimens has been found to exert a profound influence upon the extent of corrosion and the manner in which that corrosion develops.

The wrought irons were not exposed with adherent scale. Two mild steels, A and C, were cleaned and exposed under identical conditions at all the stations along with two uncleaned steels, E and F, of exactly the same batches of metal respectively. Much of the information detailed in this section is derived from a comparison of these bars. But a further source of information lies in a comparison of the behaviour of the ordinary single bars completely immersed in sea-water and seven tensile test-bars exposed under identical conditions at Plymouth. Although the area of each tensile test-bar was only 360 sq. cm. (56 sq. in.) as compared with more than twice that area, namely, 823 sq. cm. (128 sq. in.) of each single bar, the relative losses in weight of the cleaned specimens exposed in each case are very similar, as has already been mentioned (p. 51). These are the only bars that are strictly comparable, and differences observed between the remaining uncleaned single bars and the cleaned test-bars may with fair confidence be attributed to the effect of the scale. The results are included in Tables XXV and XXVI.

Aerial Corrosion.—Except at Colombo, where the conditions, as already explained, closely resembled those at half-tide, the cleaned steels A and C usually lost appreciably less in weight than the steels E and F exposed with scale. The depth of pitting also was in general slightly less except at Colombo where both bars A (Fig. 64) and C (Fig. 53) were perforated after 10 years exposure. This, however, must be regarded as exceptional, and for general practice the removal of scale from the bars before exposure to aerial corrosion seems to be an advantage.

Half-tide Tests.—Except at Plymouth the corrosion of the bars was complicated by marine growths; nevertheless, the following generalizations appear to be justified. The mean losses in weight of the cleaned steels were slightly greater than those of the uncleaned bars, so that the aerial Colombo bars fall into line with these tests. But consideration of the results in Table XXII shows that the cleaned steels had the decided advantage of being less deeply pitted than the uncleaned steels.

There can be no doubt that the mill-scale, so long as it adheres to the metal surface, offers considerable protection against corrosion, but where cracks occur, or flakes of scale break away, corrosion proceeds locally, leading to serious pitting. This explains the difference in general appearance after exposure to corrosion between the bars that were cleaned and those not cleaned. This is well illustrated by the centre bars E and A of Figs. 61 and 67 respectively, which are typical.

As in the aerial tests, a general practice of removing scale before exposure to corrosion by the sea under half-tide conditions appears to be an advantage.

Complete Immersion in Sea-water.—In these tests the differences between the types of corrosion experienced by the cleaned and the uncleaned bars were very pronounced. The cleaned bars were relatively uniformly corroded, whereas the uncleaned bars showed severe localized corrosion at places where the mill-scale had become detached. Figs. 51, 65 and 66 are typical. Thus, although in almost every case the cleaned bars lost appreciably more in weight, this disadvantage was more than countered by the less serious pitting (Table XXIII).

As already mentioned, the exposure of the cleaned tensile bars enables a comparison to be made between the cleaned and uncleaned carbon steels B and D, and the alloy steels G, H, J, K and L. The results are collated in Table XXVI. The cleaned carbon steel test-bars B and D were less deeply pitted than the uncleaned bars, thus confirming the results with steels E and A, and F and C. All the cleaned alloy steels lost more heavily in weight than the uncleaned, the percentage differences being most pronounced with the 13·5 per cent. chromium steel, J. But the alloy steels pitted much less deeply when clean except the chromium steel, J; this metal underwent very serious localized corrosion which virtually destroyed it for all practical purposes (Figs. 90 and 92). It would thus be desirable to remove mill-scale from steels generally before exposure to sea action.

Complete Immersion in Fresh Water.—In these tests the cleaned bars lost more heavily in weight than the uncleaned; but, as before, in general, pitting was less serious. The uncleaned bars were characterized by an oyster-like corrosion (Figs. 49 and 52) between areas of still adherent scale, whereas the cleaned bars showed vermiform corrosion (Figs. 42 and 43). In these tests there were no disturbing factors due to fauna, and it seems that mill-scale should in general be removed prior to exposure in fresh water also.

COPPER STEELS

The advisability of adding small amounts of copper to steel to enhance its resistance to corrosion has been much discussed of recent years and opinions are somewhat divided. Steels G and H used in this research contained respectively 0·635 and 2·185 per cent. of copper, and were otherwise comparable with the plain carbon steel F which contained only the usual traces of copper, namely, 0·087 per cent.

The mean results obtained with these steels are, for convenience, summarized in the Table on p. 76. The losses in weight (RL) are expressed relatively to the mild carbon steel F, taken as standard, as calculated from Tables XIX, XX and XXI. The mean maximum depths of pitting are expressed in mm. The metals exposed with adherent scale belong to the single-bar tests; those which were cleaned before exposure to complete immersion in sea-water were the Plymouth tensile test-bars :—

Type of Exposure	Condition of metal surface	Carbon steel F		Steel G 0·64% Cu.		Steel H 2·2% Cu.	
		RL	Pits	RL	Pits	RL	Pits
Aerial ..	With scale	100	1·54	74	1·09	51	0·71
Half-tide ..	,,	100	2·28	74	3·11	85	*
Sea-water ..	,,	100	2·59	90	2·86	95	2·48
Fresh water	,,	100	1·63	66	1·84	64	2·21
Sea-water ..	Cleaned	100	1·21	98	0·90	84	0·62

* Perforated.

The Table shows that the addition of 0·64 and 2·2 per cent. of copper has to some extent increased the resistance of the uncleaned bars to aerial corrosion and to attack by fresh water. As regards the cleaned metals there was only one set of tests involving complete immersion in sea-water. What slight advantage there was lay with the copper steels.

CHROMIUM STEEL

In both the aerial and fresh-water tests the uncleaned 13·5 per cent. chromium steel, J, proved remarkably resistant to corrosion, losing relatively little in weight and suffering but slight pitting.

In the half-tide and complete-immersion tests in sea-water the steel corroded severely in local patches. Pin-holing (Fig. 85) and localized corrosion as seen in Figs. 82, 86 and 88 were frequent, the edges being attacked and even perforated (Fig. 83). General corrosion is seen in Figs. 84, 93 and 94. The cleaned tensile test-bar was virtually destroyed at various points after 5 years in the sea (Figs. 90 and 92). Experiments carried out with heat-treated bars of steel J and eighteen bars of 12 per cent. chromium steel containing less carbon than steel J, and exposed under various conditions at Plymouth, lead to similar conclusions (Table XXVII). When exposed to aerial corrosion, either with adherent scale, or after pickling or with a high polish, the steel is remarkably resistant, the greatest resistance being obtained when the scale is removed, although the greater loss in weight of the uncleaned bars was in part due to falling away of scale. Neither annealing nor quenching and tempering appeared to affect the extent of corrosion to an appreciable degree. In the half-tide and complete-immersion tests the bars were deeply pitted. This steel, therefore, would not appear to be suitable for structures exposed to contact with sea-water.

Nickel Steels

It has long been known that the addition of nickel to ordinary carbon steel enhances its resistance to various forms of corrosion. In general it has been found that less than 3 per cent. of nickel has relatively little effect. The uncleaned 3·75 per cent. nickel steel, K, proved markedly superior to the ordinary carbon steel F in the aerial tests, losing only a little more than one-third of the weight lost by steel F, and it was, moreover, less deeply pitted. In the fresh-water tests it also proved very resistant. At half-tide level and when completely immersed in the sea, although the losses in weight were much less than those of the corresponding mild carbon steel, the pitting was extremely serious; indeed, one bar exposed for 5 years to half-tide conditions at Colombo was completely perforated (Fig. 97) at one place, whilst a second bar after 10 years exposure was perforated in two places (Figs. 98 and 101). Typical deep pitting is seen in Fig. 96. Other examples are Figs. 95, 99 and 100. No doubt the presence of the scale contributes to the serious pitting, for the cleaned tensile test-bar (Table XXVI) exposed to complete immersion in the sea at Plymouth was not so deeply pitted as the corresponding single bar exposed with adherent scale; it lost appreciably less in weight than the cleaned mild steel tensile test-bar F, and was only slightly more deeply pitted. In conclusion it would appear that the addition of 3·75 per cent. of nickel to steel greatly enhances its resistance to atmospheric and fresh-water corrosion, and whilst it exerts a beneficial effect on steel exposed to actual contact with sea-water, particularly when the metal is cleaned free from scale, that effect is less pronounced.

The 36 per cent. nickel steel, L, proved exceptionally resistant to all forms of corrosion; in the aerial and fresh-water tests it lost only, on the average, 2 and 4 per cent. respectively of the loss experienced by the wrought iron N. Slight pitting occurred in the fresh-water tests (Fig. 108). In the half-tide and complete-immersion tests in sea-water its relative losses in weight, while greater, averaged 22 and 51 per cent. respectively of those of the wrought iron N. Usually the high-nickel steel furrowed after the manner shown in Fig. 102, when continuously immersed in sea-water. The only cleaned specimen was the tensile test-bar exposed to complete immersion in the sea at Plymouth for 5 years (Table XXVI). It was uniformly corroded all over, a fibrous structure being revealed (Fig. 106) not unlike that exhibited by the wrought irons. It was only slightly pitted, although it lost somewhat more in weight per 1,000 sq. cm. than the corresponding uncleaned single bars.

Cast irons

In the aerial tests the cast irons invariably resisted corrosion exceedingly well, in most cases comparing very favourably with the 13·5 per cent. chromium steel, J, and the 36 per cent. nickel steel, L, as regards both loss in weight and freedom from pitting. When fractured it was evident that no corrosion had penetrated beneath the surface. The two kinds of cast iron, Q and R, behaved almost equally well. What little advantage there was lay in favour of the cold-blast cast iron R.

When completely immersed in fresh water the specimens showed a little corrosion beneath the surface after 10 years (Fig. 117, bars Q 38 and R 38), so that the loss in weight does not accurately represent the whole of the deterioration of the metal. The penetration, however, was not very serious, and on the whole these metals may be regarded as having withstood corrosion reasonably well in fresh water.

In the half-tide and complete-immersion in sea-water experiments, however, the case was otherwise. Fracture of the bars showed that corrosion had in many cases penetrated very seriously into the metal, as shown by the darkened outlines in Figs. 115, 116, 117 and 118. This darkened part was very hard and extremely difficult to detach from the unattacked metal. When the bars were kept in a moist place for some months it flaked off in hard brittle cakes. Some of the bars showed definite graphitization. Clearly a determination of the loss in weight and depth of pitting can afford no reliable clue in such cases to the extent of deterioration of the metal.

In addition to corrosion proper, as these effects may be termed, it has been found that corrosion may penetrate through cracks or pores into internal casting flaws, leaving an outer casing of good metal which thus makes the bar appear thoroughly sound. This was definitely found to be the case with bar Q 53 which had been exposed for 5 years at half-tide level at Auckland, and it was probably an important contributory cause of the serious internal corrosion, unique amongst the aerial specimens, of bar Q 43 after an exposure of 5 years at Colombo. When in actual contact with sea-water, therefore, cast iron may prove very unreliable.

DISSIMILAR METALS IN CONTACT

The placing of dissimilar metals in contact is well known to stimulate electro-chemical action. The results obtained in this research are summarized in Table XXVIII, except that the results for the cast irons in the half-tide and complete-immersion tests are omitted owing to their uncertainty in consequence of internal corrosion.

The half-tide and complete-immersion tests give, as would be expected, clear indication of electro-chemical action. The results may be summarized thus :—

Placing carbon steel next to high-nickel steel preserves the latter from corrosion at the expense of the former.

Bolting the high-nickel steel or chromium steel with mild-steel bolts preserves the special steel, whilst the bolts rapidly deteriorate (Figs. 89, 103 and 104).

Riveting chromium steel with mild-steel rivets leads to rapid deterioration of the rivets with a corresponding preservation of the chromium steel.

Bolting chromium steel with mild-steel bolts to Low Moor iron preserves the chromium steel at the expense of the other metals.

Placing wrought iron and steel in contact, or bolting them together with mild-steel bolts, leads to a partial preservation of the steel at the expense of the wrought iron (Figs 36 and 38).

As would be expected, where the metals in contact are closely similar the electro-chemical effect is apparently less pronounced. Thus, the rates of corrosion of the steel bars B and D were only slightly affected by riveting and bolting respectively with mild steel rivets and bolts.

In the aerial tests the effect of contact is less pronounced, being often apparently opposite in character to that just described, and the results in different series are sometimes contradictory, probably owing to the fact that the total losses in weight were frequently small, so that small fluctuations due to other effects exert a disproportionately powerful influence. Nevertheless, the following points are worthy of attention :—

Contact of carbon steel B with hot-blast cast iron, Q, resulted in reduced loss in weight of the steel B.

In general contact between wrought iron and steel, namely, N and J, and P and C, resulted in a heavier loss in the steel.

The cast irons, Q and R, in contact with mild-steel bolts experienced an enhanced loss in weight.

In eleven cases out of seventeen the corrosion of the nickel and chromium alloy steels L and J increased when they were in contact with wrought iron or steel. In the remaining six cases the reverse was the case.

The use of asbestos washers and pads to prevent electro-chemical action between dissimilar ferrous bars and between bars and nuts and bolts had no detectable influence on the results. On the other hand, in the Committee's tests with painted plates at Southampton, the employment of felt or woollen washers soaked in tar apparently proved efficacious in preventing electro-chemical action between the plates and the nuts and bolts with which they were attached to the frames.

BARS BENT AT RIGHT ANGLES

These bars had been bent cold so that the outer face was stretched and the inner face compressed at the bend. The relative losses in weight of the bent bars, the losses of the corresponding bars in the single-bar tests being taken as 100, are as follows :—

Metal	Aerial		Half-tide		Complete-Immersion			
					Sea-water		Fresh water	
	5-yr.	10-yr.	5-yr.	10-yr.	5-yr.	10-yr.	5-yr.	10-yr.
E Medium carbon steel (uncleaned)	61	59	138	112	104	83	112	97
L 36% nickel steel (uncleaned)	95	67	117	91	100	85	80	147
M Ingot iron (cleaned) ..	64	72	112	96	90	95	100	89

Although the results in the foregoing Table appear to indicate that cold working has resulted in a decrease in corrosion in the specimens exposed to aerial corrosion, the fact that the bent bars were fixed in the middles of the frames, and thus occupied sheltered positions, makes it unsafe to conclude that cold working has increased the resistance of these bars to corrosion. The 36 per cent. nickel steel showed a fibrous structure on the outer surface of the bend (Fig. 105).

The results obtained with the bars exposed at half-tide level and to complete immersion in both sea-water and fresh water are irregular and indecisive.

TABLE XVIII.—*Chemical Composition of the Bars.*

Bar	Metal	Condition	Chemical Analyses (Mean values): Per cent.							
			C	Si	S	P	Mn	Cr	Ni	Cu
N	Low Moor wrought iron	Cleaned ..	0·015	0·145	0·0125	0·1135	0·02	—	—	0·021
P	Swedish charcoal iron..	,, ..	0·03	0·03	0·019	0·022	0·02	—	—	0·063
M	Ingot iron	,, ..	0·035	0·035	0·033	0·0175	0·065	—	—	0·042
B	Mild steel, high S & P	With scale ..	0·215	0·17	0·103	0·067	0·34	—	—	0·072
F	Mild steel, 0·7% Mn. ..	,, ..	0·24	0·16	0·063	0·048	0·68	—	—	0·087
C	,, ,, ..	Cleaned ..								
E	Mild steel, low S & P ..	With scale ..	0·345	0·20	0·025	0·027	0·715	—	—	0·076
A	,, ,, ..	Cleaned ..								
D	0·4% carbon steel ..	With scale ..	0·40	0·20	0·049	0·045	0·85	—	—	0·048
G	Mild steel, 0·635% Cu.	With scale ..	0·21	0·14	0·043	0·046	0·945	—	—	0·635
H	,, 2·185% Cu.	,, ..	0·225	0·14	0·034	0·041	0·91	—	—	2·185
J	13·5% Cr. steel ..	,, ..	0·36	0·22	—	—	0·13	13·57	—	—
K	3·75% Ni. steel ..	,, ..	0·31	0·18	0·029	0·038	0·54	—	3·75	—
L	36·55% Ni. steel ..	,, ..	0·12	0·09	—	—	0·87	—	36·55	—
Q	Hot-blast cast iron ..	As cast ..	*1·01 †1·86	2·34	0·104	0·848	0·27	—	—	—
R	Cold-blast cast iron ..	As cast ..	*0·76 †2·65	1·73	0·067	0·478	0·735	—	—	—

* Combined carbon. † Graphite.

TABLE XIX.—*Losses in Weight, expressed as Grams per 1,000 sq. cm., of Single Bars exposed for 5 and 10 years respectively, to Aerial Corrosion, together with their Losses relative to Low Moor Iron as Standard.*

Bar	Metal	Condition	Halifax				Auckland				Plymouth				Colombo				Mean Relative Corrosion	Remarks
			5 Years		10 Years		5 Years		10 Years		5 Years		10 Years		5 Years		10 Years			
			Loss	R.L.*	Loss	R.L.	Loss	R.L.	Loss	R.L.	Loss	R.L.	Loss	R.L.	Loss	R.L.	Loss	R.L.		
			19†	19	20	20	3	3	2	2	28	28	29	29	10	10	11	11		
N	Low Moor wrought iron	Cleaned	119	100	198	100	219	100	425	100	569	100	856	100	1,088	100	1,900	100	100	Consistently the better wrought iron.
P	Swedish charcoal iron..	,,	119	100	251	127	267	122	588	138	799	140	1,048	122	1,262	116	2,325	122	123	
M	Ingot iron	,,	117	98	182	92	332	151	591	139	807	142	1,484	173	1,780	164	2,750	145	138	
B	Mild steel, high S & P.	With scale	137	115	220	111	262	120	945	222	854	150	1,659	194	1.441	133	2,238	118	145	Unusually erratic. The worst bar in set.
F	Mild steel, 0·7% Mn. ..	,,	103	87	187	95	150	69	399	94	784	138	1,453	170	1,496	138	2,315	122	114	
C	,, ,, ..	Cleaned	59	50	162	82	164	75	343	81	279	49	1,119	131	1,630	150	2,566	135	94	
E	Mild steel, low S & P...	With scale	84	71	168	85	172	79	399	94	630	111	1,265	148	1,560	143	2,282	120	106	
A	,, ,, ..	Cleaned	61	51	162	82	136	62	244	57	201	35	746	87	1,716	158	2,900	153	86	
D	0·4% carbon steel ..	With scale	82	69	162	82	203	93	378	89	766	135	1,405	164	1,444	133	2,181	115	110	
G	Mild steel, 0·635% Cu.	With scale	53	45	117	59	79	36	214	50	490	86	1,311	153	1,379	127	2,246	118	84	
H	,, 2·185% Cu.	,,	39	33	89	45	52	24	111	26	278	49	665	78	1,204	111	1,922	101	58	
J	13·57% Cr. steel ..	,,	9	8	16	8	15	7	22	5	17	3	13	1·5	123	11	162	9	7	Virtually equal to L.
K	3·75% Ni. steel ..	,,	23	19	61	31	44	20	101	24	109	19	69	8	1,172	108	2,127	112	43	
L	36·55% Ni. steel ..	,,	2·3	1·9	7·3	3·7	6	2·8	14	3·4	9	1·6	14	1·7	9	0·8	24	1·3	2	Uniformly the most resistant bar.
Q	Hot-blast cast iron ..	As cast	3·5	3·0	117	59	16	7	169	40	0	0	22	2·5	304	28	715	38	22	Fractures perfect. No internal corrosion.
R	Cold-blast ,, ..	,,	5·6	4·7	9·4	4·8	8	3·7	82	19	6	1	24	2·8	173	16	930	49	13	
	Total Loss in Weight		1,016·4		2,108·7		2,125		5,025		6,598		13,153		17,781		29,583			

* R.L. denotes relative loss. † This horizontal row denotes the identification number of the test-bar.

TABLE XX.—*Losses in Weight, expressed as Grams per 1,000 sq. cm., of Single Bars exposed for 5 and 10 years respectively to Half-tide Conditions, together with their Losses relative to Low Moor Iron as Standard.*

Bar	Metal	Condition	Halifax				Auckland				Plymouth				Colombo				Mean Relative Corrosion
			5 Years		10 Years		5 Years		10 Years		5 Years		10 Years		5 Years		10 Years		
			Loss	R.L.	Loss	R.L.	Loss	R.L.	Loss	R.L.	Loss	R.L.	Loss	R.L.	Loss	R.L.	Loss	R.L.	
			22	22	23	23	6	6	5	5	31	31	32	32	13	13	14	14	
N	Low Moor wrought iron	Cleaned	165	100	321	100	140	100	250	100	332	100	638	100	631	100	1,234	100	100
P	Swedish charcoal iron . .	,,	264	160	406	127	186	133	309	124	389	117	863	135	649	103	1,196	97	125
M	Ingot iron	,,	304	184	445	139	212	151	310	124	412	124	985	154	677	107	1,050	85	134
B	Mild steel, high S & P.	With scale	522	316	609	190	102	73	116	47	300	90	459	72	706	112	1,137	92	124
F	Mild steel, 0·7% Mn. . .	,,	331	201	377	118	123	88	197	79	270	81	492	77	900	143	1,243	101	111
C	,, ,, . .	Cleaned	214	130	308	96	231	165	290	116	457	138	790	124	770	122	1,407	114	126
E	Mild steel, low S & P. . .	With scale	270	164	317	99	118	84	210	84	238	71	446	70	1,288	204	1,792	145	115
A	,, ,, . .	Cleaned	172	104	261	81	214	153	302	121	448	135	789	124	1,262	200	1,941	157	134
D	0·4% carbon steel . .	With scale	323	196	379	118	104	74	160	64	296	89	441	69	829	131	1,364	111	107
G	Mild steel, 0·635% Cu.	With scale	144	87	287	89	63	45	137	55	289	87	441	69	844	134	1,135	92	82
H	,, 2·185% Cu.	,,	162	98	340	106	103	73	135	54	227	68	534	84	945	150	1,557	126	95
J	13·57% Cr. steel . .	,,	50	30	52	16	50	36	135	54	112	34	215	34	317	50	625	51	38
K	3·75% Ni. steel . .	,,	48	29	137	43	71	51	111	44	203	61	359	56	651	103	1,133	92	60
L	36·55% Ni. steel . .	,,	39	23	71	22	24	17	35	14	89	27	160	25	166	26	253	21	22
	Total Loss in Weight		3,008		4,310		1,741		2,697		4,062		7,612		10,635		17,067		

TABLE XXI.—*Losses in Weight, expressed as Grams per* 1,000 *sq. cm., of Single Bars exposed for* 5 *and* 10 *years to Complete Immersion in Sea-water and Fresh Water, together with their Losses relative to Low Moor Iron as Standard.*

Bar	Metal	Condition	Sea-Water																	Fresh Water				
			Halifax				Auckland				Plymouth				Colombo				Mean Relative Corrosion	Plymouth				Mean Relative Corrosion
			5 Years		10 Years		5 Years		10 Years		5 Years		10 Years		5 Years		10 Years			5 Years		10 Years		
			Loss	R.L.	Loss	R.L.	Loss	R.L.	Loss	R.L.	Loss	R.L.	Loss	R.L.	Loss	R.L.	Loss	R.L.		Loss	R.L.	Loss	R.L.	
			25	25	26	26	9	9	8	8	34	34	35	35	16	16	17	17		37	37	38	38	
N	Low Moor wrought iron	Cleaned	421	100	965	100	313	100	487	100	319	100	532	100	354	100	630	100	100	340	100	444	100	100
P	Swedish charcoal iron . .	,,	422	100	1,083	112	314	100	459	94	396	124	638	120	303	86	690	110	106	340	100	460	104	102
M	Ingot iron	,,	445	106	1,067	111	332	106	488	100	423	132	582	109	383	108	616	98	109	336	99	479	108	104
B	Mild steel, high S & P.	With scale	383	91	877	91	346	111	583	120	325	102	513	96	399	113	805	128	107	216	64	403	91	78
F	Mild steel, 0·7% Mn. . .	,,	371	88	772	80	347	111	618	127	410	129	601	113	393	111	766	122	110	206	61	319	72	67
C	,, ,, . .	Cleaned	364	86	822	85	386	123	655	135	501	157	666	125	439	124	830	132	121	340	100	453	102	101
E	Mild steel, low S & P. . .	With scale	371	88	905	94	341	109	569	117	363	114	611	115	459	130	841	134	113	214	63	345	78	71
A	,, ,, . .	Cleaned	421	100	874	91	456	146	782	161	414	130	717	135	566	160	994	158	135	354	104	453	102	103
D	0·4% carbon steel . .	With scale	362	86	815	84	377	120	537	110	368	115	563	106	453	128	829	132	110	236	69	400	90	80
G	Mild steel, 0·635% Cu.	With scale	344	82	760	79	317	101	582	119	343	108	557	105	330	93	639	101	99	107	32	242	55	44
H	,, 2·185% Cu.	,,	351	83	890	92	308	99	624	128	354	111	517	97	393	111	678	108	104	109	32	239	54	43
J	13·57% Cr steel . .	,,	216	51	460	48	210	67	327	67	130	41	479	90	225	64	462	73	63	15	4	27	6	5
K	3·75% Ni. steel . .	,,	336	80	649	67	258	82	441	91	296	93	513	96	301	85	625	99	87	66	19	132	30	25
L	36·55% Ni. steel . .	,,	266	63	464	48	138	44	197	41	202	63	354	67	116	33	292	46	51	11	3	18	4	4
	Total Loss in Weight		5,073		11,403		4,443		7,349		4,844		7,843		5,114		9,697			2,890		4,414		

TABLE XXII.—*Deepest Pits, expressed in Mm., in Single Bars exposed to Aerial Corrosion and to Half-tide Conditions, respectively, together with their Relative Depths of Pitting.*

Bar	Metal	Condition	Aerial												Half-tide											
			5 Years						10 Years						5 Years						10 Years					
			HX.	†NZ.	PL.	CO.	Mean	R.P.*	HX.	NZ.	PL.	CO.	Mean	R.P.	HX.	NZ.	PL.	CO.	Mean	R.P.	HX.	NZ.	PL.	CO.	Mean	R.P.
			19	3	28	10			20	2	29	11			22	6	31	13			23	5	32	14		
N	Low Moor wrought iron	Cleaned	—	1·12	1·24	1·23	0·90	100	—	—	1·25	1·34	0·65	100	3·98	—	0·74	—	1·18	100	0·47	0·42	0·93	1·87	0·92	100
P	Swedish charcoal iron..	,,	—	1·74	1·10	1·36	1·05	117	—	—	2·10	2·77	1·22	188	4·09	—	0·99	1·71	1·70	144	0·79	0·32	0·83	1·76	0·93	101
M	Ingot iron	,,	—	1·89	—	1·59	0·87	97	—	—	—	‡	‡	—	2·94	0·25	1·09	2·00	1·57	133	0·67	0·52	—	1·38	0·64	70
B	Mild steel, high S & P.	With scale	0·84	1·65	—	1·46	0·99	110	1·52	—	0·80	2·68	1·25	192	1·23	0·81	2·73	5·63	2·60	220	0·84	0·1	1·94	‡	‡	—
F	Mild steel, 0·7% Mn...	,,	—	0·97	0·59	4·56	1·53	170	—	1·78	3·20	1·20	1·55	238	3·10	0·39	1·22	5·30	2·50	212	0·51	0·1	1·89	5·69	2·05	223
C	,, ,, ..	Cleaned	0·43	—	0·53	1·68	0·66	73	—	1·96	0·48	‡	‡	—	1·02	—	0·99	0·74	0·69	59	0·65	—	—	2·48	0·78	85
E	Mild steel, low S & P...	With scale	0·43	1·67	0·65	1·37	1·03	114	—	2·35	0·80	2·04	1·30	200	5·10	0·59	1·73	4·56	3·00	254	0·76	0·27	2·11	7·5	2·66	289
A	,, ,, ..	Cleaned	—	0·63	0·29	2·17	0·77	86	—	—	1·25	‡	‡	—	2·52	0·55	1·13	1·97	1·54	130	0·55	0·25	1·22	1·71	0·93	101
D	0·4% carbon steel ..	With scale	—	1·66	1·09	1·67	1·11	123	—	2·12	1·18	1·65	1·24	191	4·73	0·69	1·04	2·30	2·19	186	0·95	0·73	1·56	4·02	1·82	198
G	Mild steel, 0·635% Cu.	With scale	—	0·87	0·75	1·77	0·85	94	—	—	3·18	2·09	1·32	203	4·18	0·72	2·25	5·09	3·06	259	0·82	0·44	2·09	9·3	3·16	343
H	,, 2·185% Cu.	,,	—	—	1·43	1·31	0·69	77	—	—	1·16	1·73	0·72	111	4·72	0·74	1·93	4·41	2·95	250	0·57	0·42	2·15	‡	‡	—
J	13·57% Cr. steel ..	,,	—	—	—	—	—	0	—	0·33	—	0·51	0·21	32	1·19	0·63	0·67	6·50	2·25	191	1·05	—	1·62	3·2	1·47	160
K	3·75% Ni. steel ..	,,	0·39	—	0·54	1·19	0·53	59	—	1·92	—	1·85	0·94	145	1·09	0·95	1·62	‡	‡	—	0·68	1·08	2·65	‡	‡	—
L	36·55% Ni. steel ..	,,	—	—	—	—	—	0	—	—	—	—	—	0	0·80	—	—	1·73	0·63	54	0·27	—	—	0·50	0·19	21
Q	Hot-blast cast iron ..	As cast	—	—	—	—	—	0	—	—	—	1·15	0·29	45												
R	Cold-blast ,, ..	,,	—	—	—	—	—	0	—	—	—	1·34	0·34	52												

* R.P. denotes Relative pitting. † N.Z. denotes Auckland. ‡ Bar perforated.

TABLE XXIII.—*Deepest Pits, expressed in Mm., in Single Bars exposed to Complete Immersion in Sea-water and Fresh Water respectively, together with their Relative Depths of Pitting.*

Bar	Metal	Condition	Sea-Water														Fresh Water			
			5 Years						10 Years						Tensile Test-Bars*		5 Years		10 Years	
			HX.	NZ.	PL.	CO.	Mean	R.P.	HX.	NZ.	PL.	CO.	Mean	R.P.	PL.	R.P.	PL.	R.P.	PL.	R.P.
			25	9	34	16			26	8	35	17					37		38	
N	Low Moor wrought iron	Cleaned	1·02	1·52	0·92	1·85	1·33	100	2·00	0·67	0·89	1·50	1·27	100	0·43	100	0·92	100	1·01	100
P	Swedish charcoal iron..	,,	—	1·29	0·75	4·85	1·72	129	1·83	1·74	1·19	2·79	1·89	149	1·08	251	0·92	100	0·63	62
M	Ingot iron	,,	0·60	2·19	1·88	5·03	2·43	183	1·96	0·66	—	3·30	1·48	116	0·78	181	1·20	130	1·06	105
B	Mild steel, high S & P.	With scale	1·81	2·28	2·05	2·45	2·15	162	1·25	2·23	2·79	4·05	2·58	203	1·45	337	1·41	153	1·88	186
F	Mild steel, 0·7% Mn...	,,	1·52	2·32	3·13	3·15	2·53	190	1·22	2·36	2·52	4·45	2·64	208	—	—	1·66	180	1·60	158
C	,, ,, ..	Cleaned	1·40	0·44	0·69	1·03	0·89	67	2·79	1·38	0·85	1·61	1·66	131	1·21	281	0·92	100	1·98	196
E	Mild steel, low S & P...	With scale	1·86	2·79	1·72	2·76	2·28	171	1·44	3·29	2·70	4·08	2·88	227	—	—	2·01	218	1·90	188
A	,, ,, ..	Cleaned	0·76	0·62	1·34	1·17	0·97	73	1·07	0·68	0·90	1·97	1·16	91	1·37	318	0·84	91	0·89	88
D	0·4% carbon steel ..	With scale	0·97	3·68	2·14	6·0	3·20	241	1·88	3·28	2·93	7·35	3·86	304	0·52	121	1·64	178	1·75	173
G	Mild steel, 0·635% Cu.	With scale	2·25	2·50	2·82	3·01	2·65	200	2·09	2·11	2·64	5·44	3·07	242	0·90	209	1·77	192	1·91	189
H	,, 2·185% Cu.	,,	0·79	3·19	1·73	3·33	2·26	170	1·82	2·67	1·37	4·92	2·70	213	0·62	144	1·95	212	2·47	245
J	13·57% Cr. steel ..	,,	3·20	1·40	0·83	6·5	2·98	224	†	3·37	1·76	2·44	†	—	2·74	637	—	0	0·78	77
K	3·75% Ni. steel ..	,,	1·74	2·71	3·23	4·42	3·03	228	1·62	4·27	3·08	4·43	3·35	264	1·70	395	1·47	160	2·40	238
L	36·55% Ni. steel ..	,,	1·90	1·19	1·28	1·38	1·44	108	2·49	0·94	—	3·13	1·64	129	0·59	137	1·08	118	1·32	131

* All surfaces cleaned before exposure.

† Bar perforated.

TABLE XXIV.—*Comparison of the Mean Relative Losses in Weight in the Single-Bar Tests with the Relative Depths of Pitting.*

Bar	Metal	Condition	Aerial				Half-Tide				Sea-Water				Fresh Water			
			5 Years		10 Years		5 Years		10 Years		5 Years		10 Years		5 Years		10 Years	
			R.L.*	R.P.†	R.L.	R.P.	R.L.	R.P.	R.L.	R.P.	R.L.	R.P.	R.L.	R.P.	R.L.	R.P.	R.L.	R.P.
N	Low Moor wrought iron	Cleaned	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
P	Swedish charcoal iron . .	,,	120	117	127	188	128	144	121	101	103	129	109	149	100	100	104	62
M	Ingot iron	,,	139	97	137	‡	142	133	126	70	113	183	105	116	99	130	108	105
B	Mild steel, high S & P.	With scale	130	110	161	192	148	220	100	‡	104	162	109	203	64	153	91	186
F	Mild steel, 0·7% Mn. . .	,,	108	170	120	238	128	212	94	223	110	190	111	208	61	180	72	158
C	,, ,, . .	Cleaned	81	73	107	‡	139	59	113	85	123	67	119	131	100	100	102	196
E	Mild steel, low S & P. . .	With scale	101	114	112	200	131	254	100	289	110	171	115	227	63	218	78	188
A	,, ,, . .	Cleaned	77	86	95	‡	148	130	121	101	134	73	136	91	104	91	102	88
D	0·4% carbon steel . .	With scale	108	123	113	191	123	186	91	198	112	241	108	304	69	178	90	173
G	Mild steel, 0·635% Cu.	With scale	74	94	95	203	88	259	76	343	96	200	101	242	32	192	55	189
H	,, 2·185% Cu.	,,	54	77	63	111	97	250	93	‡	101	170	106	213	32	212	54	245
J	13·57% Cr. steel . .	,,	7	0	6	32	38	191	39	160	56	224	70	‡	4	0	6	77
K	3·75% Ni. steel . .	,,	42	59	44	145	61	‡	59	‡	85	228	88	264	19	160	30	238
L	36·55% Ni. steel . .	,,	2	0	3	0	23	54	21	21	51	108	51	129	3	118	4	131
Q	Hot-blast cast iron . .	As cast	10	0	35	45												
R	Cold-blast ,, . .	,,	6	0	19	52												

* R.L. denotes Relative losses in weight. † R.P. denotes Relative depth of pitting. ‡ Bar perforated.

TABLE XXV.—*The Relative Corrodibilities of the Materials of the Cleaned Tensile Test-Bars as determined by their Relative Losses of Strength, Relative Losses in Weight and Relative Depths of Pitting.*

Bar	Metal	Relative losses of Strength	Relative losses in Weight	Relative depths of Deepest Pits
N	Low Moor Iron	100	100	100
P	Swedish charcoal iron	117	122	251
M	Ingot iron	133	147	181
B	Mild steel, high S & P	89	120	337
C or F	Mild steel 0·7% Mn.	133	158	281
A or E	Medium carbon steel, low S & P	100	120	319
D	0·4% carbon steel	89	114	121
G	Mild steel, 0·635% Cu.	117	154	209
H	Mild steel, 2·185% Cu.	106	133	144
J	13·5% chromium steel	156	109	637
K	3·75% nickel steel	61	118	396
L	36·55% nickel steel	56	76	137
Q	Hot-blast cast iron	—	72	389
R	Cold-blast cast iron	122	76	309

TABLE XXVI.—*Losses in Weight, expressed in Grams per 1,000 sq. cm., of Single Bars Exposed with and without Adherent Scale and of Cleaned Tensile Test-Bars after 5 years immersion in the Sea at Plymouth, together with their Maximum Depths of Pitting, expressed in Mm.*

Bar	Metal	Single-Bar Tests				Tensile Test-Bars (cleaned)		
		Condition	Loss in weight	Relative loss	Deepest Pits	Loss in weight	Relative loss	Deepest Pits
N	Low Moor wrought iron	Cleaned ..	319	100	0·92	363	100	0·43
P	Swedish charcoal iron ..	,, ..	396	124	0·75	445	122	1·08
M	Ingot iron	,, ..	423	132	1·88	536	147	0·78
C	Mild steel, 0·7% Mn. ..	,, ..	501	157	0·69	573	158	1·21
A	Mild steel, low S & P ..	,, ..	414	130	1·34	435	120	1·37
B	Mild steel, high S & P ..	With scale	325	102	2·05	436	120	1·45
F	Mild steel, 0·7% Mn. ..	,,	410	129	3·13	573	158	1·21
E	Mild steel, low S & P ..	,,	363	114	1·72	435	120	1·37
D	0·4% Carbon steel ..	,,	368	115	2·14	415	114	0·52
G	Mild steel, 0·635% Cu.	With scale	343	108	2·82	559	154	0·90
H	,, 2·185% Cu.	,,	354	111	1·73	483	133	0·62
J	13·5% Chromium steel	,,	130	41	0·83	398	109	2·74
K	3·75% Nickel steel ..	,,	296	93	3·23	427	118	1·70
L	36·55% Nickel steel ..	,,	202	63	1·28	276	76	0·59

TABLE XXVII.—*Losses in Weight and Maximum Depths of Pitting of Eighteen Soft-Grade Steel Bars.*

Classification Letter	Treatment of Bar	Condition of surface	Aerial		Half-tide		Completely immersed	
			Loss in weight	Deepest pits	Loss in weight	Deepest pits	Loss in weight	Deepest pits
			Grams	Mm.	Grams	Mm.	Grams	Mm.
S	As rolled	With scale	4·0	—	31·3	0·5	121·6	1·09
T	Annealed..	,,	2·6	—	30·7	1·52	152·0	5·12
U	,, ...	Pickled ..	1·1	—	10·4	2·92	170·1	*
V	,, ...	Polished	2·2	—	20·8	2·8	188·0	*
W	Quenched and tempered	With scale	10·8	—	18·8	3·65	121·8	5·9
X	,, ,, ...	Polished	1·1	—	7·0	3·34	156·1	4·40

	Carbon	Silicon	Sulphur	Phosphorus	Manganese	Chromium	
These bars had the following composition	0·12	0·53	0·042	0·014	0·21	11·90	per cent.

* Perforated.

TABLE XXVIII.—*Dissimilar Metals in Contact.*

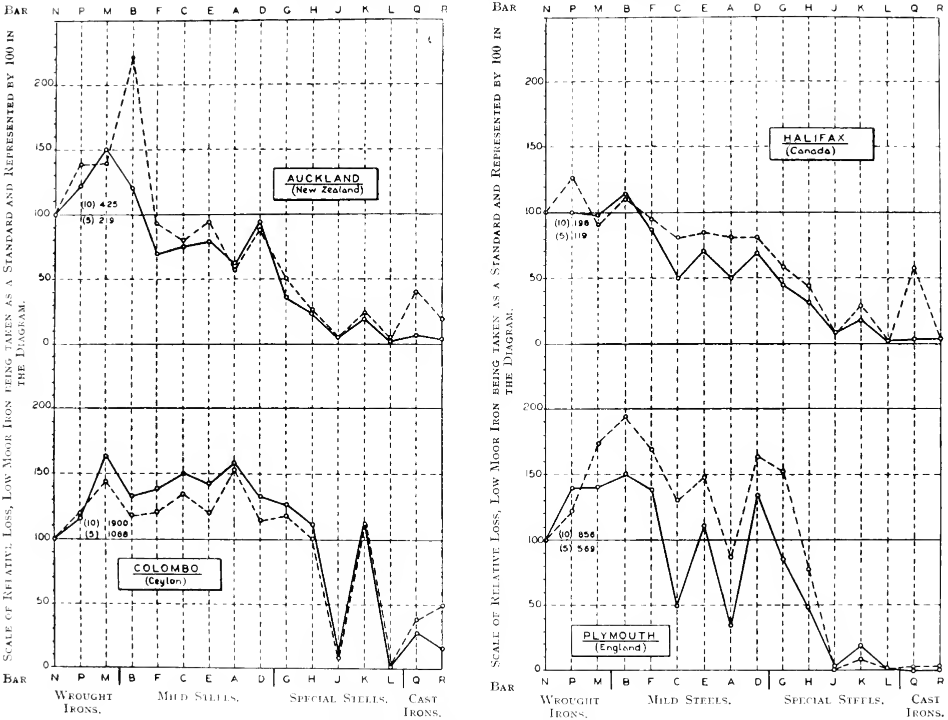
Bar	Metal	Condition	Remarks	Aerial					Half-tide					Complete-immersion				
				HX	NZ	PL	CO	Mean	HX	NZ	PL	CO	Mean	HX	NZ	PL	CO	Mean
E	Medium carbon steel . .	Paired	Loss in weight of E, B and C, per unit loss of L, Q, and N, respectively, expressed as per cent. of the loss of Single Bars E, B and C, per unit loss of Single Bars L, Q, and N in Single-Bar Series.†	79	92	57	52	70	102	493	88	355	260	1,000	758	196	262	554
L	36·5% nickel steel . .																	
B	Carbon steel	,,		14	31	0*	71	39	—	—	—	—	—	—	—	—	—	—
Q	Hot-blast cast iron . .																	
C	Carbon steel (cleaned) . .	,,		146	98	483	101	207	75	76	45	34	58	61	43	35	64	51
N	Low Moor iron (cleaned)																	
B	Carbon steel	Four mild Steel Rivets	Loss in weight per 1,000 sq. cm. expressed as per cent. of loss of corresponding bar in Single-Bar Tests.	118	75	51	93	84	95	107	63	96	90	93	71	99	97	90
J	13·5% chromium steel	,,		177	80	87	184	132	50	46	10	16	31	3	3	4	13	6
D	0·4% carbon steel . .	Four mild steel bolts	Loss in weight per 1,000 sq. cm. expressed as per cent. of loss of corresponding bar in Single-Bar Tests.	87	66	35	93	70	133	144	64	99	110	90	78	85	87	85
L	36·5% nickel steel . .	,,		150	33	66	144	98	51	4	9	7	18	0·5	1	1	4	2
Q	Hot-blast cast iron . .	,,		200	138	*	95	144	—	—	—	—	—	—	—	—	—	—
R	Cold-blast cast iron . .	,,		150	38	0*	216	135	—	—	—	—	—	—	—	—	—	—
J	13·5% chromium steel	,,		—	—	90	—	90	—	—	10	—	10	—	—	4	—	4
CC	Mild steel (cleaned) . .	Bolted together in sq. frame	Calculated in similar manner to the paired bars above.	109	81	369	85	161	119	47	29	40	59	33	32	10	29	26
PP	Swedish iron (cleaned) . .																	
JJ	13·5% chromium steel . .	,,		149	161	296	127	183	12	25	5	2	11	0·5	2	1	3	2
NN	Low Moor iron (cleaned)																	

* Omitted in calculating the mean.

† For example, the value given to E in the HX aerial series is 79, and is obtained as follows. In the single-bar tests E lost 42 grams for each gram lost by L, but in the aerial "paired" tests E lost 33·2 grams for each gram lost by L, that is only 79 per cent. of the single-bar loss. E was thus protected by contact.

FIG. 16.

RELATIVE LOSSES IN WEIGHT OF SINGLE BARS EXPOSED TO AERIAL CORROSION.



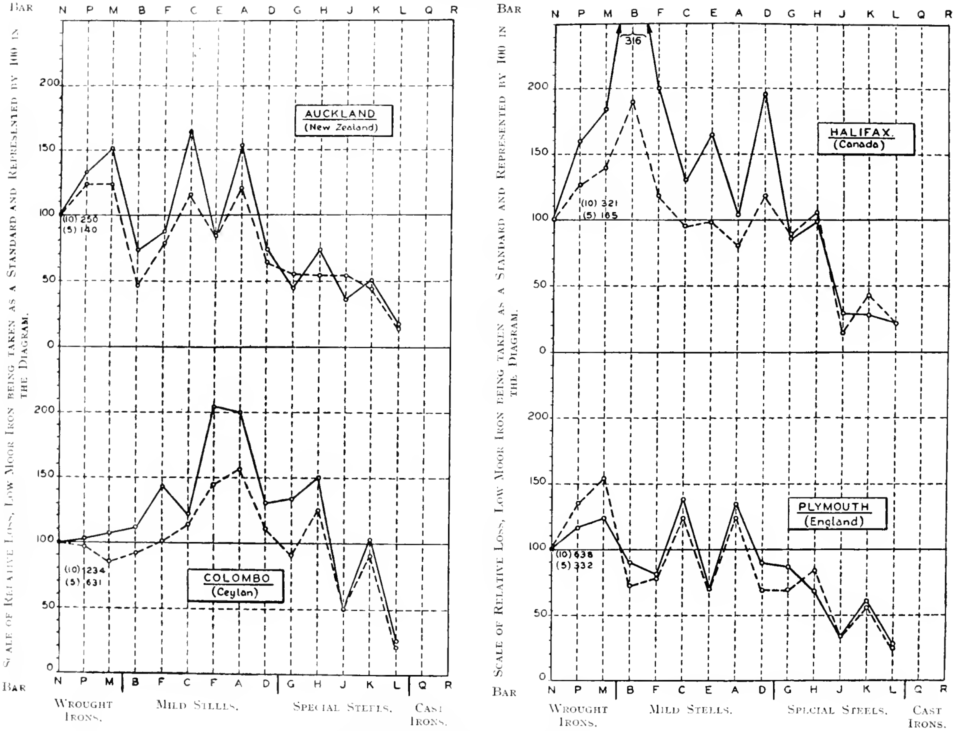
5-year Results indicated by FULL LINES.
10-year Results indicated by BROKEN LINES.
For composition of individual bars see Table XVIII.

NOTE.—Actual corrosion of Low Moor Standard Iron shown thus $\begin{matrix}(10) 425. \\ (5) 219.\end{matrix}$

The figures in brackets represent the time of exposure in years.

FIG. 17.

RELATIVE LOSSES IN WEIGHT OF SINGLE BARS EXPOSED TO HALF-TIDE CONDITIONS.



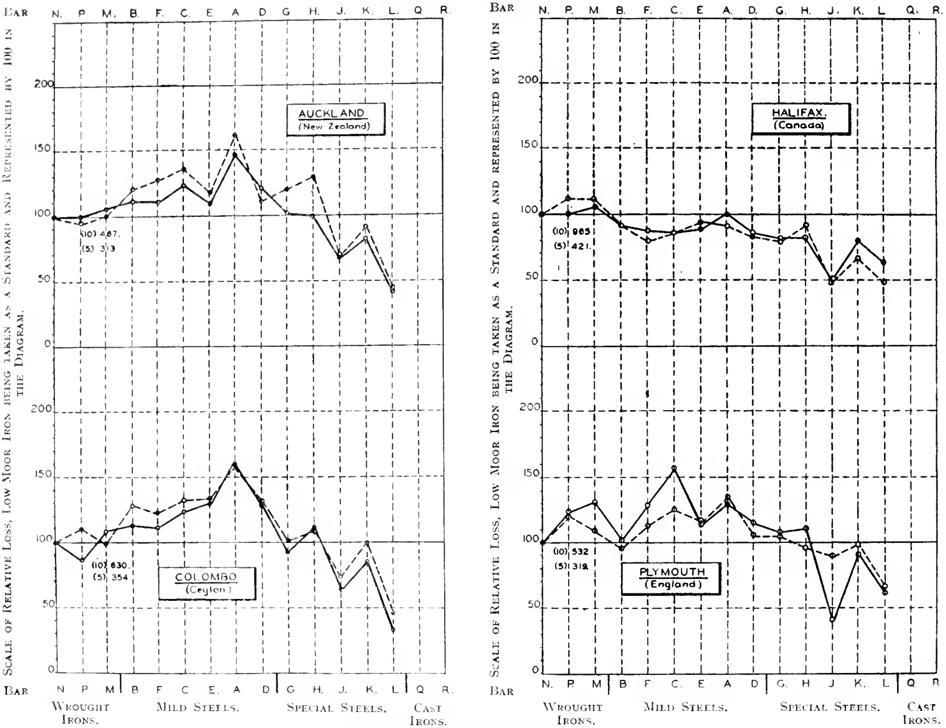
5-year results indicated by FULL LINES.
10-year results indicated by BROKEN LINES.
For composition of individual bars see Table XVIII.

NOTE.—Actual corrosion of Low Moor Standard Iron shown thus (10) 250. (5) 140.

The figures in brackets represent the time of exposure in years.

FIG. 18.

RELATIVE LOSSES IN WEIGHT OF SINGLE BARS EXPOSED TO COMPLETE IMMERSION IN SEA-WATER.



5-year results indicated by FULL LINES.
10-year results indicated by BROKEN LINES.
For composition of individual bars see Table XVIII.

NOTE.—Actual corrosion of Low Moor Standard Iron shown thus (10) 487. (5) 313.

The figures in brackets represent the time of exposure in years.

FIG.

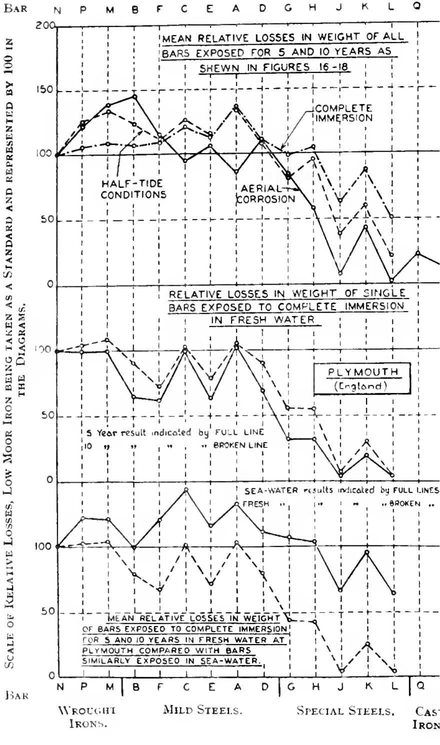
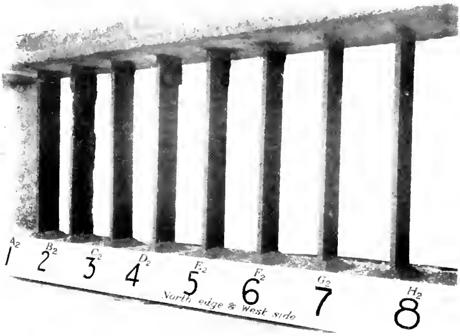
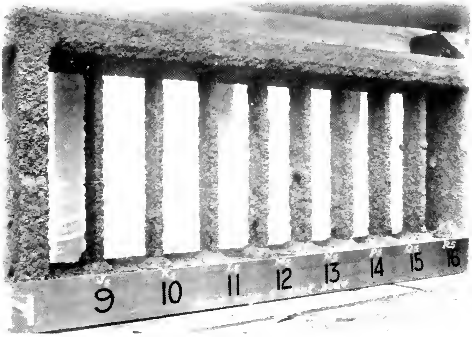

BAR
N P M B F C E A D G H J K L Q
200
150
100
50
0
MEAN RELATIVE LOSSES IN WEIGHT OF ALL BARS EXPOSED FOR 5 AND 10 YEARS AS SHEWN IN FIGURES 16-18
COMPLETE IMMERSION
HALF-TIDE CONDITIONS
AERIAL CORROSION
RELATIVE LOSSES IN WEIGHT OF SINGLE BARS EXPOSED TO COMPLETE IMMERSION IN FRESH WATER
100
50
0
PLYMOUTH
(England)
5 Year result indicated by FULL LINE
10 " " " " BROKEN LINE
SEA-WATER results indicated by FULL LINES
FRESH " " " " BROKEN "
100
50
0
MEAN RELATIVE LOSSES IN WEIGHT OF BARS EXPOSED TO COMPLETE IMMERSION FOR 5 AND 10 YEARS IN FRESH WATER AT PLYMOUTH COMPARED WITH BARS SIMILARLY EXPOSED IN SEA-WATER.
BAR
N P M B F C E A D G H J K L Q
WROUGHT IRONS.
MILD STEELS.
SPECIAL STEELS.
CAS
IRON
SCALE OF RELATIVE LOSSES, LOW MOOR IRON BEING TAKEN AS A STANDARD AND REPRESENTED BY 100 IN THE DIAGRAMS.

Fig. 20.



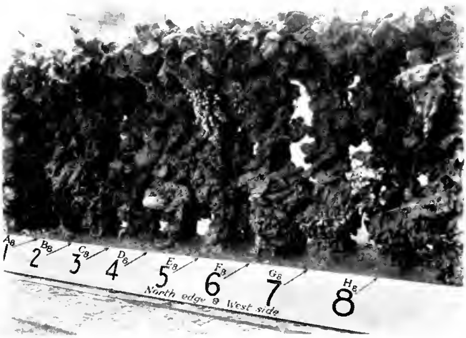
Some of the Bars exposed to Aerial Conditions at Auckland after 10 Years.

Fig. 21.



Some of the Bars exposed to Half-Tide Conditions at Auckland after 10 Years.

Fig. 22.



Shell Fauna on Bars exposed to Complete Immersion at Auckland after 10 Years.

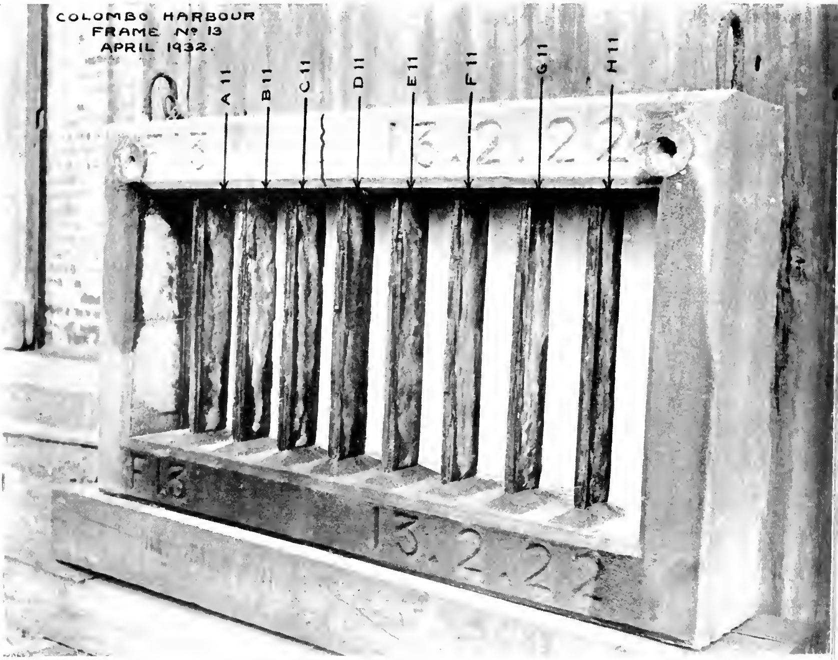
Fig. 23.

Frame H in situ, Containing Bars exposed to Aerial Conditions at Plymouth for 10 Years.

FIG. 24.

FRAME V IN SITU, CONTAINING BARS EXPOSED TO HALF-TIDE CONDITIONS AT PLYMOUTH FOR 10 YEARS.

Fig. 25.



Frame containing Bars exposed to Aerial Corrosion at Colombo for 10 Years.

FIG. 26.

FRAME CONTAINING BARS EXPOSED TO HALF-TIDE CONDITIONS (UPPER PART) AND TO COMPLETE IMMERSION IN SEA-WATER (LOWER PART) AT COLOMBO FOR 10 YEARS.

Fig. 27.

← 2½ in. → ← 2½ in. →

Shells removed from Low Moor Wrought Iron (N 41) exposed to Half-Tide Conditions at Auckland for 5 Years.

Fig. 28.

← 4⅞ in. →

Shells removed from Mild Steel and Low Moor Wrought Iron (C 42 and N 42) Paired and Completely Immersed in Sea-Water at Auckland for 5 Years.

Fig. 29.

Low Moor Wrought Iron (N 20) Exposed to Aerial Corrosion at Halifax for 10 Years, showing Pocks and Furrows.

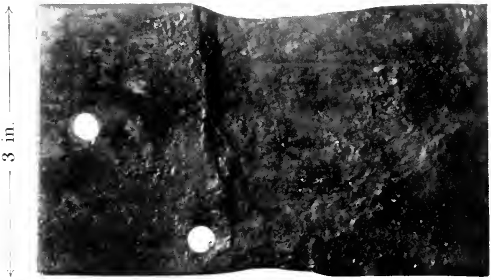
Fig. 30.

Low Moor Wrought Iron (N 69) exposed to Complete Immersion in Sea-Water at Halifax for 5 Years, showing Fibrous Structure.

Fig. 31.

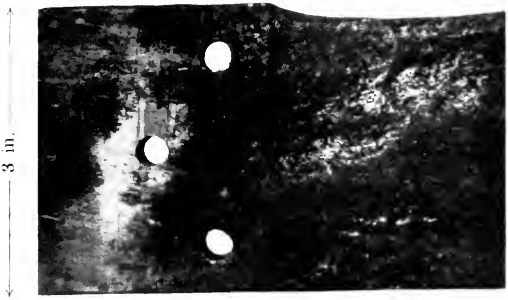
Low Moor Wrought Iron (N 42) exposed (in contact with Mild Steel) to Complete Immersion in Sea-Water at Auckland for 5 Years, showing Furrowed Structure on Face.

Fig. 32.



Low Moor Wrought Iron (N 23) exposed to Half-Tide Conditions at Halifax for 10 Years, showing Corrosion at Concrete Level.

Fig. 33.

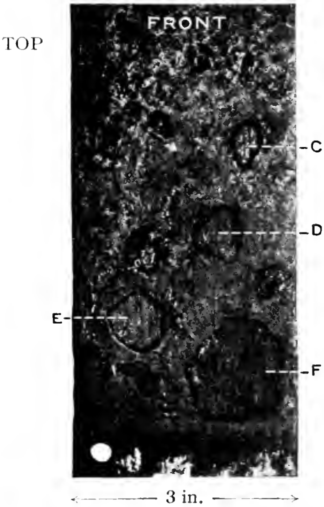


Swedish Charcoal Iron (P 2) exposed to Aerial Corrosion at Auckland for 10 Years, showing Corrosion at Lower End.

Fig. 34.

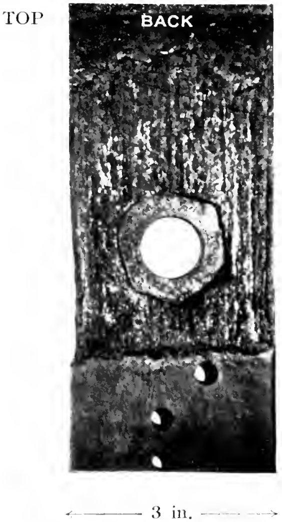
Swedish Charcoal Iron (P 2) exposed to Aerial Corrosion at Auckland for 10 Years, showing Severe Attack at Lower End.

Fig. 35.



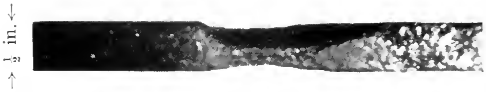
Swedish Charcoal Iron (P 22) exposed to Half-tide Conditions at Halifax for 5 Years, showing Circular Pits and Fibrous Structure.

Fig. 36.



Swedish Charcoal Iron (P 55), bolted to Mild Steel and exposed to Half-Tide Conditions at Halifax for 5 Years, showing severe Corrosion and Fibrous Structure at Lower End.

Fig. 37.



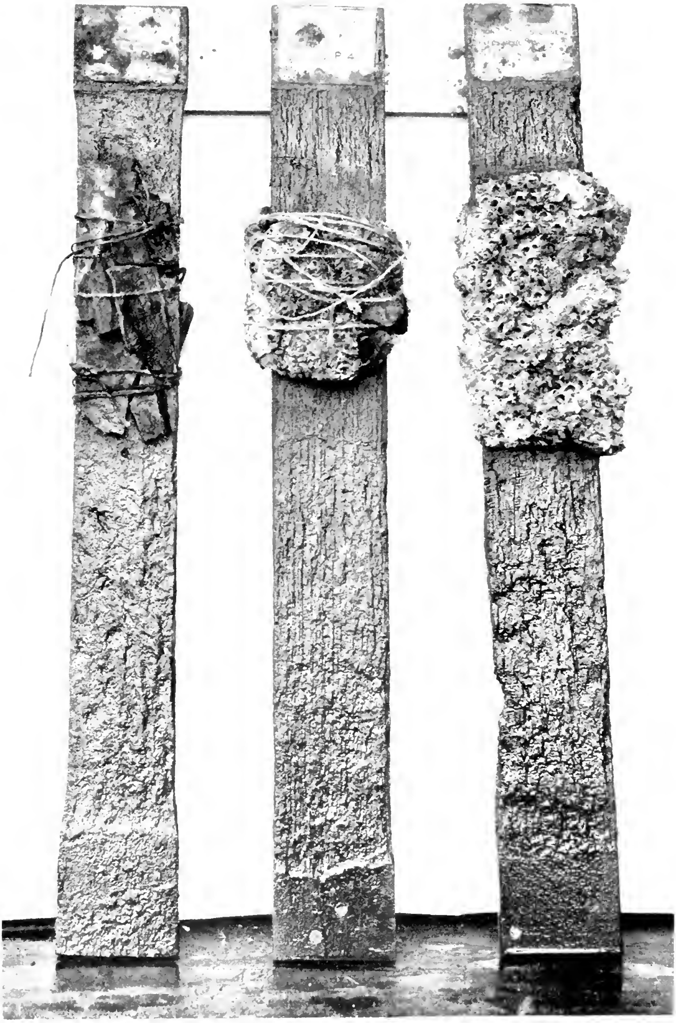
Swedish Charcoal Iron (P 23) exposed to Half-Tide Conditions at Halifax for 10 Years, showing lower Right-Hand Edge.

Fig. 38.

←—— 3 in. ——→

Swedish Charcoal Iron (P 49) Bolted to Mild Steel and exposed to Half-Tide Conditions at Colombo for 5 Years.

Fig. 39.



Aerial. Half-Tide. Immersed.

Bars of Swedish Charcoal Iron (P) exposed at Colombo for 10 Years.

FIG. 40.

INGOT IRON (M 11) EXPOSED TO AERIAL CORROSION AT COLOMBO FOR 10 YEARS.

FIG. 41.

INGOT IRON (M 23) EXPOSED TO HALF-TIDE CONDITIONS AT HALIFAX FOR 10 YEARS, BOTTOM LEFT-HAND EDGE.

FIG. 42.

INGOT IRON (M 37) EXPOSED TO COMPLETE IMMERSION IN FRESH WATER AT PLYMOUTH FOR 5 YEARS, SHOWING VERMIFORM CORROSION.

FIG. 43.

INGOT IRON (M 38) EXPOSED TO COMPLETE IMMERSION IN FRESH WATER AT PLYMOUTH FOR 10 YEARS, SHOWING VERMIFORM CORROSION.

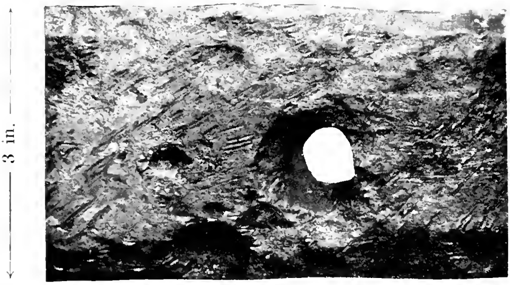
FIG. 44.

MILD STEEL (B 19) EXPOSED TO AERIAL CORROSION AT HALIFAX FOR 5 YEARS, SHOWING POCK-MARKING.

Fig. 45.

Mild Steel (B 29) exposed to Aerial Corrosion at Plymouth for 10 Years, showing Edge and Thickness of Adherent Rust before Cleaning.

Fig. 46.

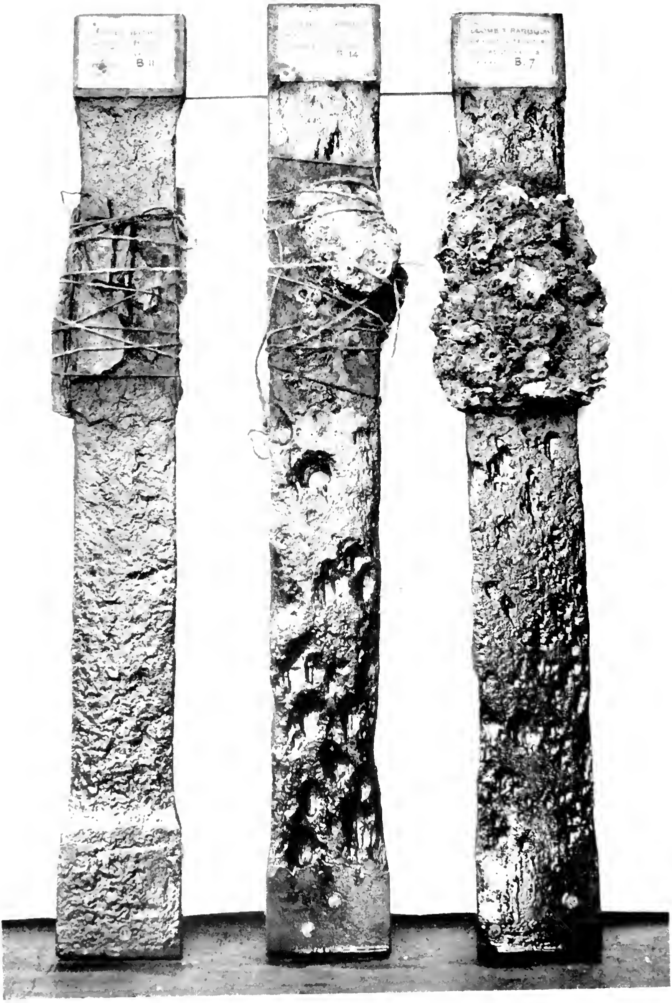


Mild Steel (B 14), High in Sulphur and Phosphorus, exposed to Half-Tide Conditions at Colombo for 10 Years.

Fig. 47.

Mild Steel (B 8), High in Sulphur and Phosphorus, exposed to Complete Immersion in Sea-Water at Auckland for 10 Years, showing Deep Pitting.

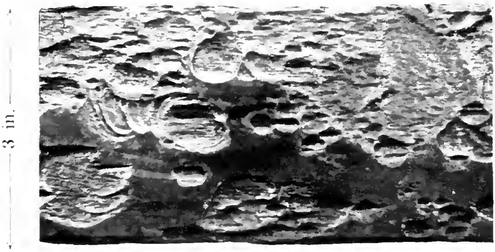
Fig. 48.



Aerial. Half-Tide. Immersed.

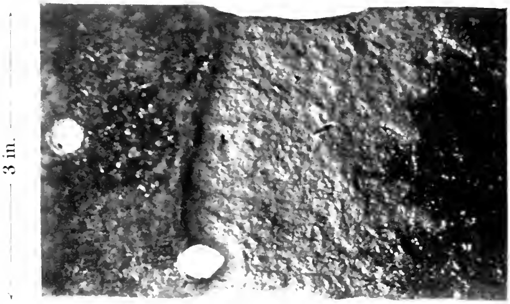
Bars of Mild Steel (B), High in Sulphur and Phosphorus, exposed at Colombo for 10 Years.

Fig. 49.



Mild Steel (B 38), High in Sulphur and Phosphorus, exposed to Complete Immersion in Fresh Water at Plymouth for 10 Years.

Fig. 50.

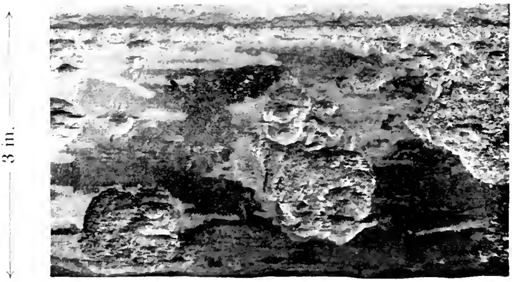


Mild Steel (F 23) exposed to Half-Tide Conditions at Halifax for 10 Years, showing Corrosion at Concrete Level.

Fig. 51.

Mild Steel (F 8) exposed to Complete Immersion in Sea-Water at Auckland for 10 Years, showing Pitting.

Fig. 52.

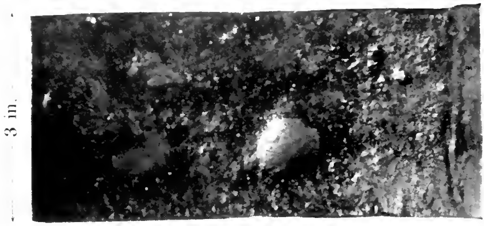


Mild Steel (F 38) exposed to Complete Immersion in Fresh water at Plymouth for 10 Years, showing Oyster-Like Pitting and Channelling near Top Edge.

Fig. 53.

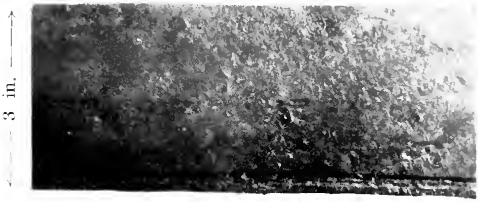
Cleaned Mild Steel (C 11) exposed to Aerial Corrosion at Colombo for 10 Years, showing Hole at Left Edge.

Fig. 54.



Cleaned Mild Steel (C 26) exposed to Complete Immersion in Sea-Water at Halifax for 10 Years, showing Pits on Back.

Fig. 55.

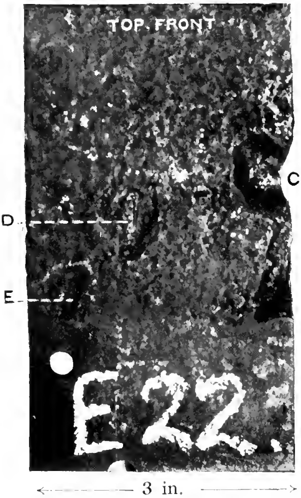


Cleaned Mild Steel (C 26) exposed to Complete Immersion in Sea-Water at Halifax for 10 Years, showing Channel near Lower Edge.

Fig. 56.

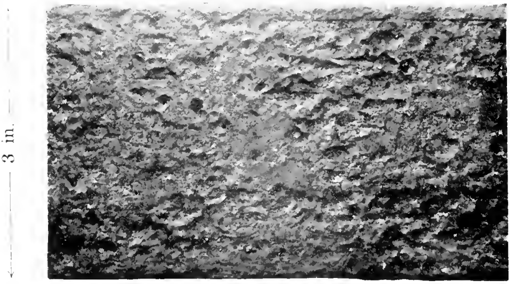
Mild Steel (C 42) exposed (in Contact with Low Moor Wrought Iron) to Complete Immersion in Sea-Water at Auckland for 5 Years, showing Isolated Pit on Face.

Fig. 57.



Medium Carbon Steel (E 22) exposed to Half-Tide Conditions at Halifax for 5 Years, showing Deep Pits at Bottom.

Fig. 58.

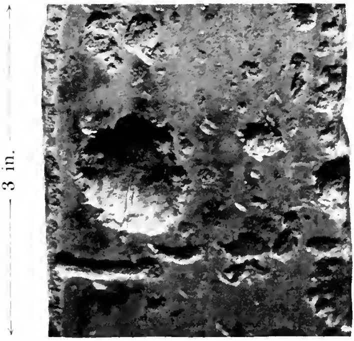


Mild Steel (E 32) exposed to Half-Tide Conditions at Plymouth for 10 Years.

Fig. 59.

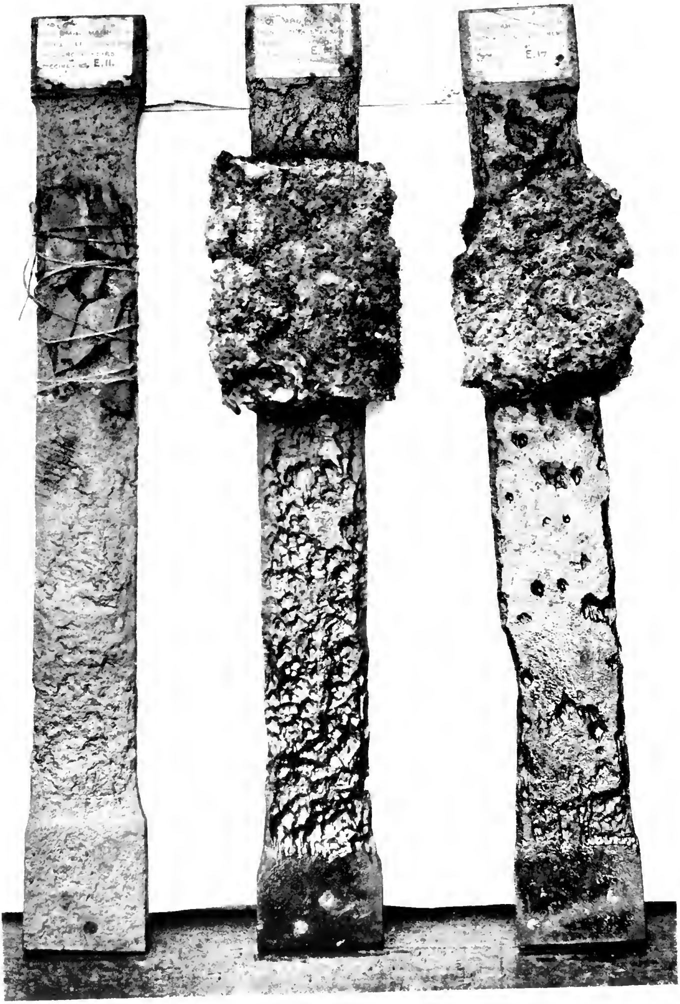
Medium Carbon Steel (E 13) exposed to Half-Tide Conditions at Colombo for 5 Years.

Fig. 60.



Medium Carbon Steel (E 59) Bent at Right Angles and exposed to Complete Immersion in Sea-Water at Plymouth for 10 Years, showing Large Pit, 3·17 mm. Deep, under Face.

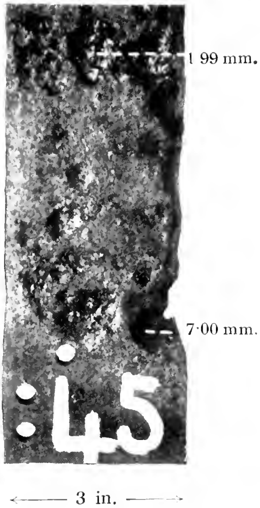
FIG. 61.



AERIAL. HALF-TIDE. IMMERSED.

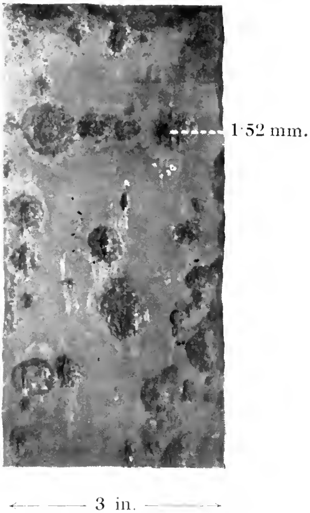
BARS OF MILD STEEL (E) EXPOSED AT COLOMBO FOR 10 YEARS.

Fig. 62.



Medium Carbon Steel (E 45) exposed (in Contact with 36 per cent. Nickel Steel) to Complete Immersion in Sea-Water at Colombo for 5 years.

Fig. 63.



Medium Carbon Steel (E 61) exposed to Complete Immersion in Fresh Water at Plymouth for 5 Years.

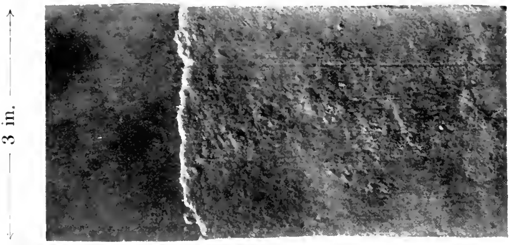
Fig 64.

Cleaned Mild Steel (A 11) exposed to Aerial Corrosion at Colombo for 10 Years, showing Hole near Right Edge.

Fig. 65.

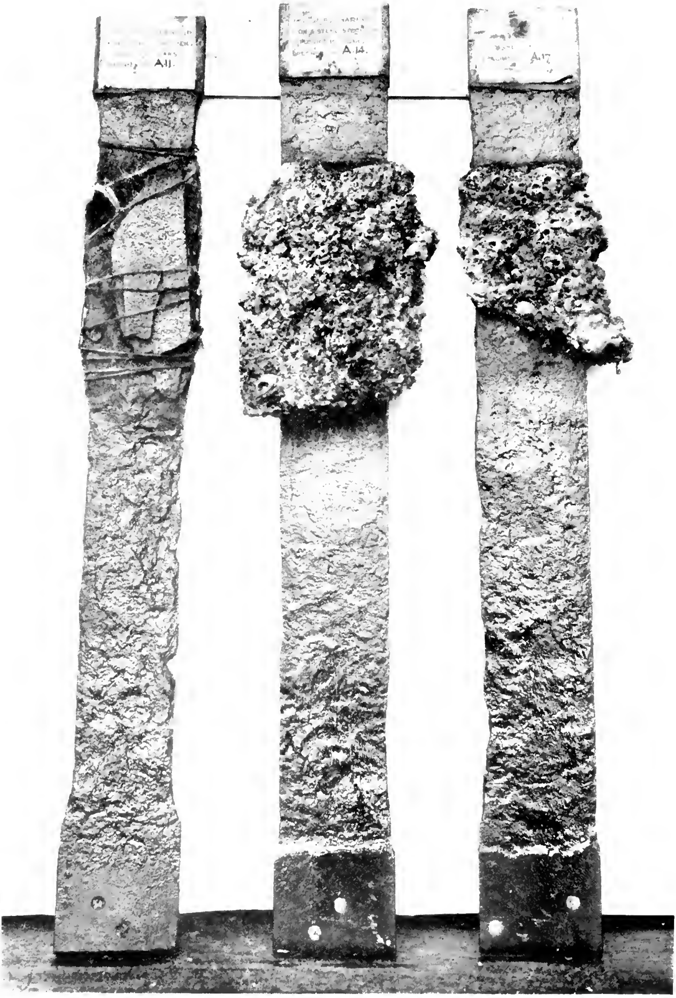
Cleaned Mild Steel (A 26) exposed to Complete Immersion in Sea-Water at Halifax for 10 Years.

Fig. 66.



Cleaned Mild Steel (A 8) exposed to Complete Immersion in Sea-Water at Auckland for 10 Years.

Fig. 67.



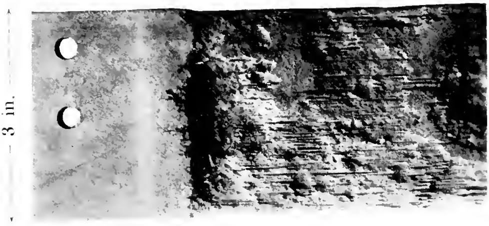
Aerial. Half-Tide. Immersed.

Bars of Cleaned Mild Steel (A) exposed at Colombo for 10 Years.

Fig. 68.

0·4 per cent. Carbon Steel (D 9) exposed to Complete Immersion in Sea-Water at Auckland for 5 Years.

Fig. 69.

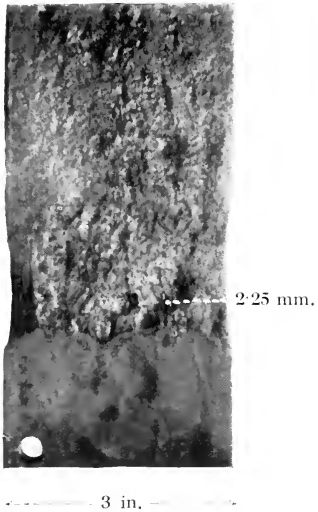


0·4 per cent. Carbon Steel (D 8) exposed to Complete Immersion in Sea-Water at Auckland for 10 Years, showing Corroded End and Sharp Rolling-Lines.

Fig. 70.

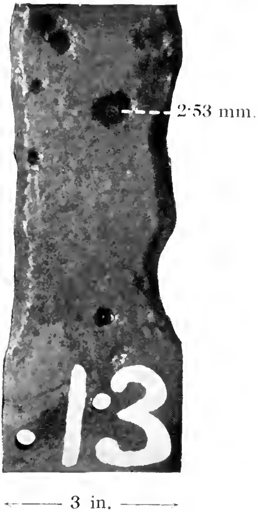
0·4 per cent. Carbon Steel (D 35) with Adherent Shells exposed to Complete Immersion in Sea-Water at Plymouth for 10 Years.

Fig. 71.



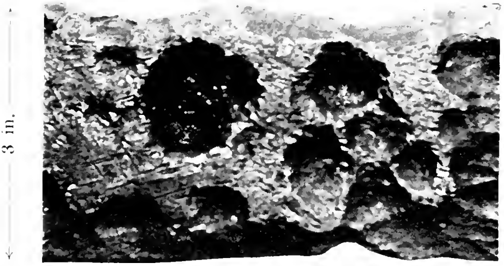
0·635 per cent. Copper Steel (G 31) exposed to Half-Tide Conditions at Plymouth for 5 Years.

Fig. 72.



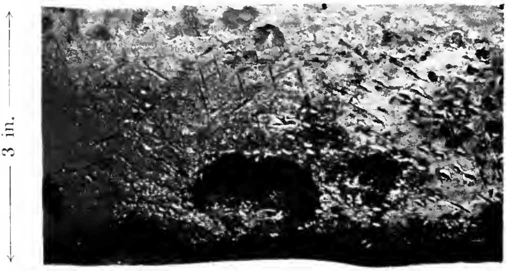
0·635 per cent. Copper Steel (G 13) exposed to Half-Tide Conditions at Colombo for 5 Years.

Fig. 73.



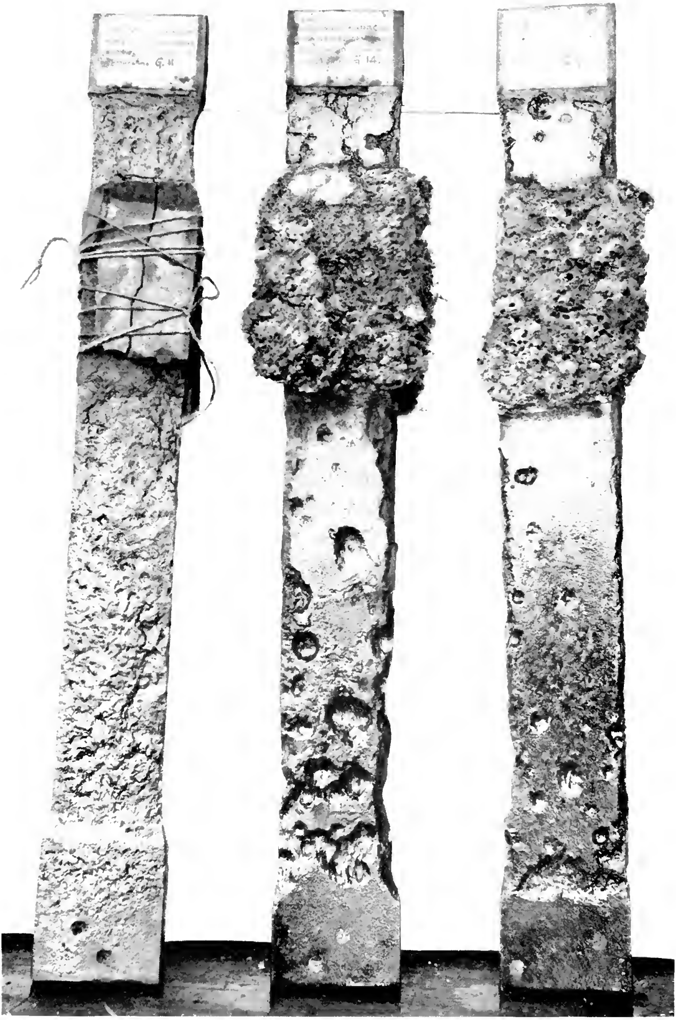
0·635 per cent. Copper Steel (G 14) exposed to Half-Tide Conditions at Colombo for 10 Years, showing Face.

Fig. 74.



0·635 per cent. Copper Steel (G 14) exposed to Half-Tide Conditions at Colombo for 10 Years, showing Back.

Fig. 75.



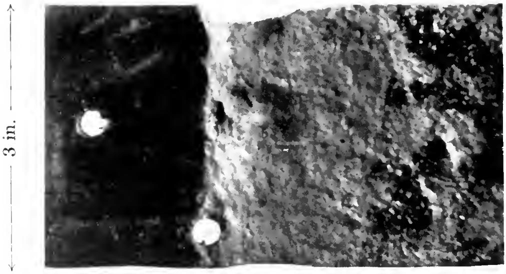
Aerial. Half-Tide. Immersed.

Bars of 0·635 per cent. Copper Steel (G) exposed at Colombo for 10 Years.

FIG. 76.

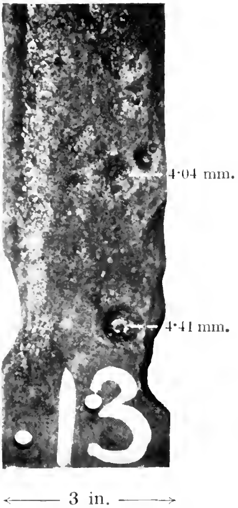
0·635 PER CENT. COPPER STEEL (G29) EXPOSED TO AERIAL CORROSION AT PLYMOUTH FOR 10 YEARS, SHOWING EDGE AND THICKNESS OF ADHERENT RUST BEFORE CLEANING.

FIG. 77.



2·185 PER CENT. COPPER STEEL (H 23) EXPOSED TO HALF-TIDE CONDITIONS AT HALIFAX FOR 10 YEARS, SHOWING DEEP CORROSION AT CONCRETE LEVEL.

Fig. 78.

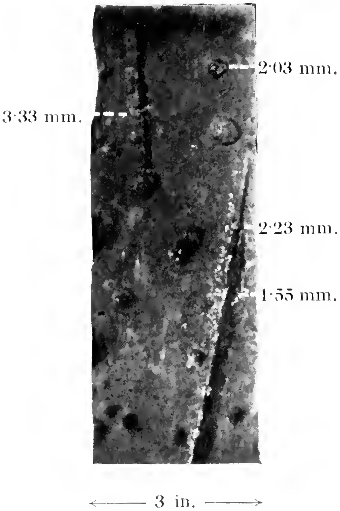


2·185 per cent. Copper Steel (H 13) exposed to Half-Tide Conditions at Colombo for 5 Years, showing Channel near Left Edge.

Fig. 79.

2·185 per cent. Copper Steel (H 14) exposed to Half-Tide Conditions at Colombo for 10 Years, showing Perforation and Deep Pitting at Lower End.

Fig. 80.



2·185 per cent. Copper Steel (H 16) exposed to Complete Immersion in Sea-Water at Colombo for 5 Years.

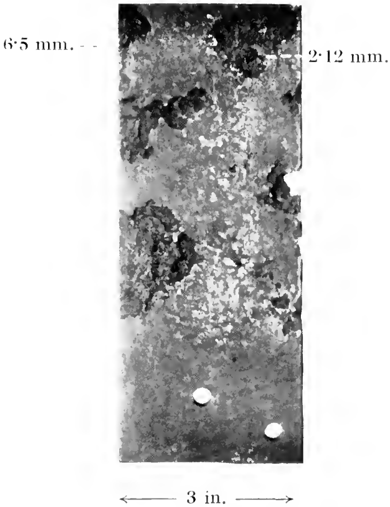
Fig. 81.

2·185 per cent. Copper Steel (H 38) exposed to Complete Immersion in Fresh Water at Plymouth for 10 Years, showing Pits within Pits.

Fig. 82.

13·5 per cent. Chromium Steel (J 23) exposed to Half-Tide Conditions at Halifax for 10 Years, showing Deep Pitting at Concrete Level.

Fig. 83.



13·5 per cent. Chromium Steel (J 13) exposed to Half-Tide Conditions at Colombo for 5 Years.

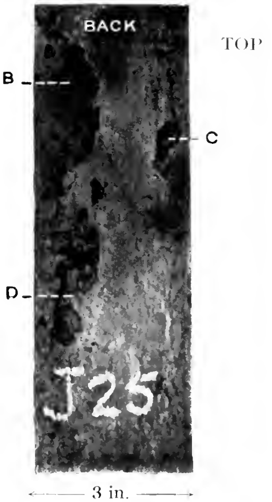
Fig. 84.

13·5 per cent. Chromium Steel (J 14) exposed to Half-Tide Conditions at Colombo for 10 Years.

Fig. 85.

13·5 per cent. Chromium Steel (J 25) after Complete Immersion in Sea-Water at Halifax for 5 Years, showing Pin-Hole Pitting.

FIG. 86.



13·5 per cent. Chromium Steel (J 25) after Complete Immersion in Sea-Water at Halifax for 5 Years, showing Deep Localized Corrosion.

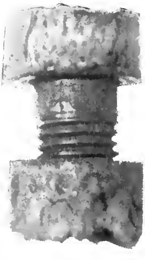
FIG. 87.

13·5 per cent. Chromium Steel (J 26) exposed to Complete Immersion in Sea-Water at Halifax for 10 Years, Perforated by Corrosion.

Fig. 88.

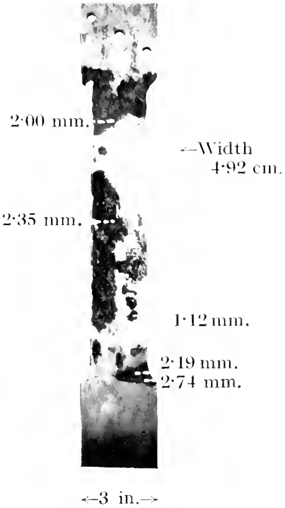
13·5 per cent. Chromium Steel (J 8) exposed to Complete Immersion in Sea-Water at Auckland for 10 Years, showing Localized Corrosion.

Fig. 89.



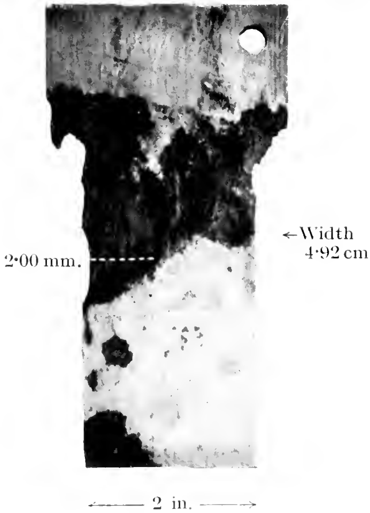
Nut and Bolt from 13·5 per cent. Chromium Steel (J 54) exposed to Complete Immersion in Sea-Water at Plymouth for 5 Years.

Fig. 90.



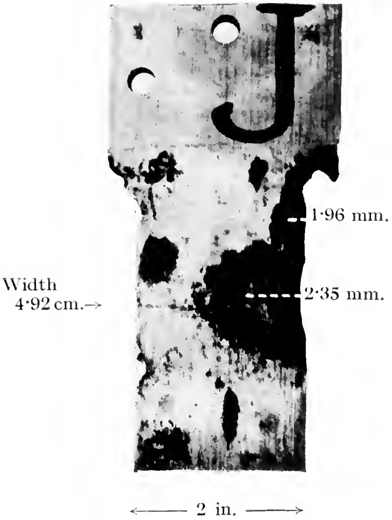
13·5 per cent. Chromium Steel Tensile Test-Bar J, ground free from Mill-Scale and exposed to Complete Immersion in Sea-Water at Plymouth for 5 Years, showing Back.

Fig. 91.



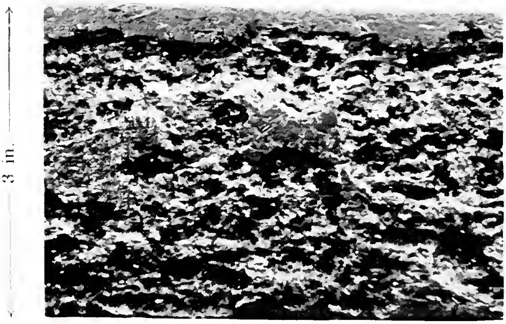
13·5 per cent. Chromium Steel Tensile Test-Bar J, ground free from Mill-Scale and exposed to Complete Immersion in Sea-Water at Plymouth for 5 Years, showing Upper End of Back.

Fig. 92.



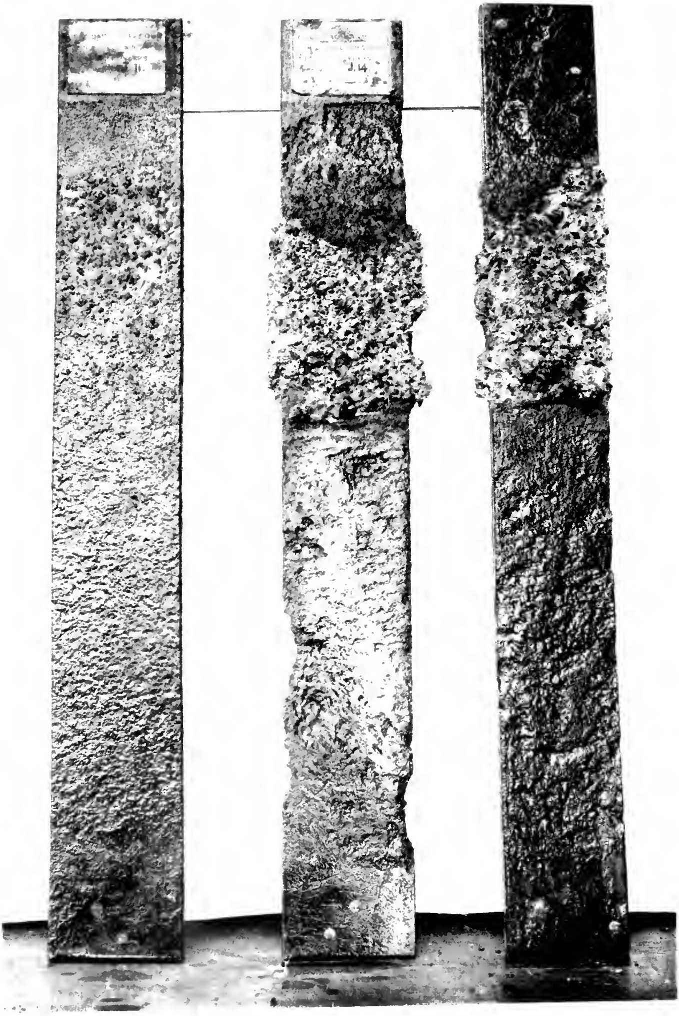
13·5 per cent. Chromium Steel Tensile Test-Bar J, ground free from Mill-Scale and exposed to Complete Immersion in Sea-Water at Plymouth for 5 Years, showing Upper End of Face.

Fig. 93.



13·5 per cent. Chromium Steel (J 35) exposed to Complete Immersion in Sea-Water at Plymouth for 10 Years.

FIG. 94.



AERIAL. HALF-TIDE. IMMERSED.

BARS OF 13·5 PER CENT. CHROMIUM STEEL (J) EXPOSED AT COLOMBO FOR 10 YEARS.

Fig. 95.

3·75 per cent. Nickel Steel (K 23) exposed to Half-Tide Conditions at Halifax for 10 Years, showing Deep Corrosion at Concrete Level.

Fig. 96.

3·75 per cent. Nickel Steel (K 32) exposed to Half-Tide Conditions at Plymouth for 10 Years, showing Deep Pits and Original Scale.

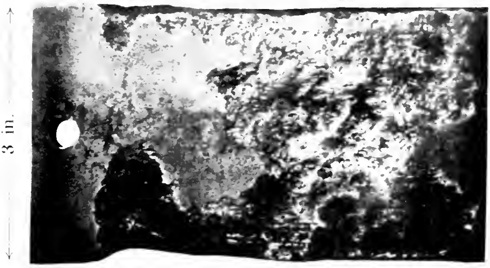
Fig. 97.

3·75 per cent. Nickel Steel (K 13) exposed to Half-Tide Conditions at Colombo for 5 Years, showing Hole 3 mm. in Diameter near Lower End, and very Deep Pit Vertically above it.

Fig. 98.

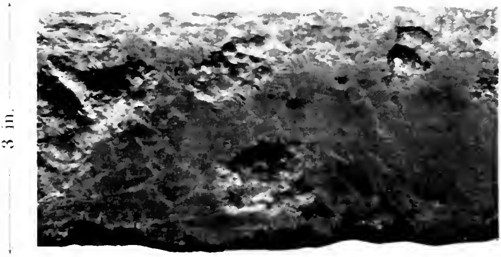
3·75 per cent. Nickel Steel (K 14) exposed to Half-Tide Conditions at Colombo for 10 Years.

Fig. 99.



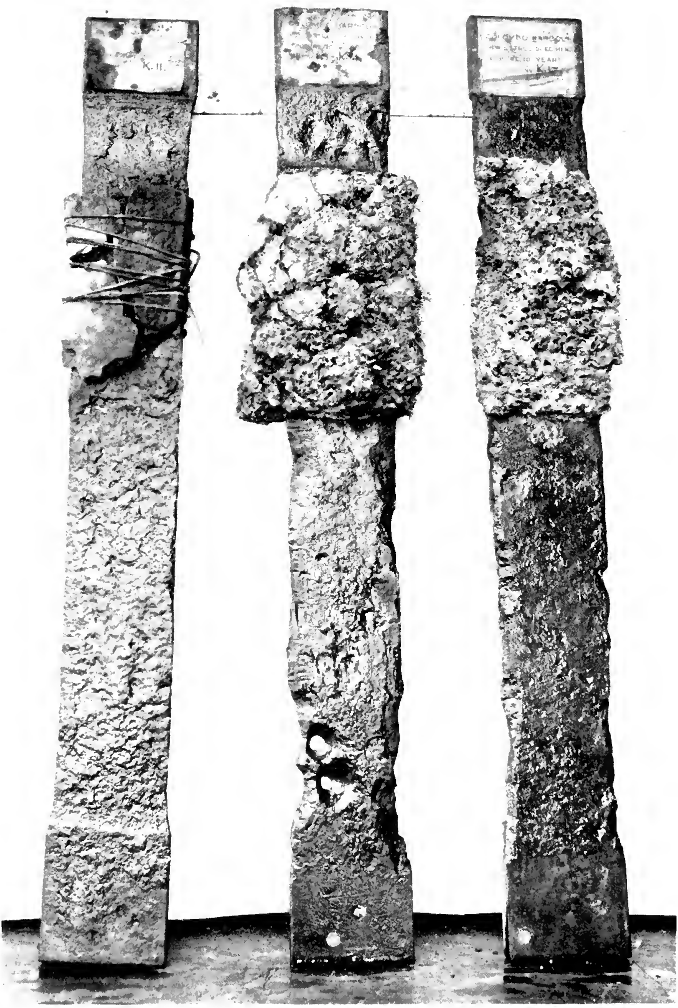
3·75 per cent. Nickel Steel (K 8) exposed to Complete Immersion in Sea-Water at Auckland for 10 Years, showing Localized Corrosion.

Fig. 100.



3·75 per cent. Nickel Steel (K 35) exposed to Complete Immersion in Sea-Water at Plymouth for 10 Years, showing Deep Pitting.

Fig. 101.



Aerial. Half-Tide. Immersed.

Bars of 3·75 per cent. Nickel Steel (K) exposed at Colombo for 10 Years.

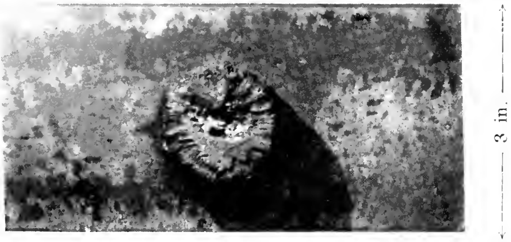
FIG. 102.

36 PER CENT. NICKEL STEEL (L 25) EXPOSED TO COMPLETE IMMERSION IN SEA-WATER AT HALIFAX FOR 5 YEARS.

FIG. 103.

36 PER CENT. NICKEL STEEL (L 60), PRESERVED BY MILD STEEL BOLTS DURING COMPLETE IMMERSION IN SEA-WATER AT HALIFAX FOR 5 YEARS.

FIG. 104.



36 PER CENT. NICKEL STEEL (L 54) EXPOSED TO COMPLETE IMMERSION IN SEA-WATER AT AUCKLAND FOR 5 YEARS, SHOWING CORROSION OF MILD STEEL BOLT.

FIG. 105.

← 3 in. →

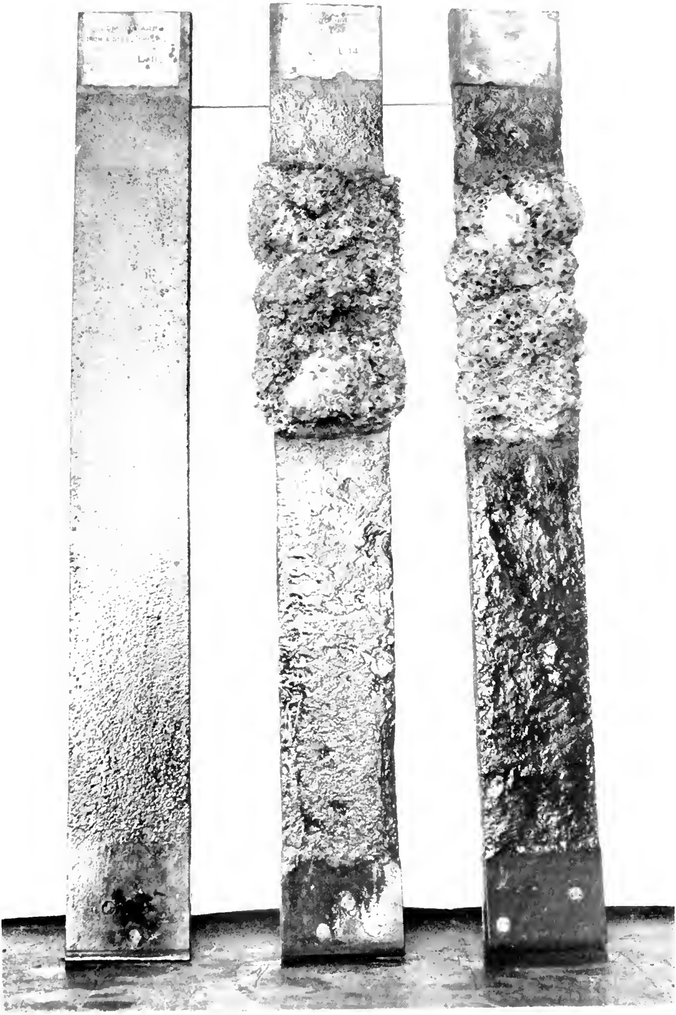
36 PER CENT. NICKEL STEEL (L 70) BENT AT RIGHT ANGLES AND EXPOSED TO COMPLETE IMMERSION IN SEA-WATER AT PLYMOUTH FOR 5 YEARS, SHOWING FIBROUS STRUCTURE AT OUTSIDE OF BEND.

FIG. 106.

← 2 in. →

36 PER CENT. NICKEL STEEL TENSILE TEST-BAR L, GROUND FREE FROM MILL-SCALE AND EXPOSED TO COMPLETE IMMERSION IN SEA-WATER AT PLYMOUTH FOR 5 YEARS, SHOWING FACE.

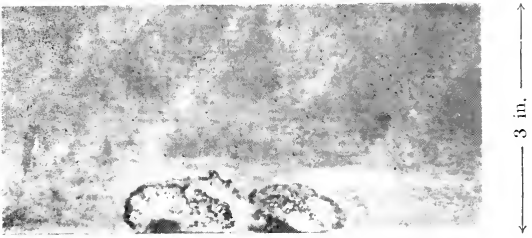
Fig. 107.



Aerial. Half-Tide. Immersed.

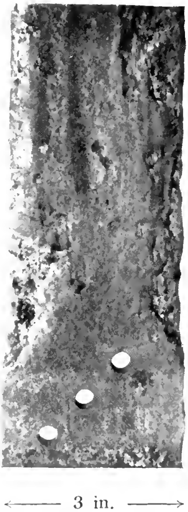
Bars of 36 per cent. Nickel Steel (L) exposed at Colombo for 10 Years.

Fig. 108.



36 per cent. Nickel Steel (L 73) exposed to Complete Immersion in Fresh Water at Plymouth for 5 Years, showing Localized Corrosion.

Fig. 109.



Hot-Blast Cast Iron (Q 56) exposed (in Contact with Mild Steel) to Half-Tide Conditions at Colombo for 5 Years.

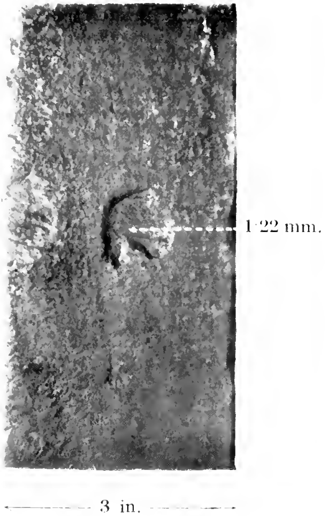
FIG. 110.

COLD-BLAST CAST IRON (R 44) CARRYING FOUR MILD STEEL BOLTS AND EXPOSED TO HALF-TIDE CONDITIONS AT COLOMBO FOR 5 YEARS.

FIG. 111.

COLD-BLAST CAST IRON (R 14) EXPOSED TO HALF-TIDE CONDITIONS AT COLOMBO FOR 10 YEARS.

FIG. 112.

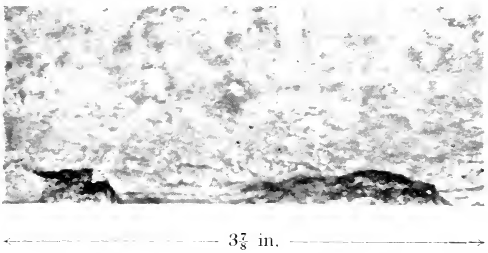


HOT-BLAST CAST IRON (Q 37) EXPOSED TO COMPLETE IMMERSION IN FRESH WATER AT PLYMOUTH FOR 5 YEARS.

FIG. 113.

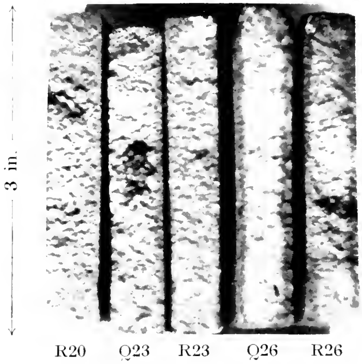
COLD-BLAST CAST IRON (R 8) EXPOSED TO COMPLETE IMMERSION IN SEA-WATER AT AUCKLAND FOR 10 YEARS, SHOWING ATTACKED EDGE.

Fig. 114.



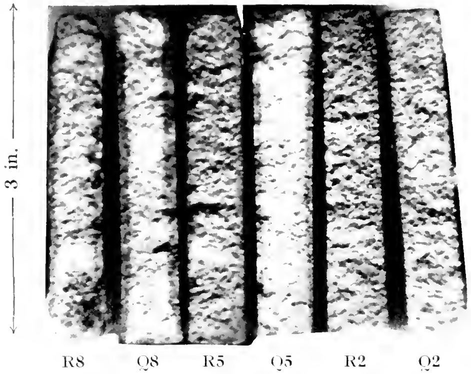
Cold-Blast Cast Iron (R 34) exposed to Complete Immersion in Sea-Water at Plymouth for 5 Years.

Fig. 115.



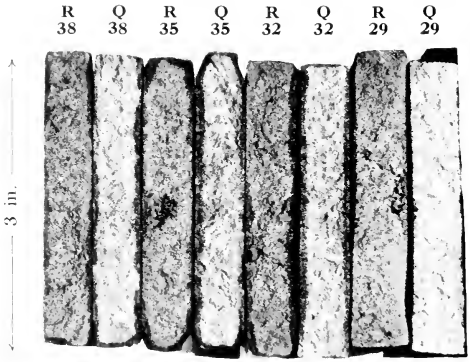
Fractures of Cast-Iron Bars Exposed at Halifax for 10 Years. R 20 Aerial; Q 23 and R 23 Half-Tide; Q 26 and R 26 Complete Immersion in Sea.

Fig. 116.



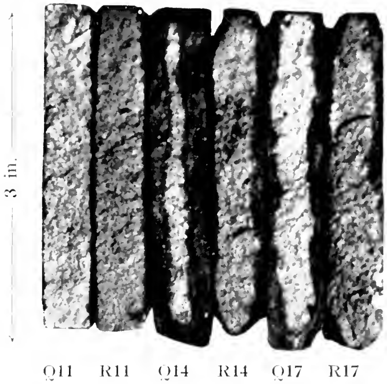
Fractures of Cast-Iron Bars exposed at Auckland for 10 Years. R 8 and Q 8 Complete Immersion in Sea; R 5 and Q 5 Half-Tide; R 2 and Q 2 Aerial.

Fig. 117.



Fractures of Cast-Iron Bars exposed at Plymouth for 10 Years. The Dark Portions in the Middle of Bars R 35 and R 29 are not due to Corrosion. R 38 and Q 38 Complete Immersion in Fresh water; R 35 and Q 35 Complete Immersion in Sea-Water; R 32 and Q 32 Half-Tide; R 29 and Q 29 Aerial.

Fig. 118.



Fractures of Cast-Iron Bars exposed at Colombo for 10 Years. Q 11 and R 11 Aerial; Q 14 and R 14 Half-Tide; Q 17 and R 17 Complete Immersion.

SECTION III

PROTECTION OF STEEL AND IRON BY MEANS OF PAINTS AND OTHER PRESERVATIVES

INTRODUCTION

In 1922 it was decided to test the relative protection against the action of sea-water of certain paints when applied to steel plates. For this purpose test-plates were exposed under three conditions, (*a*) in the air, but near sea-water, (*b*) in the sea at half-tide level and (*c*) completely immersed in sea-water.

Inspections were made from time to time and, after the plates had been exposed for suitable periods, the various sets were dismantled, the paint and rust were completely cleaned off, and notes were made of the general appearance of the plates, the loss in weight of the metal due to corrosion, and the depth of pitting, if any. The investigation was carried out under the direction of Dr. J. Newton Friend, and is described in his detailed report which follows.

The plates were all of mild steel, each 2 ft. in length, 6 in. broad, and about 0·1 in. thick. Sufficient plates were provided to allow at least five plates to be coated with each kind of preservative so as to disclose and allow for erratic behaviour of any one plate Most of the plates were pickled so as to remove mill-scale. Some of the plates after exposure in sets II and III were cleaned by sandblasting and re-used in sets IV and V. A few plates were painted over the mill-scale, and from some the mill-scale was first removed by prolonged immersion in sea-water and subsequent scraping.

Altogether nine sets of plates were exposed. Each of the sets I, II and III consisted of 110 plates covered with different coatings including various oil paints, tar and bituminous mixtures, besides a series of galvanized plates. They were exposed in air for 7 years (set I), at half-tide level for 1 year (set II) and under water for 1 year (set III)—all at Southampton. Sets IV and V each consisted of 110 plates covered with coatings again including oil paints and tars, but differing from those in sets I, II and III. They were exposed at half-tide level and also to complete immersion for 1 year at Southampton. Sets VI, VII and VIII each consisted of 60 plates all coated with tars of various kinds, and applied in various ways. Set VI was exposed at half-tide level and set VII was completely immersed, both for 28 months at Southampton. Set VIII was exposed at half-tide level for 17 months at Weston-super-Mare. Unfortunately, set IX, also exposed at Weston-super-Mare, was lost during a severe storm. The water at Weston-super-Mare is slightly less saline than at Southampton. On the other hand it is free from fuel-oil and carries more sand and the current is swifter, with the result that whereas on the half-tide plates at Southampton mud and weed collected freely, at Weston-super-Mare the plates were quite clean.

The results of the tests are full of interest. As regards the various treatments of the plate surfaces, they bring out the advantage of removing mill-scale by either pickling or sandblasting. Removal of scale by immersion in sea-water and subsequent scraping seems, however, to be unsatisfactory.

The effect of increasing the number of coats of paint proved to be beneficial in air and under water, as might be expected. Curiously, however, at half-tide level this did not seem to hold good. The reasons for this are discussed in Dr. Friend's report.

In comparing the relative protective values of the various coatings used, it should be borne in mind that they might all be described as well tried, and such as experience had proved to be useful, for example iron oxide and lead paints, bituminous mixtures and tars.

For the purposes of comparison, two coats of red iron oxide paint were adopted as a " standard." This and most of the other paints contained raw linseed oil as vehicle, though one series of plates was coated with iron oxide pigment mixed with heat-treated oil (litho-oil). This mixture proved to be very viscous and a thinner had to be added. The results in air and at half-tide level were good, but the completely-immersed plates showed no advantage over those painted with iron oxide paint mixed with raw oil. In another series the effect of adding 5 per cent. of varnish to the raw oil was tried, but it seems to have shown no special advantage. When used on some of the plates of sets IV and V the iron oxide was mixed with mineral white, kaolin, and silica. The results seemed to show that these additions had little effect. Also five iron oxides of different origin were tried, and showed some differences in results. At half-tide they all seemed to be rather better than the " standard " oxide.

The comparisons between iron oxide paint and red lead paint with various Pb_3O_4 contents are interesting. The red leads showed distinct superiority in the aerial and half-tide experiments, but this was not the case in the total-immersion tests. Similarly, plates coated with a mixture of red and white lead were better preserved in the aerial and half-tide tests than when exposed to complete immersion. In the aerial and half-tide tests there was little to choose between the red lead and the mixed lead paints, both of which gave excellent protection. In the complete-immersion tests, a lead chromate paint followed by a coat of mixed red and white lead gave distinctly better results, the plates losing less in weight and showing less severe pitting than those coated with red and white lead only.

One series of plates was first heated, after which the " standard " oxide paint was applied by spraying. The results are not as good as might be expected. Spraying, however, is not such a satisfactory method of applying the paint as the brush, and the "standard" plates with which they were compared were thoroughly dry when the paint was applied, although they were not heated, and so one of the beneficial effects of heating, namely, the removal of surplus moisture, which normally occurs in practice, was lost.

A series of galvanized plates gave interesting results. The loss in weight averaged 9·2 lb. per 100 sq. yd. in air and 34·2 lb. under water. But this probably meant little more than a loss of zinc, which originally amounted to an average of 128 lb. per 100 sq. yd. Slight signs of steel corrosion, however, appeared in the half-tide and complete-immersion plates.

Some of the most interesting results were obtained from the plates covered with tar and bituminous mixtures. The latter, though only single-coat work, compare favourably with the "standard" paint at half-tide level and under complete immersion (especially a bituminous solution) but were unsatisfactory in air. The first tarred plates, however, did remarkably well in all circumstances—so much so that sets VI to VIII were all coated with various tars and exposed for considerably longer periods (17 and 28 months) than 1 year as originally projected, so as to investigate the subject more fully. The results seem to show that for protective purposes horizontal-retort tar is better than vertical-retort tar and that the addition of slaked lime to the former is beneficial. Good results were obtained by applying tar at 200° C. thickly on cold plates. It was found that a covering coat of paint applied on the top of the tar would retain its colour provided that three coats of shellac varnish were first interposed.

Conclusions

1. It was found that steel plates which have once been exposed to corrosion should be thoroughly cleaned by sandblasting or otherwise prior to the application of a protective coat. Painting on top of mill-scale was found to be unsatisfactory as compared with painting on steel from which the scale had been removed; it resulted in greater loss of weight and deeper pitting. Removal of scale by corrosion in sea-water was however unsatisfactory.

2. Multiple coats of paint generally afforded better protection than single coats.

3. The use of litho-oil as a vehicle with iron oxide gave encouraging results in the aerial and half-tide tests.

4. The dilution of 96·5 per cent. iron oxide pigment with about 12½ per cent. of kaolin, silica or mineral white exerted no appreciable effect on the protective power of the paint.

5. On the whole there was little to choose between the different iron oxides tried.

6. Red and white lead paints proved rather superior to iron oxide in the aerial and half-tide tests, but somewhat inferior in the complete-immersion tests.

7. In general, red lead containing 65 per cent. of Pb_3O_4 proved slightly superior to that with a higher Pb_3O_4 content.

8. Red lead paints proved somewhat superior to white lead paint in the aerial and half-tide tests. In the complete-immersion tests the reverse was true, while mixtures of red lead and white lead gave intermediate results.

9. Lead chromate paint yielded promising results.

10. An anti-fouling paint containing oxides of copper and zinc gave results inferior to those obtained with the iron oxide paint in the complete-immersion tests.

11. Galvanizing proved very successful with a coating of about 20 oz. of zinc per square yard.

12. Coal-tar gave excellent results and proved, under all circumstances, much better than iron oxide and lead paints.

13. Coal-tar from horizontal retorts was superior to that from vertical retorts, whether applied hot or cold. It was improved by the addition of slaked lime.

14. Bituminous solution gave poor results in the aerial tests but excellent results in the half-tide and complete-immersion tests.

15. Oil paint was satisfactorily applied to a tarred surface after the latter had first been treated with three coats of shellac.

THE PROTECTION OF STEEL AND IRON BY MEANS OF PAINTS AND OTHER PRESERVATIVES

By J. Newton Friend, D.Sc., Ph.D.

In 1922, following the receipt of answers to a questionnaire addressed to numerous users of large quantities of paint for protecting iron and steel work (III-41), it was decided to carry out several series of large scale " field " tests with a view to comparing the relative efficiencies of various preservative coatings under different conditions. Accordingly nine sets of steel plates, suitably coated with preservative material, were exposed to natural corrosive agencies for definite periods. The plates were then cleaned, any loss in weight was determined, and the depths of any pits were measured with a spherometer. It is assumed that the losses in weight undergone by the steel plates were roughly inversely proportional to the general protective power of the coatings, and on this basis the results afford quantitative comparisons of the relative efficiencies of the various processes employed to protect the steel from corrosion under the particular conditions of the tests.

Summary of Plates Exposed.—The word " set " denotes a group of plates exposed at the same time and in the same place. The word " series " denotes a group of plates coated with the same material. The information here summarized is given in more detail in Tables XXIX, XXX and XXXI.

Set I (series I to XVII) consisted of 110 plates coated with various oil paints, tar and bituminous mixtures, one series only being galvanized. These were exposed for 7 years (1924 to 1931) on a shed roof at Southampton, freely exposed to sea air, south-west winds and rain. This was the only set exposed to aerial corrosion.

Set II (series I to XVII) consisted of 110 plates prepared at the same time as, and in a precisely similar manner to, those in set I. They were exposed for 1 year (1924 to 1925) to half-tide conditions. The frames containing the plates were fixed to the piles of a jetty in Southampton docks.

Set III (series I to XVII) consisted of 110 plates exactly similar in every respect to sets I and II. They were exposed for 1 year (1924 to 1925) to continuous immersion in sea-water, the frames containing them being attached to piles near set II, but below low-water level.

Sets IV and V (series XVIII to XXXIX) each consisted of 110 plates coated with various oil paints and tar; both sets were prepared at the same time and were precisely similar. They were exposed for 1 year (1927 to 1928) at Southampton docks under conditions exactly similar to those of sets II and III respectively.

Sets VI and VII (series XL to LII) each consisted of 60 plates, coated with various tar preparations. Both sets were precisely similar. They were exposed for 28 months (1927 to 1929) at Southampton docks under conditions exactly similar to those of sets II and III respectively.

Set VIII (series XL to LII) consisted of 60 plates coated with various tar preparations in an exactly similar manner to set VI. They were exposed for 17 months (1927 to 1928) in a wooden frame attached at half-tide level to the steel girders of Birnbeck pier, Weston-super-Mare.

Set IX (series XL to LII) consisted of 60 plates exactly similar to set VIII. They were completely immersed in 1927 in the sea near Birnbeck pier, Weston-super-Mare. Unfortunately the frame broke away from its moorings and was lost.

It is only with sets I to III that a direct comparison is possible of the behaviour of the protective coats under aerial, half-tide and complete-immersion conditions; and in considering these results it should be kept in mind that the aerial test-specimens were exposed for a considerably longer period than the others owing to the comparatively slow rate at which corrosion took place. Sets II to VIII, however, enable the effects of exposure at half-tide level and to complete immersion to be more fully studied.

The Steel Test-Plates

The plates were of mild steel, 2 ft. in length, 6 in. broad, and approximately 0·1 in. thick. Those used in the first five sets were all rolled from the same ingot and were curved in the direction of their width by hydraulic pressure in the cold to an arc of 6 in. radius. The main object in curving the plates was to ensure that they should not lie flat on the battens of the frames and that water and air should have free access to both sides (V-30). The plates in the remaining sets were similar but came from a different rolling and were not curved, as bending was found to be unnecessary and not altogether desirable for reasons given later.

As it is commercially impossible to prepare a series of plates which are perfectly homogeneous and identical in their physical condition and chemical composition, any two such plates upon exposure to the same corroding agencies will not usually rust to the same extent. Furthermore, it is extremely difficult to apply the same paint to two or more plates in such a manner that the coats possess identical protective powers. These variations clearly limit the value of the corrosion method as applied to the determination of the relative protective efficiencies of paints and other coatings. These disadvantages can, however, be largely countered by treating several plates with the same protective medium and taking the mean of the results obtained. If any plate or coating then behaves erratically it is immediately detected and the mean result can be "weighted" accordingly, if desired. Enough plates were therefore provided to enable at least five to be treated with each kind of preservative material in each of the sets. Every endeavour was made to give each plate an equivalent position in the frames so that all of them in any one set should be exposed to substantially identical corrosive agencies.

Preparation of the Plates.

The steel plates, when purchased, were covered with mill-scale and were treated in various ways before application of the protective coat.

Pickling.—The majority of the plates were pickled. They were laid for several hours in dilute sulphuric acid at ordinary temperature until all mill-scale and rust had been loosened ; they were then soaked in boiling water for several minutes to wash out most of the acid, and were finally left for an hour in boiling limewater to neutralize the last traces of acid. After being again washed in boiling water, the plates were drained and dried in warm sawdust. By this means their surfaces were rendered very smooth and free from pits. It was found, however, that the first batch of plates which constituted sets I to V inclusive, and which had been stressed by the cold bending and not subsequently annealed, developed shallow horizontal furrows, running, broadly speaking, in parallel courses from the centre line to the edges. They appeared on both the convex and concave surfaces. Although not in themselves serious it was thought that these furrows might act as nuclei for corrosion. But as all the plates were curved to the same extent the results would have the same relative value, so that this was not regarded as disadvantageous. There was, however, a difficulty in cleaning the plates after dismantling; the bituminous solution used in series XV, for example, adhered very tenaciously to the metal and could not be completely extracted from the furrows, with the result that one plate, which had undergone a negligible amount of corrosion, being wonderfully well preserved, appeared to have actually gained in weight by about 0·3 gram. Finally, as these plates were curved, it was more difficult to measure the depths of pitting, and when pitting occurred at the bottom of a furrow its depth as measured from the top of the furrow was magnified. Mainly, therefore, on account of these difficulties, the second batch of plates, used in sets VI to IX inclusive, were not curved, and so were found more easy to examine. However, in practice, the furrows did not appear to exert the marked influence on the general corrosion of the plates that was feared. They were still very evident on plates that had not suffered considerable loss in weight; but where a plate had lost about 40 grams through corrosion the furrows were found to have disappeared.

Sandblasting.—As it was found that many plates used in sets II and III were in very good condition after dismantling and cleaning, it was decided to use them again in sets IV and V. About

60 of them were therefore sandblasted in the usual commercial manner. They are referred to in this report as "old" plates. Partly because there were insufficient of these for the purposes of sets IV and V and partly also to enable a comparison to be made between the behaviour of old and new plates, the requisite number of entirely new plates from the same original batch were also sandblasted. The surfaces of the plates were thus very slightly roughened and appeared to give a slightly better grip to the paint than the pickled surfaces, but no difference was observable between the old and new sandblasted plates except that in a few cases where pitting had occurred in the first exposure of the old plates, the surfaces showed slight hollows.

Rusting.—Some of the first batch of new steel plates were exposed before painting for 7 months to sea action by immersion in the docks at Southampton. The object was to loosen the mill-scale and to render the surfaces of the plates more comparable with those of ships which have seen some service and been dry-docked to be cleaned and painted. The following procedure was adopted. After exposure the plates were washed under a tap with fresh water before the salt water had had time to dry on them ; they were then scraped, stood up to dry and finally wire-brushed, when they were regarded as ready to be painted.

Scale.—A few plates were wiped free from adherent dirt and were treated with various preservative coatings on top of their mill-scale. This latter was present to the extent of about 0·023 oz. per sq. ft. (1·28 lb. per 100 sq. yd.).

METHODS OF APPLICATION OF THE COATINGS.

Brush Work.—While it is not difficult after some practice to cover the surface of a steel plate with a uniform coat of paint with a brush, the task of applying a given quantity of the paint is less easy. When an even coat of paint has been applied it is usually found that slightly too little or too much has been given, and the final adjustment renders the task of obtaining a uniform distribution somewhat difficult. This difficulty is enhanced with paints containing dense pigments owing to the tendency of the particles of the pigment to settle to the bottom of the container, rendering repeated stirring necessary in order to ensure that thoroughly representative samples are applied to all the plates in any one series. The addition of a volatile thinner adds still further to the difficulty. If the thinner rapidly evaporates it is practically impossible to ascertain when the requisite quantity of paint has been applied. To avoid this difficulty, in the one series where a thinner was employed (series VIII) because the paint prepared with the litho-oil was too viscous to be applied neat, a high-boiling petroleum distillate was used. This began to distil at 160° C. (320° F.) and while the temperature was raised slowly to 187° C. (369° F.) one-third of the liquid distilled over, the remainder of the liquid distilling at the latter temperature. The rate of evaporation of the liquid at ordinary temperature was slow, and definite quantities of paint could be applied to the plates without serious error. The employment of a slowly evaporating thinner, however, is liable to introduce another type of error, namely, the formation of small bubbles in the paint during setting, thus rendering it porous. It is possible that the very irregular losses in weight experienced by the plates in series VIII are not unconnected with this.

Spraying.—In series IX, XXXV and XXXVI the plates were sprayed with paint by means of a pressure spray. The coat appeared to be very uniformly applied but it was not possible in general to apply exactly the requisite amount of the paint to each plate. In series IX, for example, the quantities on various plates differed by nearly 50 per cent. and considerable variation in the protection afforded by these coats to corrosion was therefore to be expected.

Galvanizing.—A few plates were galvanized in the usual commercial manner*. They were first immersed in dilute hydrochloric acid until their surfaces were properly cleaned from scale and dirt. They were then dried and immersed in molten zinc, the temperature of which was regulated, as customary, by the experience of the dippers. When properly coated, the plates were removed, cooled, immersed in clean water and dried in sawdust. The average weight of zinc, determined by analysis of several typical plates, amounted to 2·27 oz. per sq. ft. or 4·54 oz. per plate. It was of course impossible to ensure that all the plates received exactly the same amount of zinc during galvanizing or to be certain that the zinc was perfectly uniformly distributed over the steel surface. Indeed, analysis showed that the weights of zinc varied appreciably. The work was carried out by experienced hands, however, and therefore may be considered quite representative of the standard of uniformity met with in practice.

Time Allowed for Drying.—The oil paints were made on a commercial scale in a precisely similar manner to the standard paint, described in detail later. Only in series VIII, when a viscous litho-oil was used as vehicle, was a thinner employed because the neat paint was too thick to work easily under a brush. Great care was taken to ensure that the first film of paint was sufficiently hard and solid before further coats were applied; the intervals between successive coats are given in the Tables. These are probably considerably longer than would actually be required in practice, for the work was carried out in a paint room in order that the conditions might remain consistent for all the series of plates, whereas in practice painting is usually done in the open. As all the plates

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* In practice the weight of zinc per square foot of steel is found to vary greatly. Specimens have been examined containing as little as 0·5 oz. and as much as 2 oz. per sq. ft.

could not be painted at exactly the same time, it was realized that some surfaces would, upon completion of the work, have set hard and be ready for exposure, whilst others might be relatively soft. It was therefore decided to keep all the plates, when completed, for several months under cover to allow them to harden and become more uniform and so more directly comparable.

Application of Tar.—In every case the plates were coated with the several tar preparations by means of a brush. A plate was laid on the uncoated side for several days until the tar had hardened, and the other side was then coated. No plate received more than one coat of tar on each side. In series XLVII to L, the tar was applied at a relatively high temperature. The quantities of tar applied to the plates in these series were very irregular, particularly in series XLVII and XLIX. This is due to the fact that continued heating of the tar at 200° C. (390° F.) caused a considerable part of the more volatile constituents to evaporate so that the tar became increasingly viscous and more difficult to spread (Table XXXI), as the series were proceeded with; the later plates to be coated thus received a more viscous and hence a thicker coat than those first coated, with the result that the weights of the tar applied increased steadily. In series XLVIII and L this was less evident, as the plates themselves were hot when the tar was applied ; consequently the tar spread easily and the operations were carried out more rapidly.

A Standard Paint

In order to facilitate a comparison of the relative efficiencies of the various protective coats, it seemed desirable to select one paint, applied under well defined conditions, as a standard of reference. This does not mean that the standard chosen must necessarily be the most efficient ; but it is essential that it should comply with the following conditions. (1) It should be a good protector, otherwise it might be destroyed before other more efficient coats had sufficiently deteriorated and comparison would thus be rendered of little quantitative value. (2) It should be readily reproducible at any time. To this end it should consist of as few ingredients as possible and these of a kind that can readily be obtained in a standard condition.

In order to comply with these requirements it was decided to use an oil paint consisting of pigment and linseed oil, without any thinners or driers. The choice of the pigment was felt to be important. The pigment should be chemically inert, and highly insoluble in sea-water. Lead pigments, therefore, were ineligible, and it was decided to adopt a simple iron oxide pigment. The sample finally selected (and referred to as the standard iron oxide) after drying at 32° C. (90° F.) for 2 weeks, contained :—

Iron, calculated as ferric oxide, Fe_2O_3 ..	96·51	per cent.
Moisture	0·49	,,
Insoluble residue	0·10	,,

Small quantities of calcium sulphate and silica and traces of chloride were also present. As shown later, the effect of these small quantities of impurities on the protective properties of the pigment was negligible. Subsequent results fully confirmed the suitability of this pigment for the purpose. Pure Calcutta raw linseed oil was used as the liquid vehicle, its physical constants being :

Specific gravity at 15° C.	0·9322
Saponification value (KOH)	190·0
Iodine number (Wij)	183·9
Refractive index at 20° C. (68° F.) for sodium light	1·48045

The pigment was ground with the oil in a 9-in. cone grinding-mill; the resulting paint was sieved through a 200 British Standard mesh and made up to the following proportions by weight :

Pigment ..	44·4 per cent. or 80 parts
Oil	55·5 per cent. or 100 parts

The paint flowed easily under the brush, no thinner being necessary. As it set in reasonable time, no drier was added.

It was found that for easy working and in order to obtain a thoroughly satisfactory coat the following quantities of paint were required :

First coat	12 lb. per 100 sq. yd.
Second coat	8 ,, ,, ,,
Third coat	8 ,, ,, ,,

These quantities are somewhat larger than those normally employed on structural steel work by the various firms who replied to the questionnaire. Probably the main reason for this lies in the fact that in practice it is customary to thin the paint with diluents or thinners, such as turpentine. This greatly enhances the spreading power, and as the thinner is either entirely volatile or almost completely so, the weight of residual paint on a given area is proportionately reduced. The firms who prepare their paints from pure oil and pigments only, entirely free from thinners, use about the same weights of paints per unit area covered as were employed in this research (III-52).

For purposes of comparison those plates in sets I to V which had been protected with two coats of standard paint at intervals of not less than 7 days between successive coats, were chosen as standards of reference.

The Experiments

Exposure of the Plates.—All the plates for exposure were fixed vertically to stout wooden frames (V-30, Fig. 10). Each plate had two bolt-holes, one near the top and the other near the bottom. Ordinary methods of bolting could not be adopted as it was necessary not only to avoid galvanic contact with the nuts and bolts but also to ensure free circulation of air and water between the plates and the battens. The plates were gripped with galvanized nuts and bolts, packed with felt or flannel washers soaked in paint, tar, or bitumen as the case might be. This prevented the painted surface from becoming scratched when the nuts were being tightened and also galvanic action at the points of support. The bolts penetrated the horizontal battens of the frames and were fitted with collars which prevented the plates from coming close to the wood, a free space of approximately 1 in. being allowed.

The galvanized nuts and bolts used in sets II and III withstood the exposure extremely well and were used a second time without further treatment for securing the plates in sets IV and V.

Experimental Conditions at the Stations.—It was only at Southampton that any steel plates were exposed to aerial corrosion (set I) and the site chosen may be regarded as a typical seaport site. Sets II, IV and VI were exposed at half-tide level in Southampton docks so that the nature of the water and the tidal conditions have an important bearing on the results. According to the determinations of Mr. F. E. Wentworth-Sheilds, the specific gravity of the water in the docks where the plates were exposed varies from 1·0225 at L.W.N.T. to a maximum of about 1·0265 at H.W.S.T. at ordinary temperature (15° C., 59° F.). These values are somewhat lower than those usually found for pure ocean waters, such as the Atlantic, namely 1·0275, but are higher than the mean value found for Weston-super-Mare, namely 1·0204. This reduced salinity is typical of docks into which fresh water flows, but, although it may possibly affect the absolute values for the corrosion of the plates, the relative values in each set were not appreciably influenced since all the plates in each set were exposed under identical conditions.

Another factor now becoming common to dock waters generally, but entirely absent at Weston-super-Mare, is the presence of fuel-oil which, during the rise and fall of the tides, tends to cling to all partly submerged objects. This oil, being mainly of mineral origin, is likely to exert a deleterious action upon paints in which vegetable oils, such as linseed oil, have been used as vehicles. On the other hand the sticky nature of the deposit caused a thick coating of mud, slime and other material floating in the dock water to collect on the plates; this offered considerable mechanical protection to the plates, and reduced any scouring action caused by tidal movement. At Southampton the tidal range is relatively small, amounting at spring tides to 13 ft. and at neap tides to 9 ft. 6 in.

Sets III, V and VII were exposed below low-water level in the docks at Southampton and when withdrawn from the water were, with the exception of the galvanized plates, thickly covered with marine growths, but were free from any shell fauna.

Set VIII was exposed at half-tide level at Weston-super-Mare, near Birnbeck Island, where the tide flows rapidly, sometimes reaching 6 knots. The rise and fall of the ordinary spring tide is 38 ft. and of equinoctial tides 45 ft. The neap rise and fall is 17 ft. The water, in consequence of its rapid flow over mud and sand-banks and the foreshores of the Severn estuary, contains mud and sand in suspension, particularly during spring tides. It exerts, therefore, considerable scouring action on any protective paints, and during the whole period of exposure the plates were free from mud and fauna and thus contrasted markedly with the corresponding plates (set VI) exposed at Southampton. The water at Weston-super-Mare was free from oil contamination and sewage.

Extent of Corrosion.—It was clearly undesirable to allow the corrosion to proceed too far before discontinuing the experiments. When once the protective coat has begun to disintegrate and the underlying metal to corrode, further corrosion is apt to proceed rapidly, perhaps independently of, and in some cases even stimulated by, the residuum of the protective coat originally applied. The most reliable indications of the efficiencies of the protective coats are thus obtained before excessive corrosion has occurred. On the other hand, to dismantle the plates before the protective coats have undergone sufficient deterioration would lead to equally indecisive results. This explains the different periods of exposure adopted.

The Standard of Efficiency.—It is exceedingly important to select a suitable standard by which to judge the relative protective efficiencies of the media employed. The nature of this standard must clearly depend to a large extent upon the particular use for which the painted article is destined. Permanence of colour, gloss or other surface properties may be important where painting is intended to serve commercial, distinguishing or intelligence purposes, such as ships' funnels and buoys. This aspect of the subject is considered later.

The main purpose of the present research is to study the protective properties of the applied coats of paint and this may be done in two ways, namely, by careful examination of the coat itself, and of the steel plate protected by the coat. The former method, namely, the examination of the coat itself, has much to recommend it, and in practice may be the only method available. It has been adopted with set I in which the plates were exposed to aerial corrosion at Southampton. Each year the plates were examined *in situ* and reported upon, note being taken of any disintegration of the coat, any chalking of oil paint and alligatoring* of the tars and bitumen. The observations enabled the preservative coats to be roughly arranged in eight grades and, on the whole, the results were found to agree, as well as could be expected, with the quantitative data obtained later when the plates were dismantled and their losses in weight were determined. They clearly showed, for example, that

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* The trade term used to denote an appearance resembling that of an alligator's back.

series IA, X, and XIII to XVI, might be eliminated from consideration in so far as aerial corrosion is concerned. At the same time it was found that corrosion sometimes progressed under the surface of the coat more seriously than the general appearance suggested; this was particularly the case with the tarred plates; on the other hand, particularly with light coloured paints, very slight corrosion could, upon occasion, cause very considerable staining giving a general impression of serious corrosion. It would appear to be unwise, therefore, to place too much reliance on mere superficial observation unsupported by other data.

In the half-tide tests at Southampton the plates were so thickly covered with mud, slime and other accretions that examination of the coat presented considerable difficulty and there was always the danger that the removal of the dirt would damage the protective film and thus interfere with the experiments. These plates were, therefore, left undisturbed till the final examination.

The completely immersed plates at Southampton were thickly coated with marine fauna, which adhered tenaciously and could not be removed without serious damage to the protecting coat. In this case the method of examination of the paint *in situ* also breaks down. There remains, therefore, the second method, namely, the examination of the steel plate itself. For this purpose the protective coat, together with any accretions and products of corrosion, must be carefully removed. The methods adopted are explained later. The cleaned plate is then examined for loss in weight, depth of pitting and any other sign of deterioration. In this way a quantitative measure is obtained of the relative efficiencies of the preservative coats under the particular conditions of the tests.

Treatment of the Dismantled Plates.—When dismantled the plates in sets I and VIII were perfectly clean and required no preliminary treatment. The remaining sets which had been exposed at Southampton at half-tide level and to complete immersion were scraped free from the adherent organic growth, mud and other accretions. After being allowed to dry, they were packed between sheets of paper and sent to Birmingham for examination.

The plates coated with oil paint were soaked in caustic soda solution for several hours at room temperature. Experience has shown this to be one of the best methods of loosening the paint; the steel plates are not affected by the process as the metal is virtually insoluble in the alkali. After soaking, the plates were scrubbed with swabs and brushed in a large tank the water in which was frequently renewed. After being dried with cloths the plates were warmed to expel traces of water from their pores and finally freed from rust and any traces of still adherent paint by rubbing with emery cloth. They were then weighed and the depths of the deepest pits were measured with a spherometer.

The plates painted with tar and bituminous mixtures were more difficult to deal with, but after several trials the following method was found to work most efficiently. The plates were boiled in caustic soda solution in a large iron tank heated with a gas ring. They were then scraped as clean as possible in cold water, and, if necessary, the process was repeated. After drying they were soaked in naphtha to remove the last traces of tarry matter.

The galvanized plates required specially careful treatment in order to avoid damaging the zinc coating that remained. They were merely rubbed with emery cloth to remove rust and any adherent deposits.

Influence of Marine Growths.—No marine growths, mud or other accretions occurred on the tarred plates exposed at half-tide level at Weston-super-Mare (set VIII). At Southampton the plates in the various sets exposed at half-tide level were, in general, thickly coated with mud, slime, etc., and those completely immersed were very thickly coated with marine fauna, except the galvanized plates (series XVII, set III) which were entirely free. This is of considerable interest because these plates were the only examples in all the sets in which the losses in weight of the completely-immersed plates did not exceed those of the corresponding series at half-tide level. Organic growths may be expected to increase corrosion by any destructive action which these growths may exert on the protective coats of paint, more particularly oil paints. On the other hand, the tenacity with which they cling enables them to afford a certain amount of mechanical protection and thus retard corrosion. Which effect ultimately predominates must depend upon local conditions.

THE RESULTS

Old and New Plates Compared.—In sets IV and V, old and new plates which had been cleaned before treatment by sandblasting, were used side by side in the different series with the object of ascertaining whether the sandblasting completely removed the general effects, other than pitting, of the previous exposure to corrosion. If, for example, the salt water were capable of penetrating to any appreciable extent into the steel and the effect was not removed by the sandblasting, it might be expected that the old plates would corrode at a different rate from the new. In so far as loss in weight is concerned there appeared to be no difference between the old plates and the new in the half-tide tests (set IV); the average loss, as calculated from twenty-two old plates, amounted to 30·0 lb. per 100 sq. yd., whilst that calculated for new plates exposed under identical conditions was 30·8 lb. In the complete-immersion tests (set V) the old plates showed a slight advantage, their loss being 55·5 lb. per 100 sq. yd. as opposed to 60·6 lb. by the new plates. This difference of 8 per cent. is probably fortuitous, for the losses in weight of different plates varied considerably in the same series under apparently identical conditions. In any case, it is evident that the old plates were equal to the new ones in so far as loss in weight is concerned. As regards the relative tendencies of the old and new plates to develop pits the evidence is not very reliable. Sandblasting does not necessarily remove pits although it may clean them out. It is always possible, therefore, that any observed pits on the old plates merely resulted from the deepening of pits originally begun during the previous exposure. It would manifestly be incorrect to compare them directly with fresh pits on the new plates. For this reason no pitting on old plates is recorded in the accompanying Tables.

Scraped and Sandblasted Plates.—As already mentioned, some plates were allowed to corrode in the sea for 7 months and were then washed, scraped, and finally treated with paint or tar. The surfaces were thus rendered comparable with those of ships' plates that had seen some service, and it seemed important to ascertain whether or not the method adopted for cleaning was adequate. The results obtained with these plates (series XIX, XXXIII and XXXIX) and with freshly sandblasted plates exposed simultaneously with them are recorded in Table XXXII. Since the surfaces of the scraped plates were appreciably rougher than those which were sandblasted, they were, as might be expected, more "hungry" for paint, usually to the extent of 10 to 15 per cent. All the scraped plates lost more in weight and were more deeply pitted than the corresponding sandblasted plates. Caution must be observed, however, in the interpretation of the relative depths of pitting for the reasons already explained in considering the comparison between old and new plates. The fact that the scraped plates lost so much more in weight, coupled with the danger that old pits may continue to deepen, suggests the desirability, whenever possible, of thoroughly removing all rust, etc. by a suitable process, such as sandblasting, before the application of protective coats.

Effect of Mill-scale.—As is well known, when steel leaves the mills it is coated with scale (blue-black oxide of iron, Fe_3O_4) which adheres tenaciously to the metallic surface and cannot be removed as easily as rust. So long as this covering of oxide remains intact, it affords a very efficient protection to the underlying metal against corrosion. But if the scale is, through any cause, rendered discontinuous, thereby exposing some small portion of the metal, corrosion sets in and continues beneath the scale, which begins to peel off. If the metal happens to have been painted the paint will peel off with the scale. Accordingly it is preferable to remove all scale before application of paint. This may be accomplished by sandblasting, pickling or some other method. One important firm of bridge builders allow their structures to stand exposed to the weather, after erection, without any covering of paint, and when corrosion has proceeded sufficiently to loosen the scale, the rust and scale are scraped and the metal is given its first coat of paint. The Great Western Railway Company have reported in favour of this procedure

(III-48). The following experiments were made in order to determine whether or not the removal of scale before treating with a preservative coat is really necessary.

In series X and XLII the plates were coated with standard iron oxide paint and with tar respectively whilst their mill-scale was still adherent, without any preliminary pickling or cleaning other than a gentle rub with emery cloth to remove loosely adherent rust and dirt. The plates in these series are directly comparable with the pickled plates in series IB and the sandblasted plates in series XLI, and the results obtained are compared in Table XXXIII. In the aerial tests the plates exposed with adherent scale lost very much more in weight and were more deeply pitted than those that had been cleaned. In the half-tide and complete-immersion tests with both standard paint and tar the same general tendency is observable though not to the same extent as in the aerial tests. The plates were in excellent condition where the mill-scale still adhered, but where the scale had become detached the tarred plates at Weston-super-Mare showed pinholing at very many points. At Southampton, where the exposure was more prolonged and corrosion, in consequence, more severe, some of the plates had become seriously pitted.

Both painting and tarring on top of mill-scale must therefore be regarded as unsatisfactory. This appears to be realized in practice; for example, the pitting of ships' plates under the water line is attributed by Mr. Richard Williamson, shipowner, of Workington (III-48) largely to mill-scale that had not been removed before the application of paint.

Influence of Multiple Coats of Oil Paint.—It seemed reasonable to suppose that, other things being equal, two coats of paint should offer more protection than one coat. The results obtained in series I (Table XXIX) in which one, two and three coats respectively of standard iron oxide paint were applied, indicate that such is the case for aerial exposure, although the superiority of the three coats over the two is very slight. This, however, is probably because the exposure was not long enough to enable a true differentiation to be made.

In the half-tide tests (set II) increasing the number of coats of paint actually led to an increase of corrosion, whereas in the complete-immersion tests the extent of corrosion fell with an increase in the number of coats of paint. The following explanation is suggested. Since the presence of moisture is necessary for the rusting of the steel, corrosion will be continuous with the completely-immersed specimens when the water can penetrate the coat or coats of paint, but discontinuous in the half-tide sets if the plates have time to become sufficiently dry between the tides. In this latter case the extent of corrosion will increase with the total length of the periods during which the plates remain wet. By increasing the number of coats and thereby the thickness of the paint layer, the time required to dry is increased and hence also the corrosion. The plates which had had three coats of paint were found on dismantling to have been very uniformly attacked and to be free from pits. This was equally true for both half-tide and complete-immersion conditions. The plates that had received one and two coats respectively were slightly pitted.

An important point to be considered, when more than one coat of paint is applied, is the interval between successive coats. A comparison between series XVIII and XX (Table XXX) shows that the latter with a 5-day interval, did not differ very materially from the former with a 14-day interval as regards either change in weight or pitting. It appears, therefore, that it is sufficient to allow the first coat of paint to set thoroughly before the second is applied in order to obtain the best result.

Litho-Oil Paint.—Although raw linseed oil is a very convenient vehicle, and is largely employed in the manufacture of protective paints, it is far from ideal. One objection is that the oil, after it has " set " with the firm skin known as linoxyn, is porous and allows moisture to penetrate easily. An ideal vehicle for painting iron and steel should be impervious to moisture. Furthermore, the " setting " or " drying " of linseed oil is a process of oxidation. When linseed oil either alone or mixed with some pigment, to form a paint, is spread upon some non-absorbent material such as steel, it absorbs oxygen from the air and steadily increases in weight, volume and density until, after a few hours or days, according to circumstances, a maximum weight and volume are reached. The oil has now set, and if oxidation ceased at this point a very permanent, tough and elastic film would remain. But now a slow disintegrative oxidation takes place, resulting in a very slow, but continuous loss in weight and volume. The density however, continues to rise, until ultimately the toughness and elasticity of the film disappear, and the paint, now suffering from internal strain through shrinkage, cracks. The paint has now ceased to function as a protector, and it may even accelerate the corrosion of the metal beneath.

Attempts have been made to improve the oil by heat treatment. In the manufacture of litho-oil, the raw linseed oil is heated in a pot in such a manner that no appreciable oxidation occurs. The oil thickens mainly through polymerization, and the product is known variously as litho-oil, stand oil, and polymerized oil.

It was decided, therefore, to carry out a few tests with litho-oil, the preparation of which has been previously described (V-25), made from the same batch of raw Calcutta linseed oil as was employed in the other tests dealt with in this report. The oil was heated in the usual trade manner in a cast-iron, coke-fired pot, of 80 gall. capacity, capable of holding 400 lb. of oil. Oxidation was prevented by a sheet iron cover, and a small hinged lid was opened intermittently to admit a thermometer for temperature readings. The oil was heated for 70 hours, the maximum temperature being approximately 600° F. (315° C.).

When ground with the iron oxide pigment, the product was too viscous to be properly applied, and a thinner was consequently added. This consisted of a high-boiling petroleum distillate which, upon evaporation, left no solid residue. In Table XXIX, series VIII, therefore, the quantity of paint applied to the plates, namely 20 lb. per 100 sq. yd., refers to the weight of " neat " paint after all the thinner had evaporated.

In both the aerial and half-tide tests the mean losses in weight of the plates coated with litho-paint were little more than half of those coated with standard paint, and pitting was negligible. The complete-immersion tests were less promising ; the plates lost slightly more in weight than the standard, and pitting was somewhat deeper, though severely localized. Since in this case a thinner was employed it may be that it had too high a boiling-point, and, in consequence, evaporated too slowly, leaving small bubbles in the paint as the latter set, which rendered the film mechanically imperfect.

The Effect of Varnish.—It was expected that the addition of 5 per cent. of varnish to the linseed oil used in making paint with standard iron oxide would have a beneficial effect. The varnish was prepared by compounding selected Congo amber with linseed oil and white spirit. A comparison of series XXIX with series XVIII (Table XXX) shows that the effect is negligible as regards both loss in weight and depth of pitting.

The Effect of the Presence of Silica, Kaolin and Mineral White (Gypsum) in Standard Iron Oxide.—Seeing that small quantities of silica, kaolin and mineral white are frequently present in iron oxide pigments, it was thought interesting to test the effect of these substances when included in the standard oxide paint. In series XXI, XXII and XXIII (Table XXX), therefore, about 12½ per cent. of the iron oxide was replaced by a corresponding amount of these substances. In the half-tide tests it was found that there was no appreciable difference in the protective power of the paint, whilst in the complete-immersion tests it appeared that the maximum reduction in protection afforded did not exceed 16 per cent. As regards pitting, there was no appreciable difference in either the half-tide or complete-immersion tests.

In series XXII, in which silica was added to the pigment, the plates in both sets IV and V were exceedingly regular in their losses in weight, the maximum deviations from the means being only 11·3 per cent. in set IV and 11·1 per cent. in set V, as compared with 21·8 and 44·3 per cent. respectively in the standard sets, series XVIII.

Comparison of various Iron Oxide Paints.—In addition to the iron oxide used as standard (series XVIII) paints were made with five other iron oxide pigments. These were used in series XXIV to XXVIII, and the results are of great interest. Full analyses of the pigments have already been given, but for ease of reference the important data are summarized in Table XXXIV.

As regards depth of pitting, there is little difference in the results. Attention may therefore be concentrated on the relative losses in weight.

In the complete-immersion tests the other iron oxide paints afforded practically the same protection to the plates as the standard; but in the half-tide tests they all proved superior. Possibly the protective power of the iron oxides (ii) and (iii) (series XXIV and XXV) is not unconnected with the presence of lime, which is known to retard corrosion.

The paints made with iron oxides (iv) and (v) contained a high percentage of pigment, and had a lower spreading power, so that a greater weight of the paint had to be applied to give a suitable coat to the plates, as shown in Table XXXIV.

Red Lead Paints.—The replies received to the questionnaire indicate that red lead is generally in high favour as a constituent of protective paints (III-45). Several firms emphasize the importance of using freshly ground red lead in oil and state that standing over even one night is detrimental to the ready mixed paint, in a manner not common, fortunately, to most other paints. Furthermore, it was the experience of one firm that although red lead may have Venetian red (iron oxide) mixed with it without seriously affecting its protective qualities, yet the addition of any old red lead paint, mixed a day or two previously, did appear to affect it (III-53). Red lead is obtained by the oxidation of the monoxide of lead under certain conditions. When oxidation has been carried out to the fullest extent under these conditions, the material has the chemical composition indicated by the formula Pb_3O_4. It is seldom that the commercial product has been completely oxidised. In the trade the word "genuine" is applied to red lead to distinguish the unadulterated material from mixtures sometimes marketed and which contain genuine red lead mixed with cheaper diluents. Imitation red leads are also marketed which are entirely free from lead of any description, the products usually being white inorganic pigments stained with aniline dyes to a colour similar to that of red lead.

Red lead as now marketed is of two grades distinguished as "setting" and "non-setting." The essential difference between these is due to difference in the extent of oxidation, that is to the quantity of Pb_3O_4 present. The expression "non-setting" has reference to the behaviour of the product when mixed with linseed oil. At one time it was not possible to store red lead in mixture with linseed oil in the form of either paste or paint, because sooner or later the mixture became hard and caked or set in the container. This change was due to interaction between the unoxidised lead monoxide, which is present, and the oil. The difficulty is now overcome by carrying oxidation to a fuller extent than hitherto when it is desired to obtain a "non-setting" grade ; hence, the property of setting is associated with products containing smaller quantities of Pb_3O_4: as a rough guide, it may be said that materials containing less than about 92 per cent. of Pb_3O_4 are liable to set or cake, the rate of such setting being lower as the proportion of Pb_3O_4 rises. The quantity of Pb_3O_4 is not the sole determining factor.

It was originally intended to prepare a series of plates by painting them with fresh red lead paint composed of raw linseed oil and a typical sample of genuine red lead, and to prepare a second, similar series, the paint to be prepared a week or two before application. Through a misunderstanding, two batches of red lead were purchased of slightly different Pb_3O_4 content, and these were used in preparing the plates in series III and IV respectively, which were exposed during 1924 and 1925 in the case of the half-tide and complete-immersion tests, and from 1924 to 1931 in the aerial tests.

In the second group of tests, namely series XXXI, XXXII, and XXXIV, three kinds of red lead pigment were used containing different contents of Pb_3O_4. Of these red lead (ii) was from the same batch as that used in series IV, but its composition had undergone slight alteration during storage. For the sake of convenience the various results are grouped in Table XXXV.

In the aerial tests the two red lead paints proved remarkably protective, and there was little to choose between them. In the half-tide tests the red lead paints gave much better protection than the standard iron oxide paint in so far as loss in weight is concerned, but the pitting was somewhat more pronounced. In the complete-immersion tests the red lead paints did not in general show to such great advantage; in three cases the observed loss in weight was appreciably greater than with the standard paint, whilst in two cases the reverse obtained.

White Lead and Mixed White and Red Lead Paints.—Some firms use white lead paint or mixtures of red and white lead paints, and in order to gain some idea of their relative efficiencies series II and V were arranged in which the plates were coated with white lead and with mixed white and red lead. The results are summarized in Table XXXVI. In both the aerial and half-tide tests the advantage lay with the red leads. In the complete-immersion tests, however, the white lead proved the most resistant.

As was the case with the red lead paints, the white lead protected the plates much more efficiently than the standard iron oxide paint in the aerial and half-tide tests, but less efficiently in the complete-immersion tests, in so far as loss in weight is concerned, although pitting was slightly more pronounced with the white lead.

Lead Chromate.—Solutions of alkali chromates have long been known to preserve steel from corrosion in the absence of appreciable quantities of other salts. It has frequently been suggested that paints containing a slightly soluble chromate pigment, such as chrome yellow, might in an analogous manner assist in the preservation of steel surfaces. But whilst the traces of chromated pigment, which dissolve in water to which the painted metal is exposed, tend to protect the metal, this continued dissolution also tends to make the paint film porous and thus to reduce its mechanical protective efficiency. A balance must accordingly be struck between these two effects. It seemed probable, therefore, that good results might accrue if the metal were first coated with a chromate paint, this covering being followed by a coat of inert paint which would tend to reduce the rate of access of water to the undercoat. In this way the stock of chromate in the first layer would be conserved and its protective influence proportionately prolonged.

In series VI the plates were given a coat of chrome yellow (lead chromate) paint and this was followed by one of mixed red and white lead paint. The results are shown in Table XXXVII. In the half-tide tests there was little to choose between the mixed red and white lead paint and the chromate paint, both of which gave excellent protection. In the complete-immersion tests the chromate paint gave distinctly better results, the plates losing less in weight and showing less severe pitting than those coated with red and white lead only.

"Antifouling" Paint.—The mixed antifouling paint used in series XXX (Table XXX) gave promising results in the half-tide tests, but proved very inferior in the complete-immersion tests.

Application of Paint to Hot Plates.—Several cases are on record in which ships' plates have been marked with linseed oil paints whilst still hot, these painted marks having proved remarkably resistant to corrosion. In order further to study this aspect of the subject pickled plates were heated in a gas-fired stove to 230° F. (110° C.), removed, suspended by a hook and uniformly sprayed with standard iron oxide paint by means of a pressure spray. When completely covered the plates were removed to a storage room to set, and the total quantity of paint was ascertained by direct weighing. The results are given in Table XXXVIII.

In consequence of the raised temperature of the plates the paint was applied with a spray. At ordinary temperatures this method is not in general regarded as quite as satisfactory as the usual brush work. Two firms who have given the spray method a trial reported that they found it unsatisfactory (III-44). The working of the paint under the brush appears to exert a beneficial effect that is absent in the spray method, the coating having a proportionately longer life. Further, it was the experience of one firm that small bubbles of air get mixed up with and imprisoned in the paint, thus mechanically reducing its efficiency. On the other hand, the spray method is rapid and very useful in reaching otherwise inaccessible parts, and in dealing with hot metal it may happen that it is the only method available.

Since in the present tests pitting was in general of the same order in the various series, attention may be confined to the losses in weight. The protection afforded by the sprayed coat to the hot metal lies between that given by one and two coats respectively as applied by brush in the aerial tests; spraying gave better results than brush work in the half-tide tests; the sprayed coat equalled the double coat applied by brush in the complete-immersion tests.

One effect of warming the plates before application of paint is to drive off moisture and condensed gases from the surface of the metal, so that the paint can gain a better grip, and thus adhere more tenaciously. This is very important in outside painting in a damp climate. In this research, however, all the plates had been carefully dried and stored indoors, so that the standard plates (series IB) had been painted under conditions rather more favourable than usual for outdoor work. Hence the beneficial effect of warming the plates in series IX was not so evident as would be the case in actual practice.

It was thought that even better results might be obtained if the initial temperature of the steel plates was still higher, and in the second batch of experiments (Table XXX) red lead (iii) paint was sprayed on to plates at 430° F. (221° C.) (series XXXV), or sprayed on to hot plates and stoved at 430° F. (221° C.) until it had set (series XXXVI). The results did not prove as promising as was hoped, especially in the complete-immersion tests. Possibly the temperature was a little too high.

Galvanizing.—The method of galvanizing the plates has already been described. The average quantity of zinc in the coat was 4·54 oz. per plate, or 128 lb. per 100 sq. yd., but there was considerable fluctuation from plate to plate. The plates resisted corrosion exceedingly well—much better than the losses in weight given in Table XXIX indicate. The losses in the aerial tests were almost entirely due to removal of zinc, for the plates were in a practically perfect condition when dismantled. In the half-tide and complete-immersion tests the zinc coat had been penetrated locally and slight corrosion had taken place on most of the plates. The absence of marine growths on the totally-immersed specimens is of interest in view of the decided, although weak poisonous action of zinc compounds upon various organisms. It has already been observed that series XVII is the only one in which the completely-immersed plates did not lose more in weight than those at half-tide level.

Tar and Bituminous Mixtures.—In reply to the questionnaire many firms wrote recommending coal-tar, in one form or another, as affording a very efficient protection against corrosion. The outward appearance of a tarred surface and its tendency to soften when exposed to the direct action of the sun limit its usefulness somewhat severely; nevertheless, its cheapness is a strong point in its favour, and for subterranean or subaqueous work neither its black appearance nor its tendency to soften in heat will in general militate against its use. For such purposes tar is usually mixed with about 2 oz. of lime per gallon to render it non-corrosive. It is applied to the metallic surface either hot or cold, and sometimes on top of one or more priming coats of red lead.

It seemed desirable, therefore, to test each of these methods, and accordingly in the first tests one series of plates was coated with a layer of refined dehydrated coal-tar (series XI), whilst a second series was first protected with red lead paint, before the application of the tar (series XII). The tar was, in both cases, applied at 100° F. (38° C.) to the extent of 36 lb. per 100 sq. yd. of the bare metal, or 32 lb. when following a coat of 50 lb. of red lead per 100 sq. yd.

The results obtained with the tar alone were exceptionally promising, as regards both loss of weight and freedom from pitting, for all the conditions of exposure (Table XXIX). Except in the complete-immersion tests a preliminary coat of red lead paint proved beneficial, but in the totally-immersed specimens considerable irregularity occurred.

The results of the tests with "bituminous" mixtures (series XIII to XVI), particularly with bituminous solution (series XV), were very encouraging in the half-tide and complete-immersion tests. The bituminous solution proved, on the whole, equal to the dehydrated tar in efficiency. In the aerial tests, however, the results were unsatisfactory. Probably the combined action of sun and wind caused a gradual evaporation of certain tarry or bituminous constituents in the aerial tests, leading to cracks and general disintegration of the coat, whereas when the plates were kept cool by either continuous immersion or continuous wetting with the rise and fall of the tide there was less opportunity for loss of the more volatile constituents. This view receives support from the excellent condition of the plates in series XI in which pure dehydrated tar was used without any addition of naphtha or other volatile material.

In sets IV and V (Table XXX) the effect of adding about 2 per cent. of slaked lime to the dehydrated tar was tried (series XXXVII and XXXVIII). The results were not so good as might have been expected from the results of the previous tests. The whole subject, however, was more fully investigated in sets VI, VII and VIII. Tests were carried out with both vertical- and horizontal-retort tars under various conditions, and the results are detailed in Table XXXI. The essential difference between the two types of tar is due to the difference in the temperatures of their destructive distillation. The horizontal-retort tars have not been subjected to such high temperatures as the vertical-retort tars and thus possess a more bituminous nature. The physical properties and general compositions of the tar mixtures are given in Table XXXIX.

In general, the plates exposed at half-tide level at Southampton corroded more severely than the corresponding plates at Weston-super-Mare. This was to be expected in view of the longer exposure of the plates at Southampton. The exceptions are series XLVIII and L, which are referred to later. As in the oil-paint tests in the previous sets, the completely-immersed plates at Southampton lost more through corrosion than those exposed at half-tide level.

The addition of slaked lime to the horizontal-retort tar (series XL and XLI) exerted a beneficial effect at both Weston-super-Mare and Southampton. The plates coated with the neutralized tar presented a slightly superior surface after exposure, and lost slightly less in weight than those coated with horizontal-retort tar only. On the other hand, the addition of slaked lime to the vertical-retort tar had practically no effect upon its preservative qualities (series XLIII and XLIV).

The addition of 5 per cent. of paraffin wax (series XLV) appeared to improve the protective properties of the vertical-retort tar. Except in set VIII at Weston-super-Mare, where the effect was negligible, the plates lost less in weight through corrosion and were in general less deeply pitted than those coated with vertical-retort tar only (series XLIII).

The horizontal-retort tar applied at 50° C. or 80° C. (series XL) proved greatly superior to the vertical-retort tar (series XLIII), the plates in the latter series losing 3 to 6 times as much in weight as those in the former, besides suffering appreciably deeper pitting. This may be partly due to the greater thickness of the applied coat in consequence of the higher viscosity of the horizontal-retort tar. But this cannot be the full explanation since the plates in series XLVI, coated with vertical-retort tar thickened with tar pitch, were in only slightly better condition than those in series XLIII despite the greater weight of the material applied. The popular prejudice in favour of the horizontal-retort tar for protective coats for iron and steel thus appears to receive support.

Even more pronounced is the superiority of the horizontal-retort tar when applied hot to cold plates (series XLVII and XLIX), the plates coated with vertical-retort tar at 392° F. (200° C.) losing 6 to 10 times as much in weight through corrosion as the corresponding plates protected with horizontal-retort tar. In series XLVII the plates exposed at Weston-super-Mare when dismantled were almost perfect and entirely free from pitting.

In general, tar applied at 392° F. (200° C.) to cold plates gave superior results to tar applied at 176° F. (80° C.). This was particularly the case with the horizontal-retort tar, which may be in part due to the greater weight of material applied.

Application of tar at 392° F. (200° C.) to plates already heated to the same temperature did not in general prove very successful (series XLVIII and L). Not only did the tar drain off the metal, leaving only a thin film, but it lost much of its " nature," becoming brittle and easily dislodged on cooling. The temperature was undoubtedly too high. It would appear that the plates need only be warm enough to ensure their complete dryness and that the tar need not be heated much above the temperature necessary to produce the requisite fluidity. Probably a temperature between 212 and 250° F. (100 and 122° C.) is suitable for the tar under most conditions.

Oil Paint on top of Tar.—A considerable number of tests were made to determine the best method of painting on top of tar. This is particularly necessary if the tarred objects are to be distinguished for intelligence purposes, as, for example, in the case of mark buoys. The best results were obtained by giving each side of the plates, after the tar had set, three coats of shellac varnish* and then one coat of ordinary white lead paint. In series LI the plates received a second coat of white lead, and in series LII a fourth coat of shellac varnish, followed by a second coat of white lead paint.

These methods proved very successful. The white lead surface showed alligatoring but its white colour still predominated. The plates were found to be remarkably well preserved from corrosion (Table XXXI).

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* The shellac varnish was made by dissolving 3 lb. of shellac in 5 lb. of warm methylated spirit. The product was strained through muslin, and applied to the tarred surface in coats at intervals of approximately 12 hours each.

TABLE XXIX.—*Summary of Results with Sets I, II and III* (1924-1931). *All the Plates except those in Series X had been Pickled before Treatment.*

Series	Paint Treatment	Preservative used	Interval between Successive Coats		Paint per Coat per 100 sq. yd.	Total	Number of Plates exposed in each Set	SET I. AERIAL Exposed 7 years		SET II. HALF-TIDE Exposed 1 year		SET III. COMPLETE IMMERSION Exposed 1 year		Ratio of Losses	Depths of Deepest Pits		
			Concave Side	Convex Side				Mean Loss in Weight per 100 sq. yd.	Relative Loss	Mean Loss in Weight per 100 sq. yd.	Relative Loss	Mean Loss in Weight per 100 sq. yd.	Relative Loss	Set III / Set II	Aerial	Half-tide	Complete Immersion
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)
		Parts By Weight.	Days	Days	Lb.	Lb.		Lb.	Per cent.	Lb.	Per cent.	Lb.	Per cent.		Mm.	Mm.	Mm.
IA	One coat standard iron oxide paint	Raw linseed oil .. 100 Standard iron oxide 80	—	—	12	12	10	16·41	576	27·8	88	60·2	116	2·17	—	0·43	0·22
IB	Two coats standard iron oxide paint	do. ..	7	28	12, 8	20	10	2·85	100	31·4	100	52·0	100	1·66	—	0·57	0·23
IC	Three coats standard iron oxide paint	do. ..	8, 42	28, 16	12, 8, 8	28	10	2·74	96	36·1	115	46·2	89	1·28	—	—	—
II	Two coats white lead paint	Raw linseed oil .. 100 White lead 376	7	23	40, 28	68	5	0·78	27	17·7	56	57·6	111	3·25	0·18	0·83	0·53
III	Two coats red lead (i) paint used same day as mixed.	Raw linseed oil .. 100 Red lead (i) 670	7	21	46, 32	78	5	0·26	9	13·3	42	65·8	127	4·95	0·35	0·62	0·35
IV	Two coats red lead (ii) paint used several weeks after mixing.	Raw linseed oil .. 100 Red lead (ii) 670	24	18	50, 32	82	5	0·06	2	8·6	27	77·3	149	9·00	—	0·49	0·45
V	Two coats mixed red lead (ii) and white lead paint	Raw linseed oil .. 100 Red lead (ii) .. .. 245 White lead 245	8	29	46, 34	80	5	0·14	5	14·9	47	68·9	133	4·62	—	0·66	0·64
VI	One coat lead chrome paint followed by one coat mixed red and white lead paint.	Raw linseed oil .. 100 Lead chrome .. 170	20	16	34, 20	54	5	0·46	16	14·0	45	44·7*	86*	3·19*	—	0·64	—
VII	One coat mixed red and white lead paint followed by one coat standard iron oxide paint.	As above	8	16	46, 8	54	5	0·22	8	19·2	61	75·5	145	3·93	—	—	0·47
VIII	Two coats iron oxide litho-oil paint	Litho-oil .. .. 100 Standard iron oxide 80	28	48	12, 8	20	5	1·56	55	18·2	58	56·7*	109*	3·12*	—	—	0·46
IX	Standard iron oxide paint sprayed on plates at 230° F. (110° C.)	As above	—	—	16	16	5	4·12	145	19·8	63	52·5	101	2·64	—	0·48	—
X	Two coats standard iron oxide paint on plates with scale still attached.	do. ..	10	28	12, 8	20	5	41·4	1450	46·3	148	75·6	146	1·63	0·23	—	0·93
XI	One coat tar at 100° F. (38° C.)	Refined dehydrated coal-tar	—	—	36	36	5	0·48	17	3·5	11	9·6	19	2·74	—	—	—
XII	One coat red lead (ii) paint followed by one coat dehydrated coal-tar at 100° F. (38° C.)	As above	13	17	50, 32	82	5	0·38	13	2·3	7	32·5*		†	—	0·41	—
XIII	One coat "dockyard black"	Dehydrated coal-tar 10 lb. Portland cement 1 lb. Heavy coal-tar naphtha 2 pt.	—	—	14	14	5	44·5	1560	8·3	27	28·1	54	3·39	—	0·63	0·44
XIV	One coat coal-tar varnish	Coal-tar pitch .. 40 Creosote oil .. .. 2·5 Coal-tar naphtha .. 25	—	—	10	10	5	194	6800	25·1	80	49·4	94	1·97	—	0·45	0·71
XV	One coat bituminous solution	Refined Manjak bitumen 10 Heavy coal-tar naphtha 12	—	—	15	15	5	35·1	1230	1·8	6	14·0	27	7·77	—	—	0·38
XVI	One coat asphaltum paint	N. American asphaltum 10 Raw linseed oil .. 2 Heavy coal-tar naphtha 10	—	—	16	16	5	117·4	4120	15·3*	49*	22·6	44	1·48*	—	0·60	0·39
XVII	Galvanized	—	—	—	128	128	5	9·20	323	36·4	116	34·2	66	0·94	—	0·12	0·14

† Too irregular. * Irregular. To convert lb. per 100 sq. yd. to grams per 1,000 sq. cm. multiply by 0·543.

TABLE XXX.—*Summary of Results with Sets IV and V* (1927 *and* 1928). *Five Plates were Exposed in each Series in each Set.*

Series	Condition of Plates	Paint Treatment	Preservative used	Interval between Coats	Weight of Paint, etc. per 100 sq. yd.		Set IV. Half-tide Exposed 1 year		Set V. Complete Immersion Exposed 1 year		Ratio of Losses Set V / Set IV	Depths of Deepest Pits	
					First Coat	Second Coat	Mean Loss per 100 sq. yd.	Loss relative to Series XVIII	Mean Loss per 100 sq. yd.	Loss relative to Series XVIII		Set IV	Set V
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
				Days	Lb.	Lb.	Lb.	Per cent.	Lb.	Per cent.		Mm.	Mm.
XVIII	Sandblasted	2 coats standard iron oxide paint	Raw linseed oil .. 100 Standard iron oxide 80	14	12	8	43·6	100	51·2	100	1·18	0·49	0·12
XIX	Scraped ..	do.	do.	14	12	8	65·7	151	96·0	188	1·46	0·60	0·25
XX	Sandblasted	do.	do.	5	12	8	41·0	94	58·6	114	1·43	0·34	0·40
XXI	do.	2 coats iron oxide paint ..	Raw linseed oil .. 100 Standard iron oxide 70 Mineral white .. 10	14	12	8	45·1	104	59·4	116	1·32	0·49	0·41
XXII	do.	2 coats iron oxide paint ..	Raw linseed oil .. 100 Standard iron oxide 70 Silica 10	14	12	8	44·2	102	56·2	110	1·27	0·33	—
XXIII	do.	2 coats iron oxide paint ..	Raw linseed oil .. 100 Standard iron oxide 70 Kaolin 10	14	12	8	44·5	102	56·6	111	1·27	0·38	—
XXIV	do.	2 coats iron oxide paint ..	Raw linseed oil .. 100 Iron oxide (ii) .. 150	14	15·2	12	29·5	68	48·7	95	1·65	0·48	—
XXV	do.	2 coats iron oxide paint ..	Raw linseed oil .. 100 Iron oxide (iii) .. 150	14	13·2	9	28·7	66	53·9	106	1·88	0·50	—
XXVI	do.	2 coats iron oxide paint ..	Raw linseed oil .. 100 Iron oxide (iv) .. 250	14	17	16·4	35·9	82	53·1	104	1·48	0·58	—
XXVII	do.	2 coats iron oxide paint ..	Raw linseed oil .. 100 Iron oxide (v) .. 333	14	25·4	14	26·7	61	48·5	95	1·82	0·28	—
XXVIII	do.	2 coats iron oxide paint ..	Raw linseed oil .. 100 Iron oxide (vi) .. 80	14	12	8	32·5	75	40·9	80	1·26	0·36	—
XXIX	do.	2 coats varnish paint	Raw linseed oil .. 95 Standard iron oxide 80 Varnish 5	14	13·4	8	44·6	102	55·3	108	1·24	0·50	—
XXX	do.	2 coats "antifouling" paint ..	Raw linseed oil .. 100 Standard iron oxide 40 Copper oxide .. 10 Zinc oxide 30	14	12	8	34·5	79	110·2	215	3·19	0·37	0·42
XXXI	do.	2 coats red lead (ii) paint ..	Raw linseed oil .. 100 Red lead (ii).. .. 670	14	55	33·2	15·7	36	40·3	79	2·57	1·00	0·50
XXXII	do.	2 coats red lead (iii) paint ..	Raw linseed oil .. 100 Red lead (iii) .. 670	14	55	33·2	19·4	45	41·4	81	2·13	1·02	0·50
XXXIII	Scraped	do.	do.	14	60·4	36·2	54·0	124	74·5	145	1·38	0·64	1·40
XXXIV	Sandblasted	2 coats red lead (iv) paint ..	Raw linseed oil .. 100 Red lead (iv) .. 670	14	55	33·2	22·5	52	59·4	116	2·64	0·77	0·42
XXXV	do.	1 coat red lead (iii) paint sprayed on plates at 430° F. (221° C.)	Same as Series XXXII	—	44	—	22·8	52	77·0	150	3·38	0·97	0·37
XXXVI	do.	1 coat red lead (iii) paint stoved on plates at 430° F. (221° C.)	do.	—	66·7	—	17·6	40	55·8	109	3·17	0·98	(0·97)*
XXXVII	do.	1 coat dehydrated coal-tar at room temperature.	Dehydrated coal-tar	—	10	—	30·2	69	43·8	86	1·45	—	0·74
XXXVIII	do.	do.	do. neutralized with lime	—	10	—	31·7	73	54·6	107	1·72	—	0·69
XXXIX	Scraped	do.	do.	—	11·6	—	43·4	100	71·9	140	1·65	1·21	0·94

* All old plates.

To convert lb. per 100 sq. yd. to grams per 1,000 sq. cm. multiply by 0·543.

TABLE XXXI.—*Results with Tarred Plates Exposed at Weston-super-Mare and Southampton* (1927 *to* 1929.) *Summary of Results with Sets VI, VII, and VIII. Five Plates were Exposed in each Series in each Set.*

Series	Condition of Plates	Treatment	Nature of Tar	Total weight of tar: lb. per 100 sq. yd.	Mean loss in weight of plates per 100 sq. yd.: lb.			Deepest pits: mm.		
					Southampton		Weston	Southampton		Weston
					SET VI HALF-TIDE exposed 28 months	SET VII COMPLETE IMMERSION exposed 28 months	SET VIII HALF-TIDE exposed 17 months	SET VI HALF-TIDE exposed 28 months	SET VII COMPLETE IMMERSION exposed 28 months	SET VIII HALF-TIDE exposed 17 months
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
XL	Sandblasted ..	Tar A at 80° C. (176° F.)	Horizontal-retort tar	37·6	—	—	3·16	—	—	0·12
	do. ..	Tar A at 50° C. (122° F.)	do. do. ..	37·6	8·70	23·30	—	0·21	0·51††	—
XLI	do. ..	Tar B at 80° C. (176° F.)	Tar A with 2% slaked lime.	37·6	7·96	18·04	2·88	0·37	0·38	—
XLII	As rolled, mill-scale adherent	do. do. do. ..	do. do. ..	37·6	7·20	21·04	2·84	0·66	0·79	0·22*
XLIII	Sandblasted ..	Tar C at 80° C. (176° F.)	Vertical-retort tar ..	27·2	53·92	100·50	10·54	0·40	1·00	0·40*
XLIV	do. ..	Tar D at 80° C. (176° F.)	Tar C with 2% slaked lime.	27·2	56·62	100·28	11·62	0·58	0·81	0·26
XLV	do. ..	Tar E at 80° C. (176° F.)	Tar C with 5% paraffin wax	27·2	40·68	83·08	10·84	0·53	0·38	0·90**
XLVI	do. ..	Tar F at 80° C. (176° F.)	Tar C dehydrated and thickened with vertical-retort tar pitch	37·6	49·54	91·78	9·12	0·35	0·97	0·20
XLVII	do. ..	Tar B at 200–210° C. (392–410° F.) plates cold	—	74·2	—	—	0·62	—	—	—
	do. ..	do. do. do. ..	—	35·6	8·00	—	—	0·56	—	—
	do. ..	do. do. do. ..	—	49·4	—	9·20	—	—	0·44	—
XLVIII	do. ..	Tar B at 200° C. (392° F.), plates at 200° C. (392° F.)	—	8·6	—	—	126·8	—	—	0·2 approx.
	do. ..	do. do. do. ..	—	9·4	6·94	—	—	0·30	—	—
	do. ..	do. do. do. ..	—	10·8	—	31·74	—	—	0·57	—
XLIX	do. ..	Tar D at 200–210° C. (392–410° F.) plates cold	—	39·3	—	—	5·74	—	—	0·23
	do. ..	do. do. do. ..	—	26·8	52·72	—	—	0·34	—	—
	do. ..	do. do. do. ..	—	29·6	—	91·22	—	—	0·52	—
L	do. ..	Tar D at 200° C. (392° F.), plates at 200° C. (392° F.)	—	6·9	—	—	190·5	—	—	0·3 approx.
	do. ..	do. do. do. ..	—	9·0	25·72	—	—	0·56	—	—
	do. ..	do. do. do. ..	—	8·0	—	104·12	—		0·67	—
LI	do. ..	Tar A at 80° C. (176° F.), three coats shellac varnish, two coats white lead	—	37·6†	7·76	11·46	—	—	0·18	—
LII	do. ..	Tar A at 80° C. (176° F.), four coats shellac varnish, two coats white lead	—	37·6†	—	—	0·26	—	—	—

† Combined weight of tar, shellac and paint: Series LI, 66·2 lb. per 100 sq. yd; Series LII, 75·6 lb. per 100 sq. yd.

* Round the washer.

** Exceptional, next deepest pit 0·17 mm.

†† Exceptional, next deepest pit 0·39 mm.

To convert lb. per 100 sq. yd. to grams per 1,000 sq. cm. multiply by 0·543.

TABLE XXXII.—*Comparison of the behaviour of Plates Sandblasted and Plates Scraped after Immersion in Sea-water. These Sets were Exposed for 1 Year.*

Series	Set	Condition of Plates	Treatment	Weight of Paint: lb. per 100 sq. yd.	Mean loss in weight: lb. per 100 sq. yd.	Ratio of Losses Scraped / Sandblasted	Deepest Pits. Mm.
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
XVIII	IV	Sandblasted	2 coats Raw linseed oil 100 Standard iron oxide 80	20	43·6	1·51	0·49
XIX	IV	Scraped		20	65·7		0·60
XVIII	V	Sandblasted	do.	20	51·2	1·88	0·12
XIX	V	Scraped		20	96·0		0·25
XXXII	IV	Sandblasted	2 coats Raw linseed oil 100 Red lead (iii) 670	88·2	19·4	2·78	0·02
XXXIII	IV	Scraped		96·6	54·0		0·64
XXXII	V	Sandblasted	do.	88·2	41·4	1·80	0·50
XXXIII	V	Scraped		96·6	74·5		1·40*
XXXVIII	IV	Sandblasted	1 coat dehydrated coal-tar neutralized with lime	10	31·7	1·37	0·3
XXXIX	IV	Scraped		11·6	43·4		1·21†
XXXVIII	V	Sandblasted	do.	10	54·6	1·32	0·69
XXXIX	V	Scraped		11·6	71·9		0·94

* The next deepest pit in the series was 0·71 mm. † The next deepest pit was 0·59 mm.
To convert lb. per 100 sq. yd. to grams per 1000 sq. cm. multiply by 0·543.

TABLE XXXIII.—*Effect of Mill-scale.*

Series	Treatment	Place of Exposure	Plate Surface	Mean losses in weight: lb. per 100 sq. yd.			Maximum depths of pitting: Mm.		
				Air	Half-Tide	Complete Immersion	Air	Half-Tide	Complete Immersion
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
I	2 coats of standard iron oxide paint.	Southampton	Pickled	2·85*	31·4†	52·0†	—	0·57†	0·23†
X	do.	do.	With scale	41·4*	46·3†	75·6†	0·23*	—	0·93†
XLI	Tar with 2 per cent. slaked lime.	Weston-super-Mare	Sandblasted	—	2·88‡	—	—	—	—
XLII	do.	do.	With scale	—	2·84‡	-	—	0·22‡	—
XLI	do.	Southampton	Sandblasted	—	7·96§	18·04§	—	0·37§	0·38§
XLII	do.	do.	With scale	—	7·20§	21·04§	—	0·66§	0·79§

* Exposed for 7 years.
† Exposed for 1 year.
‡ Exposed for 17 months.
§ Exposed for 28 months.

TABLE XXXIV.—*Comparison of the various Iron Oxide Paints. These Sets were exposed for 1 year.*

Series	Pigment	Composition of pigment: Per cent.			Composition of Paint	Wt. of Paint: lb. per 100 sq. yd.	Relative Mean loss in weight		Depths of Deepest Pits: Mm.	
		Iron Oxide	Silica, Kaolin or Alumina	Lime	Parts of Pigment per 100 of oil		Set IV	Set V	Set IV	Set V
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
XVIII	Iron oxide (i)	97·79	1·18	Trace	80	20	100	100	0·49	0·12
XXIV	Iron oxide (ii)	84·51	10·26	2·40	150	27·2	68	95	0·48	—
XXV	Iron oxide (iii)	75·87	12·30	6·00	150	22·2	66	106	0·50	—
XXVI	Iron oxide (iv)	98·67	0·50	Trace	250	33·4	82	104	0·58	—
XXVII	Iron oxide (v)	97·73	1·18	,,	333	39·4	61	95	0·28	—
XXVIII	Iron oxide (vi)	57·26	39·05*	—	80	20	75	80	0·36	—

* Including sodium salt.

TABLE XXXV.—*Comparison of the Red Lead Paints.*

Series	Pigment	Pb_3O_4: Per cent.	Weight of paint: lb. per 100 sq. yd.	AERIAL Exposed for 7 years			HALF-TIDE Exposed for 1 year			COMPLETE IMMERSION Exposed for 1 year		
				Mean loss in weight: lb. per 100 sq. yd.	Relative mean loss	Deepest Pits: Mm.	Mean loss in weight: lb. per 100 sq. yd.	Relative mean loss	Deepest Pits: Mm.	Mean loss in weight: lb. per 100 sq. yd.	Relative mean loss	Deepest Pits: Mm.
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
IB	Standard iron oxide	—	20	2·85	100	—	31·4	100	0·57	52	100	0·23
III	Red lead (i) applied same day as mixed	53·7	78	0·26	9	0·35	13·3	42	0·62	65·8	127	0·35
IV	Red lead (ii) applied several weeks after mixing	61·6	82	0·06	2	—	8·6	27	0·49	77·3	149	0·45
XVIII	Standard iron oxide	—	20	—	—	—	43·6	100	0·49	51·2	100	0·12
XXXI	Red lead (ii)	64·8	88·2	—	—	—	15·7	36	1·00	40·3	79	0·50
XXXII	Red lead (iii)	80·5	88·2	—	—	—	19·4	45	1·02	41·4	81	0·50
XXXIV	Red lead (iv)	92·6	88·2	—	—	—	22·5	52	0·77	59·4	116	0·42

Table XXXVI.—*Comparison of Red and White Lead Paints.*

Series	Preservative	Weight of paint : Lb. per 100 sq. yd.	Aerial Exposed for 7 years			Half-tide Exposed for 1 year			Complete Immersion Exposed for 1 year		
			Mean loss in weight : lb. per 100 sq. yd.	Relative mean loss	Deepest Pits : Mm.	Mean loss in weight : lb. per 100 sq. yd.	Relative mean loss	Deepest pits : Mm.	Mean loss in weight : lb. per 100 sq. yd.	Relative mean loss	Deepest pits : Mm.
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
IB	Standard iron oxide	20	2·85	100	—	31·4	100	0·57	52·0	100	0·23
III	Red lead (i)	78	0·26	9	0·35	13·3	42	0·62	65·8	127	0·35
II	White lead . .	68	0·78	27	0·18	17·7	56	0·83	57·6	111	0·53
V	Mixed white lead and red lead (ii)	80	0·14	5	—	14·9	47	0·66	68·9	133	0·64
IV	Red lead (ii)	82	0·06	2	—	8·6	27	0·49	77·3	149	0·45

Table XXXVII—*Comparison of Lead Chromate and Mixed Red and White Lead Paints.*

Series	Paint	Aerial Exposed for 7 years		Half-tide Exposed for 1 year		Complete Immersion Exposed for 1 year	
		Mean loss in weight : lb. per 100 sq. yd.	Relative mean loss	Mean loss in weight : lb. per 100 sq. yd.	Relative mean loss	Mean loss in weight : lb. per 100 sq. yd.	Relative mean loss
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
V	Two coats of mixed red and white lead.	0·14	100	14·9	100	68·9	100
VI	One coat of lead chromate followed by one of mixed red and white lead.	0·46	329	14·0	94	44·7	65

TABLE XXXVIII—*Application of Paint to Hot Plates.*

Series	Treatment	Weight of paint: lb. per 100 sq. yd.	AERIAL Exposed for 7 years		HALF-TIDE Exposed for 1 year		COMPLETE IMMERSION Exposed for 1 year	
			Mean loss in weight: lb. per 100 sq. yd.	Relative mean loss	Mean loss in weight: lb. per 100 sq. yd.	Relative mean loss	Mean loss in weight: lb. per 100 sq. yd.	Relative mean loss
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
1A	One coat standard iron oxide applied with brush.	12	16·41	100	27·8	100	60·2	100
IX	One coat standard iron oxide applied with spray on hot plates.	16	4·12	25	19·8	71	52·5	87
IB	Two coats standard iron oxide applied with brush.	20	2·85	17	31·4	113	52·0	86

TABLE XXXIX.—*Physical Properties and General Compositions of the Tar Mixtures employed.*

Identification letter	Composition of mixture	Specific gravity	Viscosity tests (seconds)	Distillation Test			Naphthalene Per cent.	Tar Acids by volume Per cent.
				0–170° C. Per cent.	170–270° C. Per cent.	270–300° C. Per cent.		
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
A	Horizontal-retort tar ..	1·213	14	—	18·7	5·1	8·3	3·1
B	Tar A with 2 per cent. slaked lime	1·220	15	0·37	18·9	4·0	8·8	3·1
C	Vertical-retort tar	1·129	14	—	18·7	6·4	Trace	8·5
D	Tar C with 2 per cent. slaked lime	1·138	14	0·20	15·7	9·6	Trace	6·5
E	Tar C with 5 per cent. paraffin wax	1·109	40	—	13·7	8·8	Trace	5·46
F	Tar C dehydrated and thickened with vertical-retort tar pitch.	1·133	14	—	22·8	6·1	4·6	8·6

SECTION IV

DETERIORATION OF REINFORCED CONCRETE

INTRODUCTION

Owing to the numerous reports of failures in reinforced-concrete piles and structures subject to sea action, the Committee decided that a detailed investigation should be undertaken with a view to determining, if possible, the cause of these failures and the steps that should be taken to prevent their recurrence in the future.

Previous work on the subject seemed to suggest that the following were likely to assist in the preservation of reinforced concrete in sea-water :—

A concrete mixture rich in cement;
A thick cover of concrete over the steel;
A rather dry consistency;
The addition of pozzolanas (both naturally occurring and artificial).*

The investigation here described was designed especially to throw light on these points and also to give information about the behaviour in sea-water of different types of cement.

The Committee was fortunate in obtaining, at an early stage of its investigation, the advice and assistance of Dr. R. E. Stradling, M.Inst.C.E., Director of Building Research in the Department of Scientific and Industrial Research, and after due consideration it was decided that the best method of attaining the objects in view would be to carry out a series of tests on reinforced-concrete specimens in which various aggregates and cements were used, the specimens under observation being kept exposed in sea-water.

The arrangement finally adopted for carrying out this investigation was as follows. Duplicate sets of specimens or piles of reinforced concrete, 5 ft. long and 5 in. square, were exposed, one at Sheerness, where, by the consent of the Admiralty, a site was allocated for this

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* A substance is said to be pozzolanic when, while not necessarily cementitious in itself, it possesses constituents which, in the presence of moisture, will combine with hydrated lime at ordinary temperatures to form stable, insoluble compounds of cementitious value. Trass (which is a rock of volcanic origin found in Germany) is one of a number of naturally occurring materials which possess this property, while certain materials prepared artificially (e.g. spent shale from the Scotch shale-oil industry, or clay burnt under suitable conditions) can also be used for the same purpose. All three of these materials have been included in the investigations now being carried out.

purpose, at which the specimens were kept under control and subject to tidal action, and the other at the Building Research Station, Watford, where the piles were kept in artificial sea-water containing three times the quantity of the salts normally present in sea-water.

These experiments were commenced in 1929, 144 piles being exposed in the first instance at each place. This number was subsequently increased to 474 in all, which included replicas of twenty-four piles which were exposed under tropical conditions on the Gold Coast.

In each series of experiments concretes made with four types of cement were used, namely :—

(*a*) Normal Portland cement;
(*b*) A rapid-hardening Portland cement;
(*c*) A high aluminous cement;
(*d*) A Portland blast-furnace cement.

The aggregate used consisted of graded sand, screened through a ¼-in. mesh, and river shingle passing a ½-in. mesh but retained on a ¼-in. mesh. The proportions of cement to aggregate were varied, the mixtures being described as "rich," "medium" and "lean." With the rich and medium mixtures two consistencies were adopted, termed "dry" and "normal," the "dry" having a ½-in. and the "normal" a 2-in. slump. With the lean mixture a normal consistency only was found to be suitable.

In addition, some further mixtures were made in which a portion of the aggregate was replaced by trass, which for many years has been successfully used in Germany in structures exposed to sea action.

Since additions of pozzolana to Portland cement concrete, for use in sea-water, were known to have a beneficial effect and since recent investigations at the Building Research Station have shown that the characteristic properties of pozzolana can be obtained with certain spent shales and burnt clay, a further series of test-piles was prepared in which this artificial pozzolana was incorporated. As these specimens have been under observation for only 18 months, no definite conclusions can yet be drawn from their behaviour.

In all cases the steel reinforcement was so placed as to provide alternative concrete cover to the rods of 1 in. and 2 in.

The majority of the piles have now been exposed for more than 5 years, and examinations have been made twice yearly, in the spring and autumn. For this purpose the specimens are removed from the water, closely examined and photographed.

In addition to the reinforced piles 5,388 cylindrical compression test-specimens were made. After maturing under the same conditions as the reinforced piles, the cylinders were stored in three series, namely :—

(1) in fresh water;
(2) partially immersed in artificial sea-water;
(3) totally immersed in artificial sea-water.

Six cylinders of each mixture have been prepared for testing in compression at the ages of 3 and 6 months and 1, 2, 5 and 10 years.

CONCLUSIONS

These conclusions are based on the results of experiments extending over a period of 5 years, which experiments are being continued for a further period of 5 years, when a supplementary report will be issued.

It should be noted that the reinforced specimens referred to in this report were prepared under laboratory conditions, special care being given to the mixing and placing of the concrete.

1. Where a 2-in. cover of concrete was provided over the steel reinforcement, medium mixtures, of proportions 1 : 1·67 : 3·33, afforded good protection against corrosion of the reinforcement.

2. Of the cements used none showed any special advantage.

3. The addition of trass in the case of the lean mixtures proved advantageous. The reinforced specimens with this addition showed few or no signs of deterioration.

Tests in which artificial pozzolanas were used did not provide definite evidence of the value of these materials.

4. A dry mixture ($\frac{1}{2}$-in. slump) proved slightly superior to a wetter mixture (2-in. slump), but the difference was not well defined. Practically no cracks were observed on the trowelled surface of the test-piles, owing probably to the increased impermeability of the concrete due to the trowelling.

5. More piles showing cracks were found at Sheerness where they were exposed in actual sea-water, than at the Building Research Station in artificial sea-water of three times the normal strength. This was probably due to the more severe climatic conditions at Sheerness. The experiments, however, indicated that the behaviour of reinforced concrete in artificial sea-water was a very good guide to its probable behaviour in ordinary sea-water. Exposure on the Gold Coast has produced similar failures, but these are in most cases less severe than at the Building Research Station; this may in part be due to the fact that the specimens were older when exposed.

6. Cracking has nearly always occurred after signs of rust have appeared on the surface of the concrete. It would seem, therefore, that the permeability of the concrete is largely responsible. The

deterioration of the piles was chiefly due to the rusting and consequent expansion of the reinforcement, causing cracking of the concrete, rather than the attack on the concrete by sea-water.

The deterioration of the piles, as shown by cracking of the concrete, occurred, with few exceptions, in the case of all mixtures above water-level.

7. The tests made with small cylinders have not given any guidance as to the occurrence of cracking in the reinforced-concrete piles. Except with lean mixtures, the concrete of the test-specimens was not materially affected.

8. The experiments indicate that the concrete cover, so far as practicable, should be impermeable and that in the medium mixtures this can be obtained with a 2-in. cover.

EXPERIMENTAL INVESTIGATION OF THE DURABILITY OF REINFORCED CONCRETE IN SEA-WATER

By R. E. Stradling, C.B., M.C., D.Sc., Ph.D., M.Inst.C.E.

A CONSIDERABLE amount of research has already been carried out in various countries upon the action of sea-water, or solutions of its component salts, on different types of concrete, but relatively little has been done to investigate its effects upon composite structures of concrete and steel. Moreover, a wide diversity of conclusions has been reached by the different investigators. In these circumstances it appeared that the most promising method of acquiring the necessary information would be to carry out extensive experiments under conditions as nearly as possible comparable with those occurring in actual engineering practice.

In view of the divergence of views expressed on the best method to be adopted in the making of concrete capable of resisting sea action and the materials to be employed, the Committee decided, with a view to obtaining definite information on some of these points, to confine their experiments to the following variations, using in all cases the same aggregate :—

1. The use of various types of cement.
2. Variation in the quantity of cement.
3. Variation in the quantity of water used in mixing.
4. The addition of natural and artificial pozzolanas.
5. In the case of reinforced concrete, variations in the depth of cover.

The programme drawn up in collaboration with the Building Research Station envisaged the preparation of 300 reinforced-concrete specimens or piles of which 276 were to be exposed in two similar sets of 138 each in sea-water at Sheerness dockyard and in artificial sea-water at Watford and twenty-four under tropical conditions on the Gold Coast. This number was augmented at the beginning of the investigation by the addition of twelve piles to be exposed in sets of six at Sheerness and Watford. Subsequently it was decided to carry out a subsidiary set of experiments on specimens made with high alumina cement, and ninety-six piles were prepared for this purpose. At a still later date a further series of sixty-six piles was laid down with the object of obtaining comparative data on the behaviour of concrete mixtures containing artificial pozzolanas. In addition to the piles a large number of cylinders have been made for the purpose of compressive strength tests : ten were prepared for each of the 288 piles exposed at Sheerness and at Watford, 1,056 for the subsidiary series of high alumina cement concrete and 1,452 for the artificial pozzolana series. The experiments have thus involved the preparation of 474 reinforced-concrete piles and 5,388 cylinders.

The investigation falls into four sections :—

(A) main experiments at Sheerness and Watford,
(B) experiments on the Gold Coast,
(C) subsidiary experiments with high alumina cement concrete at Sheerness and Watford, and
(D) experiments with concrete containing artificial pozzolanas at Sheerness and Watford.

It will therefore be convenient to describe the piles and the results obtained up to the present under these headings.

The longest period of exposure yet experienced by any of these series is only 5½ years. Any conclusions which might be drawn at present from observations already made are therefore necessarily tentative. Further examination may lead to a modification of present views and the final opinion must necessarily be deferred.

A. MAIN EXPERIMENTS AT SHEERNESS AND WATFORD

The reinforced-concrete piles are 5 in. square in section and 5 ft. long. In one-half of the series the reinforcement consists of a round steel rod 1 in. in diameter placed in the centre of the specimen so that there is 2 in. of cover over the steel; in the other half, four ½-in. rods are placed one at each corner and so arranged as to give 1 in. of cover.

Four types of cement have been used, namely :—

Normal Portland cement.
Rapid-hardening Portland cement.
High alumina cement
Portland blast-furnace cement.

Chemical analyses of these cements are given in Appendix A.

The aggregate consisted of a uniformly graded mixture of sharp sand screened through a ¼-in. mesh and washed, and river shingle passing a ½-in. mesh and remaining on a ¼-in. mesh, also washed.

The proportions used are shown in Table XL. The concrete was mixed by hand in two consistencies, namely " dry," having a slump-test value of ½ in., and "normal" having a slump of 2 in., and three proportions by weight : " rich," 1 : 0·87 : 1·73; " medium," 1 : 1·67 : 3·33 ; and " lean," 1 : 3 : 6.

Some of the mixtures contain trass, and the method of incorporating this with the cement necessitated careful consideration. In these experiments a ratio of 2 parts by weight of trass to 3 parts of cement was selected as a result of previous researches at the Building Research Station and of recommendations of continental workers. The trass when introduced into the mixture may be considered either as a substitute for a portion of the cement or as replacing a portion of the fine aggregate. The mixtures containing trass have, therefore, been so proportioned that a rich mixture in which trass is taken as a substitute for cement has the same composition as the leaner mixtures in which trass is substituted for aggregate. Thus mixture 1B (Table XL) is the same as 2C, and 2B is the same as 3C. A set of twelve specimens was also prepared in which sand ground to the fineness of trass was used instead of trass in a lean mixture. This set should enable a distinction to be made between the chemical functions of trass as a cementing material and its physical functions as an inert filler.

The piles were cast in timber moulds. The concrete was poured in three layers, each layer being thoroughly punned, and the concreting proceeding without interruption until the pile was completed. The specimens were kept moist for 24 hours, after which the sides of the moulds were struck and the specimens were left on their base-boards for 2 days. The base-boards were then removed and the specimens were covered with damp sacking for 7 days. They were finally stored for 3 weeks in air under cover. Six piles having 1 in. of cover to the reinforcement were prepared for each mixture with a further six piles with 2 in. of cover. A schedule of the mixtures adopted for the piles is given in Table XLI.

The cylinders for compression tests were prepared and stored under the same conditions as the reinforced piles until they were 28 days old, when they were stored at the Building Research Station in three separate series, the first in fresh water, the second partly immersed in artificial sea-water of three times normal concentration, and the third totally immersed in artificial sea-water of three times normal concentration. Of the cylinders of each different mixture prepared, six were to be tested in compression at the ages of 3 and 6 months, and 1, 2, 5 and 10 years. The results which have been obtained at periods up to, and including, 5 years are given in Appendix B (p. 123) and tend to confirm the observations which have been made.

Half of the 288 reinforced piles are being exposed at Sheerness dockyard and the other half at the Building Research Station, Watford. Triplicate specimens of each mixture with each depth of cover over the reinforcement have been provided for each place.

The conditions of exposure at the two places are somewhat different. At Sheerness the lower portion of the piles is permanently immersed to a depth of about 18 in. in sea-water and a rise and fall of water-level of about 15 in. occurs automatically twice daily, following the normal change of tides; this movement is attained by a specially devised mechanism actuated by the tides themselves. At Watford, the piles stand uniformly distributed in two similar tanks only one of which is filled at any one time, the specimens being immersed to a depth of 18 in. when the tank is filled. The solution, which is an artificial sea-water of three times normal strength, is pumped from one tank to the other three times weekly, thus allowing a more thorough, though less frequent, drying out than occurs at Sheerness, where, however, the exposure to climatic conditions is the more severe. The conditions of storage at Sheerness and at Watford can be seen in Figs. 119 and 120 respectively.

Of the cylinders, all of which are exposed at Watford, one-third are immersed in fresh water, while two-thirds are exposed to artificial sea-water of three times normal concentration, half of these being completely immersed and the remainder half immersed. The water is circulated occasionally, but there is no tidal effect such as that experienced by the piles. The conditions of exposure can be seen in Fig. 120.

Examinations.—At the present time the series has been under exposure for about 5½ years. Examinations are made twice yearly, usually in spring and in autumn, the specimens being removed from the tanks and allowed to dry out so as to facilitate making the necessary observations and taking photographs. Each face is closely examined and all material changes which have occurred since previous examinations are photographically recorded. Due regard is paid to the following effects: (1) accidental damage, (2) efflorescence above water-level, surface crazing, powdering of surfaces caused by weakening of surface films of cement, and colour changes of the surface, (3) cracking due to corrosion of reinforcement, associated with rust-stains on the surface, and (4) disintegration of the corresponding test-cylinders of concrete. In addition to these visual effects, strength properties of cylinders removed at the specified periods are recorded.

Typical photographic records are shown in Figs. 121 to 131. Figs. 121 to 127 show the condition after 3–3½ years of the cylinders formed of lean mixtures of high alumina cement, rapid-hardening Portland cement without and with trass, normal Portland cement without and with trass and with sand, and Portland blast-furnace cement respectively. In Figs. 128 to 131 are shown the conditions of certain of the reinforced piles as follows: lean mixtures of high alumina cement after 4 years and of normal Portland cement after 3½ years at Watford; and lean mixture of high alumina cement after 4 years and medium mixture of rapid-hardening Portland cement after 2½ years at Sheerness.

Observations.—Generally in the early stages, minor effects were observed in the piles, such as efflorescence, powdering, deposition of insoluble material, and small isolated rust-marks. Within a year the cylinders of lean mixtures of high alumina, rapid-hardening Portland and Portland blast-furnace cements were beginning to disintegrate, and in the first named, the corresponding piles were beginning to disintegrate at water-level. Gradually, cracks began to appear, often connected with rust-marks already existing, though sometimes rust did not appear until later. Often the lean mixtures were affected before the medium mixtures. The early cracks were associated with piles having 1 in. of cover, but ultimately, though in the lean mixtures only, several piles with 2 in. of cover became affected. Judging from the positions in which they occurred, the cracks (which ranged in length from a few inches to several feet), could usually be definitely associated with the reinforcement, and they were found to extend to all the triplicates, within a short period of their appearance. The subsequent exposure has generally enhanced the effects, and the cracks have increased in size. In certain cases, however, there appears to be a tendency for them to be sealed with insoluble material.

One particular mixture seems to have shown a somewhat anomalous behaviour. Generally, the rich mixtures of normal Portland cement and trass with 1 in. of cover to the reinforcement, exposed at Watford, were cracked in the early stages, without any subsequent increase. A similar mixture, however, made later, has shown no signs of cracks after more than 3 years exposure. The apparent anomaly is emphasized by the fact that the corresponding lean mixture is, at present, the only lean mixture of the whole series which is entirely intact.

In judging the behaviour of the trass mixtures designated as lean, it must be borne in mind that in these particular cases the proportions of materials were so chosen that the mixture can be considered as lean or medium according as the trass is considered to function as sand or as cement respectively. The general behaviour of the individual cements and mixtures under test over the period of 5–5½ years is summarized in Tables XLII to XLVII. The present condition of the series, as observed at the tenth examination in November, 1934, is summarized in Table XLVIII.

High Alumina Cement. Reinforced Piles.—The outstanding feature in the observations made on this cement was the erosion above high-water level at Sheerness and at the base of the piles at Watford, which was becoming serious at the end of the first year of exposure. The surfaces of the specimens of the lean mixture were beginning to disintegrate at high-water level at Sheerness and at the base of the piles at Watford, and this was obviously due to attack on the concrete itself since it occurred irrespective of the cover to the reinforcement. This effect in the lean mixture increased continuously, but no such effect has yet appeared on piles made from the medium and rich mixtures.

Cracks in the lean mixture were masked by the presence of considerable rusting. The rate at which the various mixtures have become attacked is shown in Table XLII. Only the rich mixture is intact, and the medium mixture of dry consistency has suffered less than the corresponding mixture with normal consistency, only one of the twelve piles of the former mixture being cracked.

Cylinders.—Up to the present time the cylinders of the rich and medium mixtures have remained entirely unchanged. Those of the lean mixture, however, had become fragile and showed blistering at water-level within the first year—an effect which correlates with the erosion observed on the corresponding reinforced specimens. Thereafter the disintegration became rapidly worse and the cylinders can be considered as destroyed.

Rapid-hardening Portland Cement. Reinforced Piles.—No disintegration of the concrete has been observed but considerable cracking has occurred. Even in the rich mixture, two piles at Sheerness became cracked within 3½ years, but the cracks appeared to be sealed with insoluble matter. Both medium mixtures are considerably affected but only in specimens having 1 in. of cover. All specimens of the lean mixture, however, at both Sheerness and Watford, are cracked, even though the onset of cracking in this mixture was somewhat delayed. The rate at which cracks have appeared is indicated in Table XLIII.

Cylinders.—Within 12 months cylinders of all mixtures were heavily coated with insoluble deposits which consisted chiefly of the carbonates of magnesium and calcium, owing to the action of the sea-water on the concrete, and those of the lean mixture were swelling and becoming mushy at the bases. A progressive increase in this effect in the cylinders of the lean mixture has been shown in subsequent examinations and their present condition is very bad. After 5 years exposure to sea-water, the cylinders of the lean mixture were so badly disintegrated that they have been removed from the test. Only recently have the medium mixtures begun to soften.

Rapid-hardening Portland Cement—Trass Mixture. Reinforced Piles.—The trass mixtures have been singularly free from defects. No changes have occurred in the rich mixtures, and only two specimens with 1 in. of cover of the lean mixture, one at Sheerness and the other at Watford, have become cracked. The rate at which cracks have appeared is indicated in Table XLIV.

Cylinders.—No deposits of insoluble material have occurred on any mixture. The two rich mixtures are still intact, but the lean mixture has become somewhat soft during the last 2½ years, though the effect is not very serious. In all mixtures, however, the hot weather during the summer of 1934 produced a powdering above water-level, as a result of increased evaporation and resultant deposition of salt from the sea-water, the submerged portions being unaffected. In general, even if the lean mixture used in the piles and the cylinders is considered as equivalent to a medium mixture, the behaviour of this mixture still compares very favourably with that of the other plain cement mixtures.

Normal Portland Cement. Reinforced Piles.—Cracking, while absent from the rich mixtures, is considerable in the medium and lean mixtures, and, while somewhat delayed, is now most serious in the lean mixture, in which all piles with 1 in. of cover at both Sheerness and Watford are cracked. The effect however, has not, yet extended to any specimens with 2 in. of cover to the reinforcement, in contrast to the corresponding mixture of rapid-hardening Portland cement. The rate at which cracks have appeared is indicated in Table XLV.

Cylinders.—Heavy deposits occurred in all mixtures simultaneously with those in mixtures made from the rapid-hardening Portland cement, but after 3½ years exposure only the cylinders of lean mixture had begun to swell at the base. Compared with other plain cements, this cement appears to have given the best general results.

Normal Portland Cement—Trass and Sand Mixtures. Reinforced Piles.—Rather anomalously, cracks appeared in specimens of a rich trass mixture at Watford during the early stages of exposure, and eventually extended to four piles of rich mixtures, all with 1 in. of cover. There has been very little change in these piles since the cracks were first observed. No defects have occurred in the specimens formed with the lean mixture, which remains at present the only one of the medium and lean mixtures of the series which is still intact.

The corresponding lean mixture containing finely ground sand resembled the lean trass mixture in the early stage, but ultimately cracking occurred in all piles of this mixture with 1 in. of cover to the reinforcement, and the cracking subsequently extended. The rate at which cracks have appeared is indicated in Table XLVI.

Cylinders.—The cylinders of all mixtures, both those containing trass and that containing sand, have shown excellent resistance to disintegration. At the eighth examination, however, all mixtures had become powdery above water-level in a manner comparable with the behaviour of the corresponding mixtures containing rapid-hardening Portland cement. The general behaviour of the sand mixture resembles that of the corresponding trass mixture.

Portland Blast-furnace Cement. Reinforced Piles.—Cracks were first observed in the lean mixture at the second examination; they gradually extended to four specimens, and remained thus until the tenth examination, when two more specimens were found to be cracked, all with 1 in. of cover to the reinforcement. In the medium mixtures one pile was seen to be cracked at the fifth examination, but this was exceptional inasmuch as after 4½ years only one of the twenty-four piles of these mixtures was affected. Within the next year, however, three further piles of medium mixtures, all at Sheerness, became cracked near the base. The rate at which cracks have appeared is indicated in Table XLVII.

Cylinders.—The cylinders of lean mixture were becoming soft at the second examination and disintegration thereafter was very rapid. At present these cylinders are almost destroyed, and owing to their bad state of disintegration they have been removed from test. Heavy deposits occurred below water-level on the rich and medium mixtures, but except for slight disintegration in one of the latter, very little further change has occurred.

General Observations

Table XLVIII summarizes the present condition of the piles.

The reality of the effects is emphasized in many mixtures by the fact that cracking, when it occurs, has affected all triplicates in a like manner. The effects in the lean mixtures usually occur at high-water, and in the medium mixtures at low-water level.

Depth of cover to the reinforcement, and richness of mixture which controls the permeability, are important factors in determining resistance to sea-water. Covers of 2 in. in lean mixtures and 1 in. in medium mixtures appear to be insufficient. No pile with 2 in. of cover in the medium mixtures is yet affected, and so far the specimens with 2 in. of cover which are cracked are confined to lean mixtures of two particular cements. Medium mixtures of dry consistency appear to be less affected than the corresponding mixtures of normal consistency.

The trass mixtures compare very favourably with the plain cement mixtures. Thus, the lean mixture of normal Portland cement and trass is the only one of the lean and medium mixtures of the series entirely unaffected. A similar superiority is also observable in the cylinders of these lean mixtures when compared with lean mixtures of plain cements.

The exceptionally poor behaviour of the lean mixture of the high alumina cement and the good behaviour of the trass mixtures has led to the testing of the two further series, C and D, already referred to.

B. Experiments on the Gold Coast

Simultaneously with the main series of exposures at Sheerness and at Watford, a representative series of twenty-four piles has been undergoing test on the Gold Coast for 4 years. The same brands of cements and the trass mixtures as used in the main series (namely, a high alumina cement, rapid-hardening and normal Portland cements with and without trass, and a Portland blast-furnace cement) were used in the medium and lean mixtures, and in each case there are duplicates having 1 in. of cover to the reinforcement. A schedule of the piles is given in Table XLIX.

The conditions of exposure are different from those at Sheerness and at Watford. The piles are strapped to concrete beams between the buttresses of the breakwater at Sekondi harbour, and are exposed to the sea between high- and low-water levels. The feet always rest slightly in water and at high tide the specimens are almost submerged. The sea-water is of normal strength, but the climate allows a much more thorough drying than is likely to occur in this country. The immersion was begun in December, 1929, and reports are received from the authorities at Sekondi each year.

The most prominent feature after 4 years exposure is the disintegration of the piles made with high alumina cement. In the medium mixture, the reinforcing-bars of one pile are exposed for a few inches; one of the piles of lean mixture is affected similarly while the other is so disintegrated that the tops of the reinforcing-bars are completely exposed for a length of about 2 ft. This behaviour correlates well with that of the corresponding mixtures being tested in this country. Of the remaining piles, one of the lean mixture of Portland blast-furnace cement has its reinforcement exposed for about 4 in. from the top, and other specimens are showing some small signs of rusting.

TABLE XLIX. *Schedule of Piles exposed on the Gold Coast*

Type of Cement used	Parts by Weight		
	Cement	Pozzolana	Graded Aggregate
Normal Portland	1	—	5
Normal Portland	1	—	9
Rapid-hardening Portland	1	—	5
Rapid-hardening Portland	1	—	9
Normal Portland and trass	1	$\frac{2}{3}$	$4\frac{1}{3}$
Normal Portland and trass	1	$\frac{2}{3}$	$8\frac{1}{3}$
Rapid-hardening Portland and trass ..	1	$\frac{2}{3}$	$4\frac{1}{3}$
Rapid-hardening Portland and trass ..	1	$\frac{2}{3}$	$8\frac{1}{3}$
High alumina	1	—	5
High alumina	1	—	9
Portland blast-furnace	1	—	5
Portland blast-furnace	1	—	9

C. SUBSIDIARY EXPERIMENTS WITH HIGH ALUMINA CEMENT CONCRETE

The results obtained with the lean mixture of high alumina cement of the main series of reinforced piles were unexpected; consequently it was decided to expose a further series made with a new batch of the same brand as well as another brand of high alumina cement. The series consists of forty-eight piles made with each cement, with the corresponding number of cylinders, half being at Sheerness, and the remainder at Watford. The piles are of the same size as before, namely 5 in. by 5 in. by 5 ft. Similar groups of four different concrete mixtures were made with each brand of cement. One rich mixture was used, having a dry consistency corresponding to a slump of $\frac{1}{2}$ in. and composed of 1 part of cement, 0·87 sand and 1·73 gravel by weight. Medium mixtures of 1 : 1·67 : 3·33 were of the two consistencies used in the main experiment. A lean 1 : 3 : 6 mixture was also made with a slump of 2 in. The concretes were mixed by machine and placed in a specimen-mould in three layers carefully punned.

The series was made and deposited in October 1931. The only departure from the old curing schedule was the time of demoulding of specimens. In the present series the piles were removed from the moulds after 8 hours, instead of the 24 hours adopted originally in the whole of the main series, thus minimizing the effects resulting from the heating which appears to be typical of this type of cement. The conditions of exposure are identical with those in the main series. The series has now been under test for 3 years. So far the crumbling of the concrete, which occurred in the first year on both piles and cylinders of lean mixture of the original high alumina cement, has not been reproduced. In the lean mixture of the cement of the same brand (Y) as that used in the old series, some of the cylinders are cracking and swelling at water-level, two piles with 1 in. of cover at Watford are cracked and all three are badly rusted below water-level, while all three piles with 1 in. of cover at Sheerness have become cracked at high-water level—an indication that in all six piles with 1 in. of cover the reinforcement is being attacked.

In the case of the cement of a different brand (Z), one cylinder of lean mixture is cracked and swollen at water-level, and the feet of all three reinforced piles with 1 in. of cover and of lean mixture at Watford are rusted below water-level, one of these being cracked, while at Sheerness all three corresponding piles are cracked at high-water level.

Both cements show a superiority over the corresponding one in the old series, but it is not possible to forecast to what extent the effects originally observed will be reproduced. The cracking in medium mixtures observed in the older series, is, however, at present absent.

In order that this series may be compared with the corresponding group in the main experiment, the observations made on the lean mixtures of these two cements are given in Table L. All specimens of the richer mixtures are apparently sound.

The results of compression tests on cylinders exposed to water and sea-water for periods up to 2 years are given in Appendix B and have been subjected to a statistical analysis. These tend to confirm the observations made periodically.

D. SUBSIDIARY EXPERIMENTS WITH CONCRETE CONTAINING ARTIFICIAL POZZOLANAS

Partly as a result of the apparently beneficial effects which attend the use of trass in admixture with cements, and partly because work at the Building Research Station had shown that the characteristics of natural pozzolanas can be reproduced in certain other materials by suitable preparation, a series of concretes in which artificial pozzolanas are incorporated has been exposed at Sheerness and at Watford. In general, the mixtures are similar to the trass mixtures of the main series, but, as a result of experience gained with that series, the number of specimens has been reduced to the minimum consistent with the information which it is desired to obtain.

TABLE L

Examination	Location	Lean Mixture, Normal Consistency	
		Cement Y	Cement Z
1st	Sheerness Watford	Uncracked Uncracked Cylinders : Sound	Uncracked Uncracked Cylinders : Sound
2nd	Sheerness Watford	Uncracked Uncracked. Rusting on 3 1-in. Cylinders : Powdery above water	Uncracked Uncracked. Rusting on 3 1-in. Cylinders : Powdery above water
3rd	Sheerness Watford	Uncracked Uncracked Cylinders : Cracking at W.L.	Uncracked Uncracked Cylinders : Sound
4th	Sheerness Watford	3 1-in. cracked at H.W.L. Uncracked Cylinders : Unchanged	Uncracked Uncracked Cylinders : Sound
5th	Sheerness Watford	3 1-in. cracked at H.W.L. Uncracked Cylinders : Swelling at W.L.	2 1-in. cracked at H.W.L. 1 1-in. cracked Cylinders : Unchanged
6th	Sheerness Watford	3 1-in. cracked at H.W.L. 2 1-in. slightly cracked Cylinders : Swelling below W.L.	3 1-in. cracked at H.W.L. 1 1-in. cracked Cylinders : Slight cracking and swelling.

The mixtures are compounded of normal and rapid-hardening Portland cements with finely ground spent shale (the residue from the distillation of Scottish oil shale) and burnt clay. Only mixtures of normal consistency have been employed. The cover to the reinforcement is 1 in. with the rich and medium mixtures and both 1 in. and 2 in. with the lean mixtures. Eleven mixtures have been used, and the specimens are in triplicate. The conditions of making, maturing, etc., were identical with those for the main series. The total number of piles is sixty-six, of which twenty-seven are exposed at Sheerness and the remainder at Watford.

These specimens have been under test for only about a year and a half, and in view of the short duration of the exposure, no conclusions can be drawn regarding the efficacy of these pozzolanic additions.

APPENDIX A

Chemical Analyses of Cements used in the Reinforced Concrete Experiments

High Alumina Cement.	
SiO_2	7·18
Al_2O_3	35·88
FeO	7·31
Fe_2O_3	7·06
TiO_2	2·86
CaO	38·52
MgO	0·68
SO_3	0·15
K_2O	0·16
Na_2O	0·37
	100·17

Rapid-Hardening Portland Cement.	
Loss on ignition	2·16
SiO_2	20·95
Al_2O_3	5·72
Fe_2O_3	2·79
TiO_2	0·31
CaO	64·75
MgO	0·92
K_2O	0·49
Na_2O	0·41
SO_3	1·80
	100·30

Normal Portland Cement.	
Loss on ignition	1·26
SiO_2	22·40
Al_2O_3	4·89
TiO_2	0·36
Fe_2O_3	3·20
CaO	63·75
MgO	0·65
Na_2O	0·73
K_2O	0·52
SO_3	1·92
	99·68

Portland Blast-furnace Cement.	
Loss on ignition	0·92
SiO_2	22·59
Al_2O_3	7·48
Fe_2O_3	1·38
TiO_2	0·23
CaO	60·22
MgO	3·48
K_2O	0·39
Na_2O	0·41
SO_3	2·55
	99·65

APPENDIX B.

The crushing-strengths of cylinders determined at various periods are given in Table LI and are also plotted in Figs. 132 to 135. The following explanatory notes are given :—

Cements are denoted by

A, Y, Z (High alumina, A and Y being the same brand).
RH and P (Rapid-hardening and normal Portland).
PB (Portland blast-furnace).
RHT, PT (The Portland cements plus trass).
PS (Normal Portland cement plus finely divided sand).

Mixture is denoted by R (Rich), M (Medium), L (Lean).

Consistency is denoted by D (Dry), N (Normal).

Curing. Cements Y and Z (Series C) differed in curing treatment from cement A (and other cements of Series A) in that the cylinders were taken from the moulds 8 hours after making, instead of 24 hours as previously.

Arrowheads on the graphs indicate disintegration to a state in which specimens were unfit for strength tests.

A statistical examination of the individual results in the various series (of which only the averages are here recorded) has been carried out. This confirms in general the conclusions to be drawn from the curves and the results of visual inspection of the cylinders. An interesting result is obtained with the lean trass mixtures. With these a significant drop in strength is found to occur between the ages of 2 and 5 years, although no changes are apparent in the specimens. It will be recalled that, in lean mixtures, reinforced piles containing trass showed by far the best resistance, only two out of twenty-four piles being cracked. This must mean that the presence of trass does not entirely preserve the concrete from attack, although the rate of attack is reduced, and that corrosion of reinforcement and failure of the piles may be expected to occur in time.

TABLE XL.—*Proportioning of Concrete Mixtures by Weight.*

	Plain Mixtures	Pozzolanic Mixtures	
		Replacement of Cement	Replacement of Aggregate
Rich	(1A) 1 cement 2·6 aggregate	(1B) 0·6 cement 0·4 trass 2·6 aggregate	Replacement of aggregate by trass is unadvisable, owing to excessive shrinkage
Medium ..	(2A) 1 cement 5 aggregate	(2B) 0·6 cement 0·4 trass 5·0 aggregate	(2C) 0·6 cement 0·4 trass 2·6 aggregate
Lean	(3A) 1 cement 9 aggregate	Replacement of cement by trass is unadvisable owing to the extreme weakness that would result.	(3C) 0·6 cement 0·4 trass 5·0 aggregate

Note:—Mixture 1B is identical with 2C, and 2B with 3C.

TABLE XLI.—*Schedule of Mixtures adopted for Reinforced Piles exposed at Sheerness Dockyard and in Artificial Sea-water at the Building Research Station.*

Type of Cement used	Parts by Weight			Consistency of mixture
	Cement	Pozzolana	Graded Aggregate	
Normal Portland	1	—	$2\frac{3}{5}$	Dry
	1	—	$2\frac{3}{5}$	Normal
	1	—	5	Dry
	1	—	5	Normal
	1	—	9	Normal
Rapid-Hardening Portland	1	—	$2\frac{3}{5}$	Dry
	1	—	5	Dry
	1	—	5	Normal
	1	—	9	Normal
Normal Portland and Trass	1	$\frac{2}{3}$	$4\frac{1}{3}$	Dry
	1	$\frac{2}{3}$	$4\frac{1}{3}$	Normal
	1	$\frac{2}{3}$	$8\frac{1}{3}$	Normal
Rapid-Hardening Portland and Trass.	1	$\frac{2}{3}$	$4\frac{1}{3}$	Dry
	1	$\frac{2}{3}$	$4\frac{1}{3}$	Normal
	1	$\frac{2}{3}$	$8\frac{1}{3}$	Normal
High Alumina	1	—	$2\frac{3}{5}$	Dry
	1	—	5	Dry
	1	—	5	Normal
	1	—	9	Normal
Portland Blast-furnace ..	1	—	$2\frac{3}{5}$	Dry
	1	—	5	Dry
	1	—	5	Normal
	1	—	9	Normal
Normal Portland and Sand	1	$\frac{2}{3}$	$8\frac{1}{3}$	Normal

TABLE XLII.—*General Behaviour of Specimens with High Alumina Cement.*

Examination	Situation	Rich		Medium		Lean
		Dry	Normal	Dry	Normal	Normal
1st (Dec. 1929)	Sheerness	Uncracked ..	—	Uncracked ..	Uncracked ..	Uncracked : efflorescence.
	Watford	Uncracked ..	—	Uncracked ..	Uncracked ..	Uncracked : powdery surface.
		Cylinders : Sound	—	Cylinders : Sound	Cylinders : Sound	Cylinders : Sound.
2nd (July 1930)	Sheerness	Uncracked ..	—	Uncracked ..	Uncracked ..	Signs of serious disintegration.
	Watford	Uncracked ..	—	Uncracked ..	1 1-in. cracked ..	do. do.
		Cylinders : Sound	—	Cylinders : Sound	Cylinders : Sound	Cylinders : Fragile and blistering at W.L.
3rd (March 1931)	Sheerness	Uncracked ..	—	Uncracked ..	Uncracked ..	Increased disintegration at H.W.L.
	Watford	Uncracked ..	—	Uncracked ..	1 1-in. cracked ..	do. do. at feet.
		Cylinders : Sound	—	Cylinders : Sound	Cylinders : Sound	Cylinders : Increased disintegration.
4th (Oct. 1931)	Sheerness	Uncracked ..	—	Uncracked ..	3 1-in. cracked at H.W.L.	2 1-in. and 1 2-in. cracked at H.W.L.
	Watford	Uncracked ..	—	Uncracked ..	2 1-in. cracked ..	Uncracked.*
		Cylinders : Sound	—	Cylinders : Sound	Cylinders : Sound	Cylinders : Almost destroyed above W.L.
5th (April 1932)	Sheerness	Uncracked ..	—	1 1-in. cracked at H.W.L.	3 1-in. cracked at H.W.L.	3 1-in. and 1 2-in. cracked at H.W.L.
	Watford	Uncracked ..	—	Uncracked ..	2 1-in. cracked ..	Uncracked.*
		Cylinders : Sound	—	Cylinders : Sound	Cylinders : Sound	Cylinders : Destroyed.
6th (Oct. 1932)	Sheerness	Uncracked ..	—	1 1-in. cracked at H.W.L.	3 1-in. cracked at H.W.L.	3 1-in. and 1 2-in. cracked at H.W.L.
	Watford	Uncracked ..	—	Uncracked ..	3 1-in. cracked ..	Uncracked.*
		Cylinders : Sound	—	Cylinders : Sound	Cylinders : Sound	Cylinders : Disintegrating throughout.
7th (May 1933)	Sheerness	Uncracked ..	—	1 1-in. cracked at H.W.L.	3 1-in. cracked at H.W.L.	3 1-in. and 3 2-in. cracked at H.W.L.
	Watford	Uncracked ..	—	Uncracked ..	3 1-in. cracked ..	3 1-in. cracked.
		Cylinders : Sound	—	Cylinders : Sound	Cylinders : Sound	Cylinders : Further disintegration.
8th (Oct. 1933)	Sheerness	Uncracked ..	—	1 1-in. cracked at H.W.L.	3 1-in. cracked at H.W.L.	3 1-in. and 3 2-in. cracked at H.W.L.
	Watford	Uncracked ..	—	Uncracked ..	3 1-in. cracked ..	3 1-in. cracked.
		Cylinders : Sound	—	Cylinders : Sound	Cylinders : Sound	Cylinders : Further disintegration.
9th (April 1934)	Sheerness	Uncracked ..	—	1 1-in. cracked at H.W.L.	3 1-in. cracked at H.W.L.	3 1-in. and 3 2-in. cracked at H.W.L.
	Watford	Uncracked ..	—	Uncracked ..	3 1-in. cracked ..	3 1-in. cracked.
		Cylinders : Sound	—	Cylinders : Sound	Cylinders : Sound	Cylinders : Further disintegration.
10th (Nov. 1934)	Sheerness	Uncracked ..	—	1 1-in. cracked at H.W.L.	3 1-in. cracked at H.W.L.	3 1-in. and 3 2-in. cracked at H.W.L.
	Watford	Uncracked ..	—	Uncracked ..	3 1-in. cracked ..	3 1-in. cracked.
		Cylinders : Sound	—	Cylinders : Sound	Cylinders : Rather soft.	Cylinders : Removed from test.

* Though apparently uncracked, there was serious corrosion of reinforcement, judging from quantity of rust.

TABLE XLIII.—*General Behaviour of Specimens with Rapid-Hardening Portland Cement.*

Examination	Situation	Rich		Medium		Lean
		Dry	Normal	Dry	Normal	Normal
1st	Sheerness	Surface crazing ..	—	Uncracked ..	Surface crazing ..	Mottled.
	Watford	Efflorescence .. Cylinders : Sound	— —	Efflorescence .. Cylinders : Sound	Uncracked .. Cylinders : Sound	Uncracked. Cylinders : Sound.
2nd	Sheerness	Uncracked ..	—	Uncracked ..	1 1-in. cracked at L.W.L.	Uncracked.
	Watford	Uncracked .. Cylinders : heavy deposits.	— —	1 1-in. cracked .. Cylinders : heavy deposits.	Uncracked .. Cylinders : heavy deposits.	Uncracked. Cylinders : Mushy at feet.
3rd	Sheerness	Uncracked ..	—	Uncracked ..	2 1-in. cracked at L.W.L.	Uncracked.
	Watford	Uncracked .. Cylinders : heavy deposits.	— —	1 1-in. cracked .. Cylinders : heavy deposits.	Uncracked .. Cylinders : heavy deposits.	Uncracked. Cylinders : disintegrating.
4th	Sheerness	Uncracked ..	—	2 1-in. cracked at L.W.L.	3 1-in. cracked at L.W.L.	2 1-in. cracked at H.W.L.
	Watford	Uncracked .. Cylinders : heavy deposits.	— —	1 1-in. cracked .. Cylinders : heavy deposits, soft edges.	Uncracked .. Cylinders : heavy deposits, mushy feet.	3 1-in. and 1 2-in. cracked. Cylinders : Bad disintegration.
5th	Sheerness	Uncracked ..	—	3 1-in. cracked at L.W.L.	3 1-in. cracked at L.W.L.	3 1-in. and 1 2-in. cracked at H.W.L.
	Watford	Uncracked .. Cylinders : heavy deposits.	— —	1 1-in. cracked .. Cylinders : heavy deposits.	Uncracked .. Cylinders : heavy deposits.	3 1-in. and 1 2-in. cracked. Cylinders : Increased disintegration.
6th	Sheerness	Uncracked ..	—	3 1-in. cracked at L.W.L.	3 1-in. cracked at L.W.L.	3 1-in. and 1 2-in. cracked at H.W.L.
	Watford	Uncracked .. Cylinders : heavy deposits.	— —	1 1-in. cracked .. Cylinders : heavy deposits.	Uncracked .. Cylinders : heavy deposits.	3 1-in. and 1 2-in. cracked. Cylinders : Very bad disintegration.
7th	Sheerness	2 1-in. cracked at feet.	—	3 1-in. cracked at L.W.L.	3 1-in. cracked at L.W.L.	3 1-in. and 3 2-in. cracked at H.W.L.
	Watford	Uncracked .. Cylinders : heavy deposits.	— —	1 1-in. cracked .. Cylinders : Disintegrating.	1 1-in. cracked .. Cylinders : Disintegrating.	3 1-in. and 1 2-in. cracked. Cylinders : Almost destroyed.
8th	Sheerness	2 1-in. cracked at feet.	—	3 1-in. cracked at L.W.L.	3 1-in. cracked at L.W.L.	3 1-in. and 3 2-in. cracked at H.W.L.
	Watford	Uncracked .. Cylinders : heavy deposits but sound.	— —	1 1-in. cracked .. Cylinders : Disintegrating.	1 1-in. cracked .. Cylinders : Disintegrating.	3 1-in. and 3 2-in. cracked. Cylinders : Almost destroyed.
9th	Sheerness	2 1-in. cracked at feet.	—	3 1-in. cracked at L.W.L.	3 1-in. cracked at L.W.L.	3 1-in. and 3 2-in. cracked at H.W.L.
	Watford	Uncracked .. Cylinders : heavy deposits but sound.	— —	1 1-in. cracked .. Cylinders : Disintegrating.	1 1-in. cracked .. Cylinders : Disintegrating.	3 1-in. and 3 2-in. cracked. Cylinders : Almost destroyed.
10th	Sheerness	3 1-in. cracked at feet.	—	3 1-in. cracked at L.W.L.	3 1-in. cracked at L.W.L.	3 1-in. and 3 2-in. cracked at H.W.L.
	Watford	Uncracked .. Cylinders : heavy deposits but sound.	— —	1 1-in. cracked .. Cylinders : Disintegrating.	2 1-in. cracked .. Cylinders : Disintegrating.	3 1-in. and 3 2-in. cracked. Cylinders : Removed from test.

TABLE XLIV.—*General Behaviour of Specimens with Trass and Rapid-Hardening Portland Cement.*

Examination	Situation	Rich		Medium		Lean
		Dry	Normal	Dry	Normal	Normal
1st	Sheerness	Uncracked	Uncracked	—	—	Uncracked.
	Watford	Mottled	Mottled	—	—	Mottled
		Cylinders : Sound	Cylinders : Sound	—	—	Cylinders : Sound
2nd	Sheerness	Uncracked	Uncracked	—	—	Surface above W.L. powdery.
	Watford	Uncracked	Uncracked	—	—	do. do.
		Cylinders : Sound	Cylinders : Sound	—	—	Cylinders : Powdery above W.L.
3rd	Sheerness	Uncracked	Uncracked	—	—	1 1-in. cracked at H.W.L.
	Watford	Uncracked	Uncracked	—	—	Uncracked.
		Cylinders : Sound	Cylinders : Sound	—	—	Cylinders : Powdery above W.L.
4th	Sheerness	Uncracked	Uncracked	—	—	1 1-in. cracked at H.W.L.
	Watford	Uncracked	Uncracked	—	—	Feet slightly soft.
		Cylinders : Sound	Cylinders : Sound	—	—	Cylinders : Powdery above W.L.
5th	Sheerness	Uncracked	Uncracked	—	—	1 1-in. cracked at H.W.L.
	Watford	Uncracked	Uncracked	—	—	Feet slightly soft.
		Cylinders : Sound	Cylinders : Sound	—	—	Cylinders : Powdery above W.L.
6th	Sheerness	Uncracked	Uncracked	—	—	1 1-in. cracked at H.W.L.
	Watford	Uncracked	Uncracked	—	—	Feet slightly soft.
		Cylinders : Sound	Cylinders : Sound	—	—	Cylinders : Feet slightly soft.
7th	Sheerness	Uncracked	Uncracked	—	—	1 1-in. cracked at H.W.L.
	Watford	Uncracked	Uncracked	—	—	1 1-in. cracked.
		Cylinders : Sound	Cylinders : Sound	—	—	Cylinders : Feet slightly soft.
8th	Sheerness	Uncracked	Uncracked	—	—	1 1-in. cracked at H.W.L.
	Watford	Uncracked	Uncracked	—	—	1 1-in. cracked.
		Cylinders : Powdery above W.L.	Cylinders : Powdery above W.L.	—	—	Cylinders : Disintegrating above W.L.
9th	Sheerness	Uncracked	Uncracked	—	—	1 1-in. cracked at H.W.L.
	Watford	Uncracked	Uncracked	—	—	1 1-in. cracked.
		Cylinders : Powdery above W.L.	Cylinders : Powdery above W.L.	—	—	Cylinders : Disintegrating above W.L.
10th	Sheerness	Uncracked	Uncracked	—	—	1 1-in. cracked at H.W.L.
	Watford	Uncracked	Uncracked	—	—	1 1-in. cracked.
		Cylinders : Powdery above W.L.	Cylinders : Powdery above W.L.	—	—	Cylinders : Slightly powdery.

TABLE XLV.—*General Behaviour of Specimens with Normal Portland Cement.*

Examination	Situation	Rich		Medium		Lean
		Dry	Normal	Dry	Normal	Normal
1st	Sheerness	Surface crazing ..	Uncracked ..	Uncracked ..	Uncracked ..	Surface crazing.
	Watford	Efflorescence .. Cylinders : Sound	Efflorescence .. Cylinders : Sound	Uncracked .. Cylinders : Sound	Uncracked .. Cylinders : Sound	Uncracked. Cylinders : Sound.
2nd	Sheerness	Uncracked ..	Uncracked ..	Uncracked ..	Uncracked ..	Uncracked.
	Watford	Uncracked .. Cylinders: Deposits	Uncracked .. Cylinders: Deposits	1 1-in. cracked .. Cylinders: Deposits	1 1-in. cracked .. Cylinders: Deposits	Uncracked. Cylinders : Heavy deposits.
3rd	Sheerness	Uncracked ..	Uncracked ..	Uncracked ..	3 1-in. cracked at L.W.L.	Uncracked.
	Watford	Uncracked .. Cylinders: Deposits	Uncracked .. Cylinders: Deposits	1 1-in. cracked .. Cylinders: Deposits	1 1-in. cracked .. Cylinders: Deposits	Uncracked. Cylinders : Heavy deposits.
4th	Sheerness	Uncracked ..	Uncracked ..	Uncracked ..	3 1-in. cracked at L.W.L.	Uncracked.
	Watford	Uncracked .. Cylinders : Fairly heavy deposits.	Uncracked .. Cylinders : Fairly heavy deposits.	1 1-in. cracked .. Cylinders : Fairly heavy deposits.	1 1-in. cracked .. Cylinders : Fairly heavy deposits.	Uncracked. Cylinders : Bases slightly soft.
5th	Sheerness	Uncracked ..	Uncracked ..	Uncracked ..	3 1-in. cracked at L.W.L.	3 1-in. cracked at H.W.L.
	Watford	Uncracked .. Cylinders : Fairly heavy deposits.	Uncracked .. Cylinders : Fairly heavy deposits.	1 1-in. cracked .. Cylinders : Fairly heavy deposits.	1 1-in. cracked .. Cylinders : Fairly heavy deposits.	2 1-in. cracked. Cylinders : Bases slightly soft.
6th	Sheerness	Uncracked ..	Uncracked ..	2 1-in. cracked at L.W.L.	3 1-in. cracked at L.W.L.	3 1-in. cracked at H.W.L.
	Watford	Uncracked .. Cylinders : Fairly heavy deposits.	Uncracked .. Cylinders : Fairly heavy deposits.	1 1-in. cracked .. Cylinders : Fairly heavy deposits.	1 1-in. cracked .. Cylinders : Fairly heavy deposits.	3 1-in. cracked. Cylinders : Bases soft.
7th	Sheerness	Uncracked ..	Uncracked ..	2 1-in. cracked at L.W.L.	3 1-in. cracked at L.W.L.	3 1-in. cracked at H.W.L.
	Watford	Uncracked .. Cylinders : Fairly heavy deposits.	Uncracked .. Cylinders : Fairly heavy deposits.	1 1-in. cracked .. Cylinders : Fairly heavy deposits.	1 1-in. cracked .. Cylinders : Fairly heavy deposits.	3 1-in. cracked. Cylinders : Bases slightly swelling.
8th	Sheerness	Uncracked ..	Uncracked ..	2 1-in. cracked at L.W.L.	3 1-in. cracked at L.W.L.	3 1-in. cracked at H.W.L.
	Watford	Uncracked .. Cylinders : Fairly heavy deposits.	Uncracked .. Cylinders : Fairly heavy deposits.	1 1-in. cracked .. Cylinders : Fairly heavy deposits.	1 1-in. cracked .. Cylinders : Fairly heavy deposits.	3 1-in. cracked. Cylinders : Bases slightly swelling.
9th	Sheerness	Uncracked ..	Uncracked ..	2 1-in. cracked at L.W.L.	3 1-in. cracked at L.W.L.	3 1-in. cracked at H.W.L.
	Watford	Uncracked .. Cylinders : Fairly heavy deposits.	Uncracked .. Cylinders : Fairly heavy deposits.	1 1-in. cracked .. Cylinders : Fairly heavy deposits.	1 1-in. cracked .. Cylinders : Fairly heavy deposits.	3 1-in. cracked. Cylinders : Bases slightly swelling.
10th	Sheerness	Uncracked ..	Uncracked ..	2 1-in. cracked at L.W.L.	3 1-in. cracked at L.W.L.	3 1-in. cracked at H.W.L.
	Watford	Uncracked .. Cylinders : Fairly heavy deposits.	Uncracked .. Cylinders : Fairly heavy deposits.	1 1-in. cracked .. Cylinders : Fairly heavy deposits.	1 1-in. cracked .. Cylinders : Fairly heavy deposits.	3 1-in. cracked. Cylinders : Slightly powdery.

TABLE XLVI.—*General Behaviour of Specimens with Trass and Normal Portland Cement and with. Sand Mixture and Normal Portland Cement.*

Examination	Situation	Cement and Trass Mixture					Cement and Sand Mixture
		Rich		Medium		Lean	Lean
		Dry	Normal	Dry	Normal	Dry	Normal
1st	Sheerness	Uncracked	Surface crazing	—	—	Uncracked	Uncracked
	Watford	Mottled	Uncracked	—	—	Uncracked	Uncracked
		Cylinders : Sound	Cylinders : Sound	—	—	Cylinders : Sound	Cylinders : Sound
2nd	Sheerness	Uncracked	Uncracked	—	—	Surface above H.W.L. powdery	Surface above H.W.L. powdery
	Watford	Uncracked	1 1-in. cracked	—	—	Surface above W.L. powdery	Surface above W.L. powdery
		Cylinders : Sound	Cylinders : Sound	—	—	Cylinders : Sound	Cylinders : Sound
3rd	Sheerness	Uncracked	Uncracked	—	—	Uncracked	Uncracked
	Watford	Uncracked	1 1-in. cracked	—	—	Uncracked	Uncracked
		Cylinders : Sound	Cylinders : Sound	—	—	Cylinders : Sound	Cylinders : Slightly powdery
4th	Sheerness	Uncracked	Uncracked	—	—	Uncracked	Uncracked
	Watford	1 1-in. cracked	3 1-in. cracked	—	—	Uncracked	3 1-in. cracked
		Cylinders : Sound	Cylinders : Sound	—	—	Cylinders : Sound	Cylinders : Sound
5th	Sheerness	Uncracked	Uncracked	—	—	Uncracked	3 1-in. cracked
	Watford	1 1-in. cracked	3 1-in. cracked	—	—	Uncracked	3 1-in. cracked
		Cylinders : Sound	Cylinders : Sound	—	—	Cylinders : Sound	Cylinders : Sound
6th	Sheerness	Uncracked	Uncracked	—	—	Uncracked	3 1-in. cracked at H.W.L.
	Watford	1 1-in. cracked	3 1-in. cracked	—	—	Uncracked	3 1-in. cracked
		Cylinders : Sound	Cylinders : Sound	—	—	Cylinders : Sound	Cylinders : Sound
7th	Sheerness	Uncracked	Uncracked	—	—	Uncracked	3 1-in. cracked at H.W.L.
	Watford	1 1-in. cracked	3 1-in. cracked	—	—	Uncracked	3 1-in. cracked
		Cylinders : Sound	Cylinders : Sound	—	—	Cylinders : Sound	Cylinders : Sound
8th	Sheerness	Uncracked	Uncracked	—	—	Uncracked	3 1-in. cracked at H.W.L.
	Watford	1 1-in. cracked	3 1-in. cracked	—	—	Uncracked	3 1-in. cracked
		Cylinders : Sound	Cylinders : Sound	—	—	Cylinders : Sound	Cylinders : Sound
9th	Sheerness	Uncracked	Uncracked	—	—	Uncracked	3 1-in. cracked at H.W.L.
	Watford	1 1-in. cracked	3 1-in. cracked	—	—	Uncracked	3 1-in. cracked.
		Cylinders : Sound	Cylinders : Sound	—	—	Cylinders : Sound	Cylinders : Sound
10th	Sheerness	Uncracked	Uncracked	—	—	Uncracked	3 1-in. cracked at H.W.L.
	Watford	1 1-in. cracked	3 1-in. cracked	—	—	Uncracked	3 1-in. cracked
		Cylinders : Sound	Cylinders : Sound	—	—	Cylinders : slightly powdery	Cylinders : Slightly powdery

TABLE XLVII.—*General Behaviour of Specimens with Portland Blast-furnace Cement.*

Examination	Situation	Rich		Medium		Lean
		Dry	Normal	Dry	Normal	Normal
1st	Sheerness	Uncracked ..	—	Uncracked ..	Uncracked ..	Uncracked.
	Watford	Uncracked .. Cylinders: Sound	— —	Uncracked but mottled. Cylinders : Sound	Uncracked but mottled. Cylinders : Sound	Uncracked but mottled. Cylinders : Sound.
2nd	Sheerness	Uncracked ..	—	Uncracked ..	Uncracked ..	Uncracked.
	Watford	Uncracked .. Cylinders : Sound	— —	Uncracked .. Cylinders : Sound	Uncracked .. Cylinders : Sound	1 1-in. cracked. Cylinders : Bases mushy.
3rd	Sheerness	Uncracked ..	—	Uncracked ..	Uncracked ..	Uncracked.
	Watford	Uncracked .. Cylinders : Sound	— —	Uncracked .. Cylinders : Sound	Uncracked .. Cylinders : Sound	1 1-in. cracked. Cylinders : Bad disintegration.
4th	Sheerness	Uncracked ..	—	Uncracked ..	Uncracked ..	Uncracked.
	Watford	Uncracked .. Cylinders: Heavy deposits.	— —	Uncracked .. Cylinders : Heavy deposits.	Uncracked .. Cylinders : Heavy deposits.	3 1-in. cracked. Cylinders : Bad disintegration.
5th	Sheerness	Uncracked ..	—	Uncracked ..	1 1-in. cracked at L.W.L.	1 1-in. cracked at H.W.L.
	Watford	Uncracked .. Cylinders: Heavy deposits.	— —	Uncracked .. Cylinders : Heavy deposits.	Uncracked .. Cylinders : Heavy deposits.	3 1-in. cracked. Cylinders : Bad disintegration.
6th	Sheerness	Uncracked ..	—	Uncracked ..	1 1-in. cracked at L.W.L.	1 1-in. cracked at H.W.L.
	Watford	Uncracked .. Cylinders: Heavy deposits.	— —	Uncracked .. Cylinders : Heavy deposits.	Uncracked .. Cylinders : Heavy deposits.	3 1-in. cracked. Cylinders : Bad disintegration.
7th	Sheerness	Uncracked ..	—	Uncracked ..	1 1-in. cracked at L.W.L.	1 1-in. cracked at H.W.L.
	Watford	Uncracked .. Cylinders: Heavy deposits.	— —	Uncracked .. Cylinders : Heavy deposits.	Uncracked .. Cylinders : Slight disintegration.	3 1-in. cracked. Cylinders : Destroyed at feet.
8th	Sheerness	Uncracked ..	—	Uncracked ..	1 1-in. cracked at L.W.L.	1 1-in. cracked at H.W.L.
	Watford	Uncracked .. Cylinders: Heavy deposits.	— —	Uncracked .. Cylinders : Heavy deposits.	Uncracked .. Cylinders : Slight disintegration.	3 1-in. cracked. Cylinders : Destroyed at feet.
9th	Sheerness	Uncracked ..	—	Uncracked ..	1 1-in. cracked at L.W.L	1 1-in. cracked at H.W.L.
	Watford	Uncracked .. Cylinders: Heavy deposits.	— —	Uncracked .. Cylinders : Heavy deposits.	Uncracked .. Cylinders : Slight disintegration.	3 1-in. cracked. Cylinders : Destroyed at feet.
10th	Sheerness	Uncracked ..	—	1 1-in. cracked at foot.	3 1-in. cracked at foot.	3 1-in. cracked at H.W.L.
	Watford	Uncracked .. Cylinders: Heavy deposits.	— —	Uncracked .. Cylinders : Heavy deposits.	Uncracked .. Cylinders : Slight disintegration.	3 1-in. cracked. Cylinders: Removed from test.

TABLE XLVIII.—*General Summary of Observations on Reinforced Piles at Tenth Examination.*

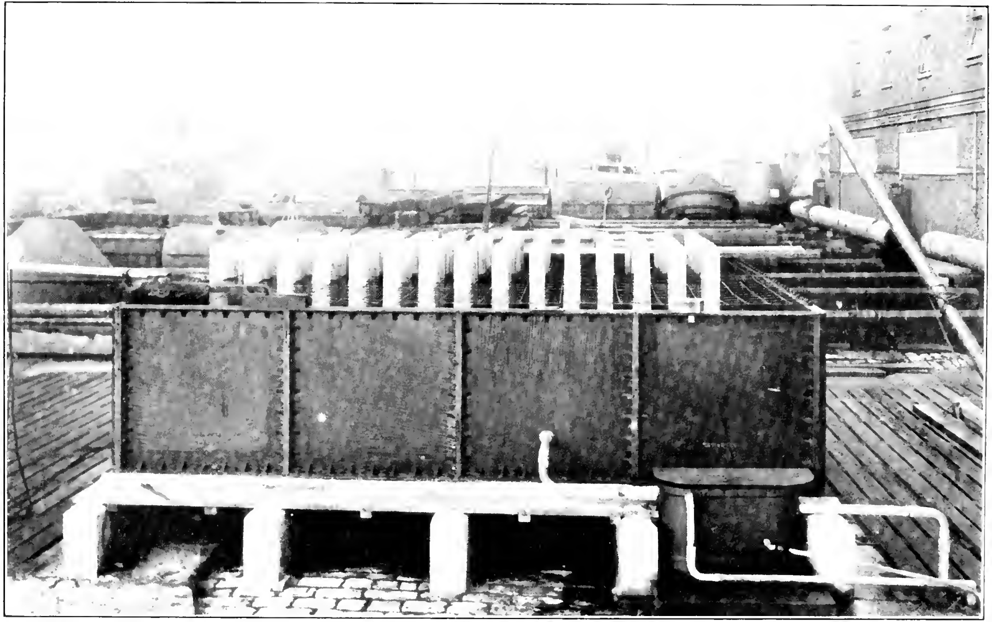
Cement or Mixture.	Situation	Rich		Medium		Lean
		Dry	Normal	Dry	Normal	Normal
High Alumina ..	Sheerness	Uncracked ..	—	1 1-in. at H.W.L.	3 1-in. at H.W.L.	3 1-in. and 3 2-in. at H.W.L.
	Watford	Uncracked ..	—	Uncracked ..	3 1-in.	3 1-in.
Rapid - Hardening Portland	Sheerness	3 1-in. at feet ..	—	3 1-in. at L.W.L.	3 1-in at L.W.L.	3 1-in. and 3 2-in. at H.W.L.
	Watford	Uncracked ..	—	1 1-in	2 1-in.	3 1-in. and 3 2-in.
Rapid - Hardening Portland—trass	Sheerness	Uncracked ..	Uncracked ..	—	—	1 1-in. at H.W.L.
	Watford	Uncracked ..	Uncracked ..	—	—	1 1-in
Normal Portland	Sheerness	Uncracked ..	Uncracked ..	2 1-in at L.W.L.	3 1-in. at L.W.L.	3 1-in. at H.W.L.
	Watford	Uncracked ..	Uncracked ..	1 1-in.	1 1-in.	3 1-in.
Normal Portland —trass	Sheerness	Uncracked ..	Uncracked ..	—	—	Uncracked
	Watford	1 1-in.	3 1-in. at feet ..	—	—	Uncracked
Normal Portland —sand	Sheerness	—	—	—	—	3 1-in. at H.W.L.
	Watford	—	—	—	—	3 1-in.
Portland blast-furnace	Sheerness	Uncracked ..	—	1 1-in. at foot ..	3 1-in at feet ..	3 1-in. at H.W.L.
	Watford	Uncracked ..	—	Uncracked ..	Uncracked ..	3 1-in.
Total Cracked	Sheerness	3 1-in. (out of 18)	—	7 1-in. (out of 12)	12 1-in (out of 12)	16 1-in. (out of 21) 6 2-in. (out of 21)
	Watford	1 1-in. (out of 18)	3 1-in. (out of 9)	2 1-in (out of 12)	6 1-in. (out of 12)	16 1-in. (out of 21) 3 2-in. (out of 21)

TABLE LI.—*Compressive Strength of Concretes used in the Research.*

Identification Mark			Proportions of Mixture (by weight)			Water/Cement Ratio	Slump: In.	Compressive Strength: lb. per sq. in. (Size of Test-Pieces 6-in. by 3-in. dia. cylinders.)																
								Preliminary Curing		Immersed in Water					Immersed in Artificial Sea-Water. (3 times normal concentration)					Half Immersed in Artificial Sea-Water. (3 times normal concentration)				
										Age at Test					Age at Test					Age at Test				
Cement	Mixture	Consistency	Cement	Trass	Agg.			7 days under damp sacks.	7 days under damp sacks 21 days air	3 Months	6 Months	1 Year	2 Years	5 Years	3 Months	6 Months	1 Year	2 Years	5 Years	3 Months	6 Months	1 Year	2 Years	5 Years
A	R	D	1	—	2⅗	0·31	½	5618	6225	5917	6158	6752	6050	7007	5652	6127	7082	7750	7438	6825	6771	6463	7403	7153
A	M	D	1	—	5	0·46	½	5952	5122	5598	5304	5873	5832	6128	5490	5253	5560	5788	6368	5347	5636	5979	5948	6560
A	M	N	1	—	5	0·53	2	3849	4675	4708	4726	4745	4865	5127	4522	5107	5503	5343	6080	5193	5295	5633	5750	6387
A	L	N	1	—	9	0·93	2	1524	2703	1806	1842	1700	1826	1933	1740	2241	2116	1828	No Test	2003	1960	1860	1714	No Test
RH	R	D	1	—	2⅗	0·37	½	4191	5346	5738	5898	6367	6590	7510	5673	5479	5350	5365	5400	4783	5370	5586	5560	6100
RH	M	D	1	—	5	0·53	½	3083	4000	4501	4744	5095	5392	5573	4342	4570	4771	4757	4177	4355	4663	4601	5152	4662
RH	M	N	1	—	5	0·57	2	3235	4575	3926	4582	4550	4734	5363	3987	4460	4360	4475	3325	3923	4446	4342	4532	3323
RH	L	N	1	—	9	0·98	2	1382	2202	2025	2229	1954	2275	2197	1982	1926	1836	1540	No Test	1759	2262	1842	1313	No Test
RHT	R	D	1	⅔	4⅓	(0·70)*	½	2146	3375	3982	4523	4645	5022	5410	4068	4205	4293	4935	5187	3959	4634	4479	4835	4680
RHT	R	N	1	⅔	4⅓	(0·76)*	2	2270	3705	3793	3948	4350	4642	4900	3728	3929	3854	4211	4583	3698	3865	4003	4293	4183
RHT	L	N	1	⅔	8⅓	(1·07)*	2	1130	2016	2608	2987	3021	3352	3562	2754	2874	3087	3678	3345	2942	3164	3155	3531	3218
P	R	D	1	—	2⅗	0·35	½	3504	5120	6213	6408	6388	7327	7725	5692	5836	5917	6690	6873	5824	6178	6055	6923	7252
P	R	N	1	—	2⅗	0·38	2	3397	5185	5786	6199	6657	7338	7632	5820	6156	6104	5913	6765	5696	5835	6287	6810	6640
P	M	D	1	—	5	0·50	½	2820	3872	4600	5134	5601	5978	6472	4398	4707	4696	5017	5083	4212	4540	4737	5030	5415
P	M	N	1	—	5	0·59	2	2129	3420	4038	4529	5231	5340	5965	4028	4051	4512	4506	4333	3843	4141	4561	4627	4797
P	L	N	1	—	9	0·96	2	650	1365	1690	2064	2417	2623	2955	1718	1884	1873	1687	1345	1684	1727	1743	1733	1823
PT	R	D	1	⅔	4⅓	(0·69)*	½	1831	3198	3435	4032	4341	4785	4930	3628	3808	4451	4596	5168	3900	3951	4575	5090	4857
PT	R	N	1	⅔	4⅓	(0·73)*	2	1740	3043	3569	3746	4152	4603	4873	3637	3587	4014	4209	4813	3014	3930	3912	4325	4159
PT	L	N	1	⅔	8⅓	(1·00)*	2	680	1558	2209	2547	2902	3320	3640	2456	2547	2967	3311	3508	2297	2385	2873	3432	3080
PS	L	N	1	(⅔ Sand)	8⅓	(0·98)*	2	694	1628	1835	2272	2680	3066	3557	1689	1931	2272	2567	2520	1788	2166	2345	2685	2375
PB	R	D	1	—	2⅗	0·37	½	4577	5950	6058	6136	6712	6773	6633	5897	6092	6327	6353	5717	5735	6210	6268	6490	6128
PB	M	D	1	—	5	0·47	½	3262	4816	4315	5101	5340	5698	5967	4832	4979	5209	5583	5878	4576	5097	5237	6170	5715
PB	M	N	1	—	5	0·52	2	2836	4197	4877	5231	5370	5808	6190	4737	5115	5302	5684	5035	5198	5460	5543	6163	5430
PB	L	N	1	—	9	0·86	2	1481	2380	2665	2818	2974	2866	3054	2568	2406	2685	2802	No Test	2686	2908	2830	2729	No Test
Y	R	D	1	—	2⅗	0·325	½	5840	6500	6890	6950	7320	7700	Not Due For Test	6960	7480	7580	7610	Not Due For Test	6920	7260	7460	8260	Not Due For Test
Y	M	D	1	—	5	0·45	½	5560	6470	6370	6820	6710	7160		6270	7030	6720	7150		6510	7270	6320	6810	
Y	M	N	1	—	5	0·475	2	6100	7250	6740	7420	7720	7430		6870	7490	7520	7960		6950	7300	7860	8270	
Y	L	N	1	—	9	0·85	2	3240	3280	3170	2940	2935	3140		3420	3820	3725	3990		3280	4050	3590	3600	
Z	R	D	1	—	2⅗	0·29	½	6890	7430	7800	7300	7020	7480		7330	7350	7470	7330		7420	7660	8000	7570	
Z	M	D	1	—	5	0·45	½	6470	6900	7140	6760	6890	7800		6930	7000	7610	8150		7070	7220	7400	8090	
Z	M	N	1	—	5	0·475	2	6230	6520	7100	6780	6960	7300		6850	7130	7900	8160		6870	6930	7350	8400	
Z	L	N	1	—	9	0·85	2	3250	3250	2630	2810	3125	2665		3450	3480	3990	3710		3260	3060	3370	3720	

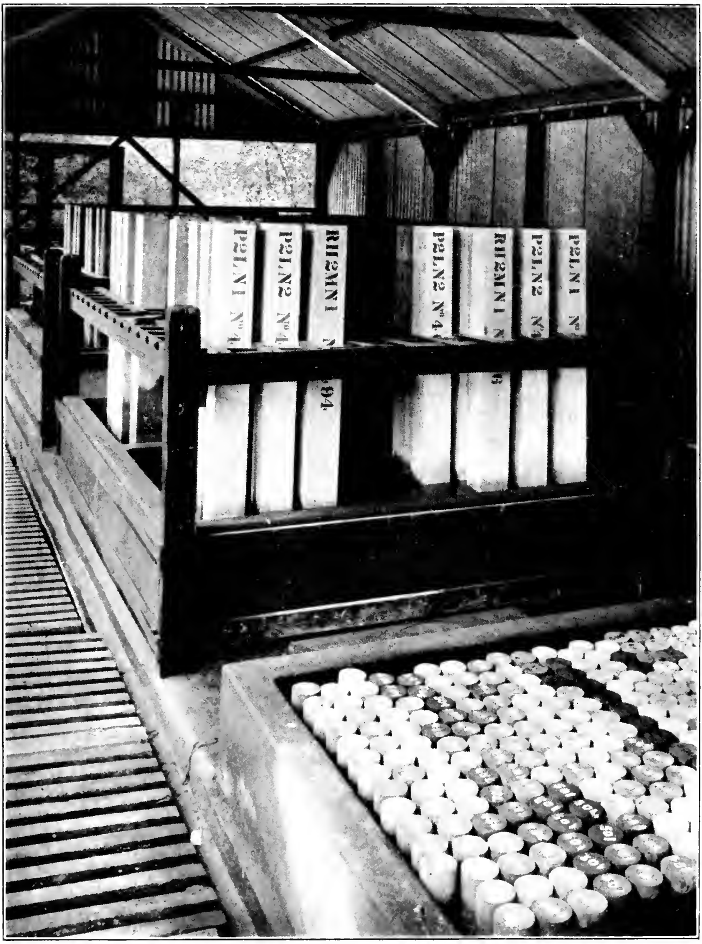
* In these Trass and finely ground Sand mixtures, *w/c* ratio is based on *Cement* alone.

Fig. 119.



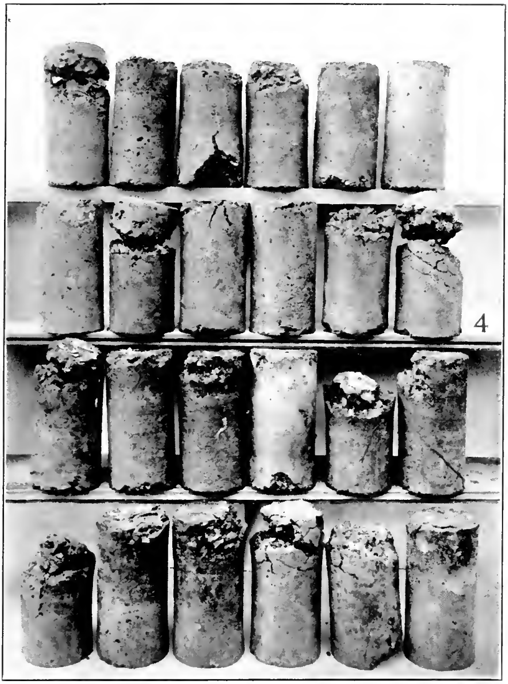
Exposure Tank at Sheerness.

Fig. 120.



Exposure Tanks at Watford.

FIG. 121.



Partially immersed.

Totally immersed.

Partially immersed.

Totally immersed.

LEAN MIXTURE OF HIGH ALUMINA CEMENT IN ARTIFICIAL SEA-WATER OF THREE TIMES NORMAL CONCENTRATION, AT WATFORD, AFTER 3–3½ YEARS.

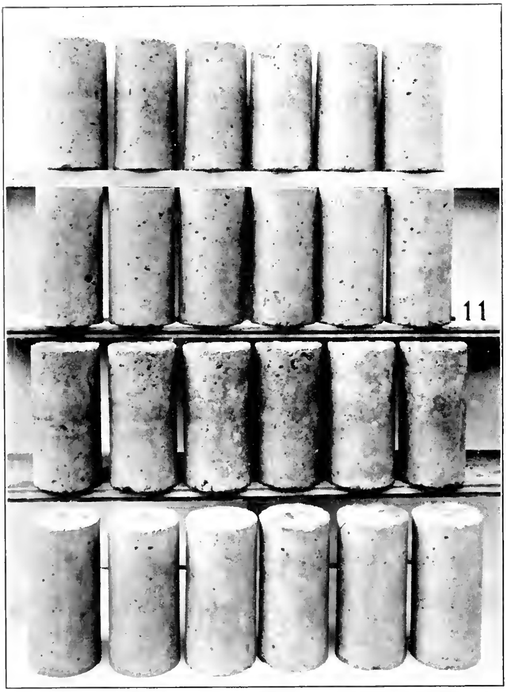
1 part cement.
3 parts sand.
6 ,, gravel.

Fig. 122.

Lean mixture of rapid-hardening Portland cement, in artificial sea-water of three times normal concentration, at Watford, after 3–3½ years.

1 part cement.
3 parts sand.
6 ,, gravel.

FIG. 123.



Partially immersed.

Totally immersed.

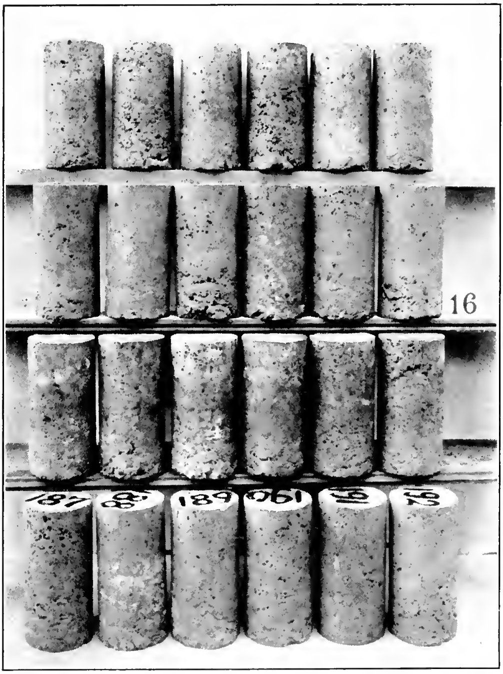
Partially immersed.

Totally immersed.

LEAN MIXTURE OF RAPID-HARDENING PORTLAND CEMENT-TRASS MIXTURE, IN ARTIFICIAL SEA-WATER OF THREE TIMES NORMAL CONCENTRATION, AT WATFORD, AFTER 3–3½ YEARS.

1 part cement.
$\frac{2}{3}$,, trass.
$2\frac{7}{9}$ parts sand.
$5\frac{5}{9}$,, gravel.

Fig. 124.



Partially immersed.

Totally immersed.

Partially immersed.

Totally immersed.

Lean mixture of normal Portland cement, in artificial sea-water of three times normal concentration, at Watford, after 3–3½ years.

1 part cement.
3 parts sand.
6 ,, gravel.

FIG. 125.

Partially immersed.

Totally immersed.

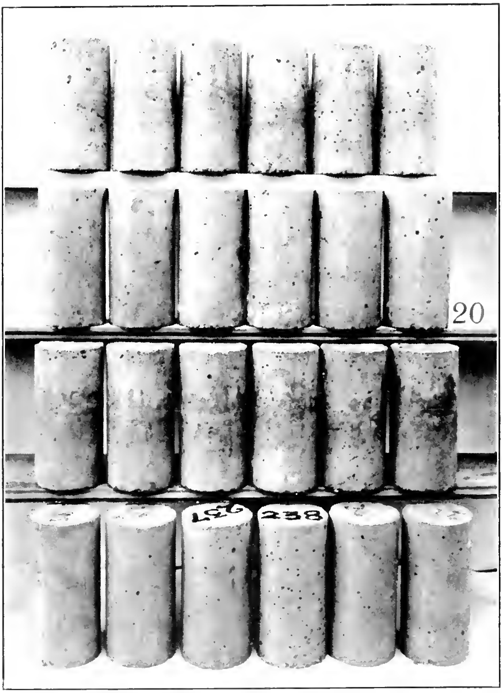
Partially immersed.

Totally immersed.

LEAN MIXTURE OF NORMAL PORTLAND CEMENT TRASS MIXTURE IN ARTIFICIAL SEA-WATER OF THREE TIMES NORMAL CONCENTRATION, AT WATFORD, AFTER 3–$3\frac{1}{2}$ YEARS.

1 part cement.
$\frac{2}{3}$,, trass.
$2\frac{7}{9}$ parts sand.
$5\frac{5}{9}$,, gravel.

Fig. 126.



Lean mixture of normal Portland cement (finely ground) sand mixture, in artificial sea-water of three times normal concentration, at Watford, after 3–3½ years.

1 part cement.
$\frac{2}{3}$,, finely ground sand.
$2\frac{7}{9}$ parts sand.
$5\frac{5}{9}$,, gravel.

Fig. 127.

Partially immersed.

Totally immersed.

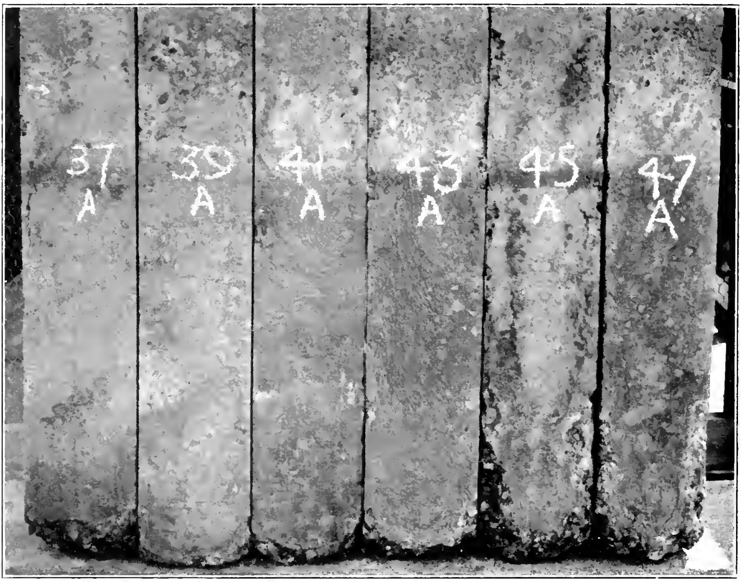
Partially immersed.

Totally immersed.

Lean mixture of Portland blast-furnace cement in artificial sea-water of three times normal concentration, at Watford, after 3–3½ years.

1 part cement.
3 parts sand.
6 ,, gravel.

Fig. 128.

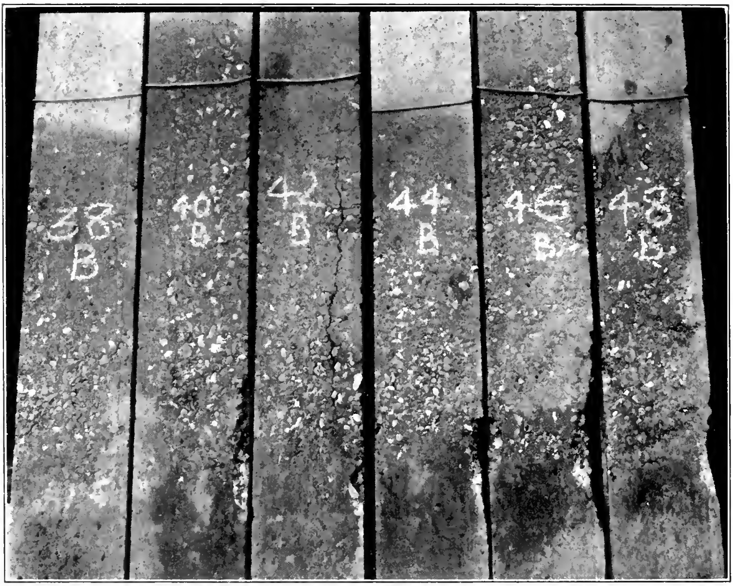


Lean mixture of high alumina cement (1 : 3 : 6), normal consistency, after 4 years in artificial sea-water of three times normal concentration, at Watford.

Fig. 129.

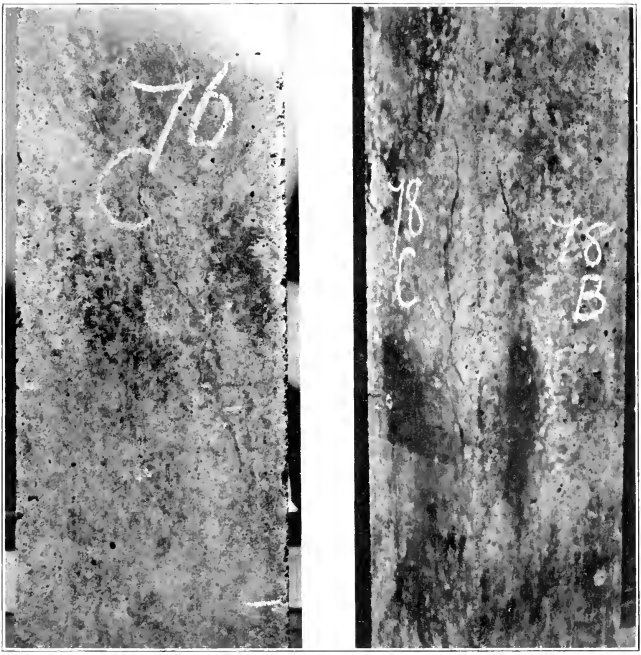
Lean mixture of normal Portland cement (1 : 3 : 6), normal consistency, after $3\frac{1}{2}$ years in artificial sea-water of three times normal concentration, at Watford.

Fig. 130.



Lean mixture of high alumina cement (1 : 3 : 6), normal consistency, after 4 years in sea-water at Sheerness.

Fig. 131.



Medium mixture of rapid-hardening Portland cement (1 : $1\frac{2}{3}$: $3\frac{1}{3}$), normal consistency, after $2\frac{1}{2}$ years in sea-water at Sheerness.

FIG. 132.—EFFECTS OF AGE ON COMPRESSIVE STRENGTHS OF PORTLAND CEMENT AND RAPID-HARDENING CEMENT CONCRETES (*a*) WHEN IMMERSED IN FRESH WATER, (*b*) WHEN PARTLY, AND (*c*) WHEN WHOLLY IMMERSED IN ARTIFICIAL SEA-WATER. D DENOTES DRY CONSISTENCY AND N DENOTES NORMAL CONSISTENCY.

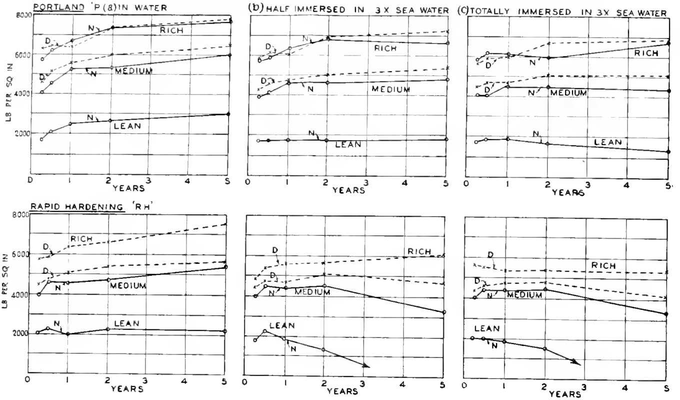


FIG. 133.—EFFECTS OF AGE ON COMPRESSIVE STRENGTHS OF PORTLAND CEMENT AND RAPID-HARDENING CEMENT CONCRETES WITH TRASS (*a*) WHEN IMMERSED IN FRESH WATER, (*b*) WHEN PARTLY, (*c*) AND WHEN WHOLLY IMMERSED IN ARTIFICIAL SEA-WATER. D DENOTES DRY CONSISTENCY AND N DENOTES NORMAL CONSISTENCY.

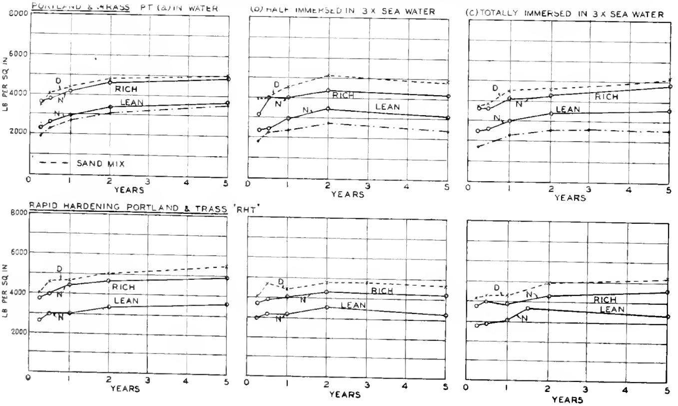


FIG. 134.—EFFECTS OF AGE ON COMPRESSIVE STRENGTHS OF HIGH ALUMINA "A" AND PORTLAND BLAST-FURNACE CEMENT CONCRETES (*a*) WHEN IMMERSED IN FRESH WATER, (*b*) WHEN PARTLY, AND (*c*) WHEN WHOLLY IMMERSED IN ARTIFICIAL SEA-WATER. D DENOTES DRY CONSISTENCY AND N DENOTES NORMAL CONSISTENCY.

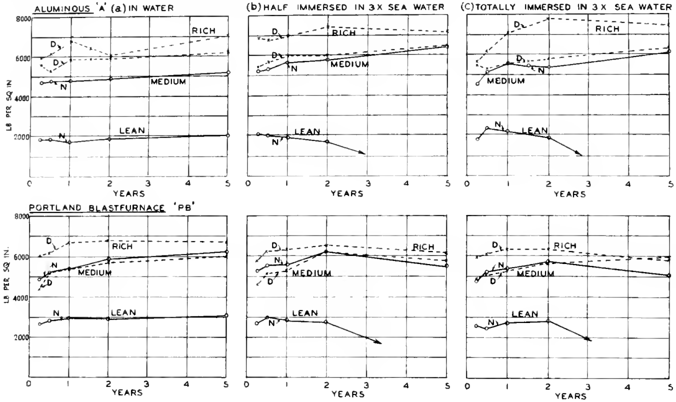
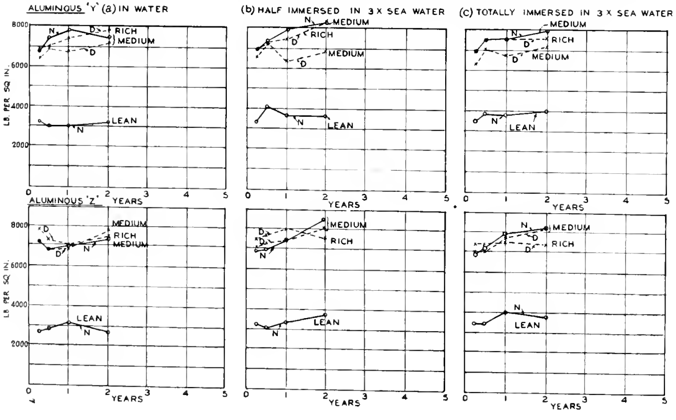


FIG. 135.—EFFECTS OF AGE ON COMPRESSIVE STRENGTHS OF HIGH ALUMINA "Y" AND HIGH ALUMINOUS "Z" CEMENT CONCRETES (*a*) WHEN IMMERSED IN FRESH WATER, (*b*) WHEN PARTLY, AND (*c*) WHEN WHOLLY IMMERSED IN ARTIFICIAL SEA-WATER. D DENOTES DRY CONSISTENCY AND N DENOTES NORMAL CONSISTENCY.



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Total number of Subscribers—90.

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Printed under the authority of His Majesty's Stationery Office
By Eyre and Spottiswoode Limited, East Harding Street, E.C. 4
Printers to the King's most Excellent Majesty.

x (382)11393 Wt 3682—2692 1250 2/36

S.O. Code No. 47-37-15

Institution of civil engineers, London
Deterioration of structures of timber, metal, and concrete exposed to the action of sea-water. London, Stationery, 19

344567