

11 January, 1921.

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in the Chair.

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WILLIAM HUGH GORTON.  
CHARLES MCFADZEAN.  
HENRY EDGAR MORTON.

ALBERT ERNEST PRESCOTT, *D.S.O.*  
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JOSEPH STANLEY WESTERDALE, *B.Sc.*  
(Engineering) (*Lond.*).

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(*Wales*).  
ARTHUR RAY KELSEY, *B.A. (Cantab.)*.  
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THOMAS DALRYMPLE STRAKER-SMITH,  
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ROBERT EDGAR WALSH, *M.C., B.Sc.*  
(Engineering) (*Lond.*).  
ALFRED ROBERT WEISS.  
WILLIAM JAMES WELLS, *B.Sc. (En-*  
*gineering) (Lond.)*.

(*Paper No. 4351.*)

“Reinforced Concrete for Ship-Construction.”

By Professor THOMAS BERTRAND ABELL, *O.B.E., M.Eng.*

IN connection with the adoption by the Admiralty of reinforced concrete for the construction of ships, tests and experiments were made during 1917-18 by the department of the Controller General of Merchant Shipbuilding, and also by contractors engaged in the construction of these ships, acting on their own initiative. The fact that much of this information was accumulated at public expense furnishes a special reason why the department should make it generally available. With the sanction of the Controller General of Merchant Shipbuilding this Paper has therefore been prepared, to place before the engineering profession the results of tests carried out with the object of securing a satisfactory concrete for use in the construction of ships, to which purpose, under the exceptional conditions brought about by the war, it had been decided to apply reinforced concrete.

At the time reinforced-concrete ship-construction was commenced in this country there was already much information at hand relating to the manufacture and properties of concrete, but the bulk of the published matter had reference to questions connected

particularly with building construction, rather than problems arising in ship-construction.

The essential requirements of a material for ships may be stated as follows:—

- (1) It shall have known, sensibly uniform, and reliable mechanical properties, comprised under the comprehensive terms strength and elasticity.
- (2) It shall have a known and sensibly uniform density.
- (3) It shall be water-excluding in all circumstances.

The higher the mechanical properties, the more suitable will the material be.

*Materials of Construction: Concrete.*—Experience has shown that concretes varying greatly in quality result from the use of the same cement and the same aggregate in different proportions. Again, mixtures having the same proportions give differing results if the nature, size, and shape of the aggregate be modified, or if the nature and size of the cement particles be altered. Care in proportioning thus becomes of great importance in order to secure the results desired.

The material in a steel ship is manufactured away from the construction-yard, and is tested before leaving the steel-mills. In a concrete ship the material of construction—the concrete—is manufactured on the site immediately before incorporation in the work, and can be tested only when it is part of the ship. The mixture to be used needs, therefore, to be very carefully determined in advance. It has to be remembered that after placing the concrete complete hydration is only ensured by a sufficiency of water. Close attention is required to ensure this.

*Cement.*—It was decided to use Portland cement, the only cement manufactured on a large scale. It is a material which, if carefully prepared, has reliable properties.

Cement being the active agent providing tensile and compressive strength, and watertightness, it was essential that the mixtures should be “rich” in cement, with an excess over that required to fill the voids. The specification of the concrete used required that there should be at least 35 per cent. of cement by volume in the finished concrete. This proved sufficient to ensure watertightness in the test slabs under a pressure of 30 lbs. per square inch, and in the vessels under working conditions. Cement of somewhat increased strength is obtained by finer grinding, and some contractors on their own initiative required a higher degree of fineness than that specified.

*Aggregate.*—The type of aggregate used in the construction of the ships depended upon the geological formation in the neighbour-

hood of the shipyard. In the southern and south-eastern district the aggregate used was beach- or river-gravel, mainly of flinty character. That in the north and north-western districts was of igneous rock, granite or trap. In one case beach-gravel consisting mainly of igneous rock was to have been used.

The size of the aggregate was governed by the minimum cover of the reinforcement, namely,  $\frac{1}{2}$  inch; it was required to pass a screen with  $\frac{3}{8}$ -inch square mesh or one having  $\frac{1}{2}$ -inch round holes, whichever was preferred by the contractor. Granite or whin chips have been used equally with crushed and uncrushed gravel. Concrete made with either was able to fulfil the requirements of the specification. It had been believed, and many experiments supported the view, that a large aggregate of broken stone would yield better crushing results than rounded gravel. With aggregate of the size specified, very rounded gravel, such as that from the Chesil Beach, gave results certainly not inferior to those of any concrete specimens tested. Indeed by far the best crushing strengths have been obtained with such a gravel, reaching 4,750 lbs. per square inch at 7 days, and over 7,000 lbs. at 28 days, using 4-inch cubes for test-pieces.

There are, indeed, many good reasons for adopting a beach-gravel for ship-construction: it is generally clean, the softer elements of the basic rock have usually been removed, and—most important—it is generally better graded than an artificially prepared aggregate. Concrete with a rounded aggregate is also easier to place within confined moulds than an angular aggregate, which is liable to catch on the reinforcement and create voids.

It must not be inferred that no difficulty was experienced by the use of natural gravel. This was not the case. It is, however, true that no difficulty was found where beach-gravel was used, because it can be obtained clean and free from vegetable matter. No distinction has here been drawn between coarse and fine aggregate.

The aggregates were in all cases practically impervious to water. They comprised Chesil Beach gravel, Shoreham gravel, Whitby Beach gravel, Thames Ballast, Ham River ballast, granite—Aberdeen, Malvern, Threlkeld—Stranraer gravel, whin chips, and sands both of siliceous and granitic origin.

*Water.*—The proportion of water was not specified, not because it was believed to be unimportant, but because it was thought that the proportion to be used might very well be left to the engineer in charge. It would have been difficult to specify a proportion which could have been used in all cases, because of the different methods of construction adopted. This must be particularly so in a ship

which is constructed of thin slabs. For example, a far stiffer concrete can be used in placing a concrete deck than in placing a bulkhead. The proportion of water to be used depends upon the type of construction, and the position of the slab to be cast. The degree of fluidity desired in the concrete for the type of construction being decided, it was then possible to determine the amount of water necessary to ensure this.

*Proportions.*—The mixtures used generally ranged around:—

1 part of cement :  $1\frac{1}{3}$  part of sand :  $2\frac{1}{4}$  parts of aggregate ; or, conveniently, a 1 : 3·375 mixture.

The richest mixture used was 1 : 2·67, the poorest 1 : 3·66. It does not follow that the richest mixture, using the volumetric method of proportioning, contains the greatest volume of cement per cubic foot of the finished concrete. The percentage quantity of cement will depend upon the grading and type of the aggregate.

*Density.*—The weight per cubic foot of the concrete (unreinforced), under similar conditions as to age and dryness, ranged from 142·5 lbs. per cubic foot to 152·5 lbs. per cubic foot. This was a very wide variation, necessitating in some types of vessel a careful consideration of the dimensions of the vessel, particularly where it is one of “constant draught,” i.e., where the variable load carried is small, and where there is no large reservoir of cargo deadweight capacity to draw upon in the event of the concrete hull weight exceeding the estimate. This variation cannot be properly compared to the rolling margin on steel plates, since it is largely due to the different types of aggregate used. There is, however, in concrete ship-construction a variation in concrete prepared from the same aggregate, which may be compared to the rolling margin. This variation is not large, though it may amount to 4 lbs. or 5 lbs. per cubic foot, and is due to the want of strict uniformity in concrete mixed by the volumetric method of proportioning, in which the water is a very variable quantity.

A “weight” method of proportioning, using dry materials or materials containing known proportions of moisture, should overcome this difficulty and secure greater uniformity in density. It would, however, involve very tedious mixing, because in concrete vessels, generally speaking, the quantities of concrete to be mixed and placed at one time are small.

Absorption of water after launching adds sensibly to the weight of the ship, and may amount to 2 per cent. of the light weight of the concrete hull.

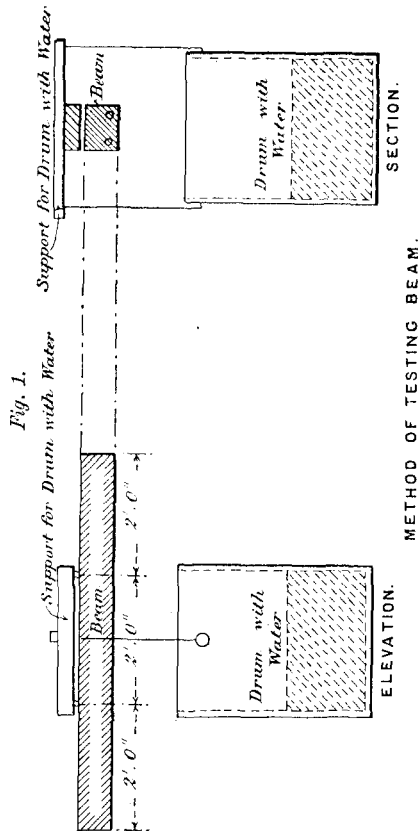
Steps were taken by individual builders to make an artificial aggregate much lighter than natural aggregate. Some samples show that the crushing-strength of the concrete thus prepared is

certainly not inferior to the best so far obtained, but the aggregate used was porous.

*Crushing-Strength.*—The minimum permissible crushing-strength at 7 days was specified to be 1,600 lbs. per square inch, and at 28 days not less than 3,200 lbs. per square inch. Of the samples prepared and submitted to test, the crushing-strength determined by 4-inch cubes cast in metal moulds ranged from 1,450 lbs. per square inch to 4,750 lbs. per square inch at 7 days, and from 3,000 lbs. per square inch to 7,000 lbs. per square inch at 28 days. The figures given are the means of three specimens all prepared from batches of concrete to be actually used in the construction of vessels. This variation in strength was considerable; but a percentage variation of equal amount in the elastic limit of steel used in ship construction is not unknown.

A further series of tests were made with beams having sufficient reinforcement on the tension side to ensure failure taking place by crushing of the concrete, in order to determine whether there was any appreciable difference in the stress at failure in bending or uniform compression as in cube tests. The method of test, the particulars of the beams, and the load-deflection diagrams are shown in *Figs. 1, 2, and 3.* The load-curve No. 5 shows the effect of releasing the load before fracture and reapplying it. The concrete consisted of 1 part cement and 3 parts of sand and Thames ballast mixed.

The strength of concrete of specified age being dependent upon so many factors, and so variable, it was not possible to take advantage to the fullest extent of the results of concrete tests. For

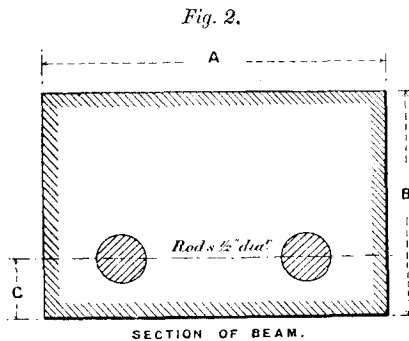


example, with concrete possessing a crushing-strength of 7,000 lbs. at 28 days, it should be practicable to design a vessel using 1,400 lbs. as the working-stress if this crushing-strength could be maintained throughout the main portions of the structure. A little carelessness in using or placing a batch of concrete, or inattention during the first period of maturing, might very well reduce the ultimate strength of the concrete to 4,000 lbs., for which a working-stress of 1,400 lbs. would be inadmissible.<sup>1</sup>

The best compressive results were obtained with a 1 : 2·9 mixture, whilst the poorest were obtained with a 1 : 3·45 mixture. Both of these mixtures are within the extreme limits mentioned before. The poorness of the result in the latter mixture was found to be due

to one of the commonest causes of failure of concrete ("dirty" aggregate), which can readily be avoided by examination and ordinary care; but these results emphasized the necessity of caution in selection of aggregate, and in the preparation of the concrete.

Detailed particulars of some experiments carried out upon a natural gravel, and a crushed stone from the same parent rock of igneous origin, are given in Table I (Appendix). The difference in crushing-strength between the washed and unwashed gravel



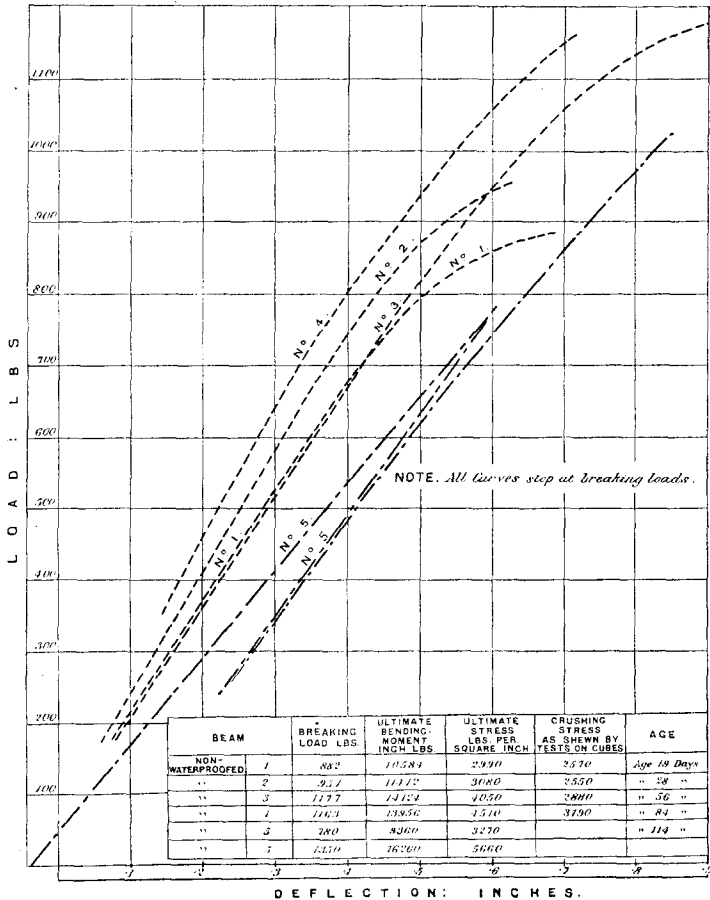
BEAM	DIMENSION A	DIMENSION B	DIMENSION C
1	3·54	2·48	·53
2	3·54	2·50	·49
3	3·54	2·46	·52
4	3·54	2·36	·54
5	3·54	2·5	·78

aggregate is marked, the latter being the stronger by 16 to 18 per cent. This state of affairs was reversed when the coarse aggregate consisted of equal parts of gravel and crushed gravel. The washed aggregate was then definitely the better by 2 to 15 per cent. It is unfortunate that a comparison was not made with crushed gravel stone alone as the coarse aggregate, for it is reasonable to suppose that the advantage of washing would have been much more marked, because of the resulting large quantity of fine powder, removable by washing.

<sup>1</sup> It is understood that the United States Shipping Board proposed a permissible stress for design purposes of 1,500 lbs. per square inch in compression for concrete having an ultimate crushing-strength of 4,000 lbs. at 28 days.

*Tensile Strength.*—The general practice in the design of land structures is to neglect concrete in tension, though in some land structures subject to rapidly applied loads a limit is put upon the computed value of the tensile stress. At a very early stage in the

Fig. 3.



consideration of reinforced-concrete ship-construction it was realized that the tensile strength of concrete could not be ignored entirely, and in the case of self-propelled reinforced-concrete vessels it was also thought advisable to impose such a limit. In the absence of any special information on the subject, it was considered that a limit

approaching the breaking-strength of the unreinforced concrete at 28 days would be reasonable, having regard to the experimental knowledge that concrete when reinforced does develop a computed tensile strength greater than unreinforced concrete. The permissible computed tensile stress was limited provisionally to 325 lbs. per square inch. In actual cases it amounted to 350 lbs. per square inch.

Experiments were made to determine the tensile strength of concrete, both plain and reinforced. In the former, pure tensile tests were made with specimens 6 inches by 3 inches in cross section, in order to get a test representative of the shell slab of the vessel. In connection with these tests the tensile and other properties of the cement actually used in making the concrete were also determined. Full particulars are given in Table II (Appendix).

The tensile strength of the cement at 28 days, indicated by 1-inch-square test-pieces, was 756 lbs. per square inch with a variation of 3 per cent. up and 5 per cent. down. The strength of the concrete at 31 days was very uncertain, the maximum stress at rupture reaching 316 lbs. per square inch. There was, therefore, a large variation which is not easily explained, since the concrete was a very rich mixture, 1 : 2.67, and made of fine aggregate ( $\frac{3}{8}$  inch or less). The differences were greater than would be expected from fortuitous local accumulations of aggregate at the place of fracture. A further test (see bottom of Table II) on three specimens using the same aggregate gave very uniform results, with a mean of 286 lbs. per square inch at 42 days. With smaller specimens it is quite probable higher results would be obtained, but it is doubtful whether a smaller specimen would be representative. It would appear, therefore, that a rich concrete can certainly be made under practical conditions to have a tensile strength of 250 lbs. per square inch or, say, about one-third of the strength of the neat cement.

As the specimens had to be transported by rail a long distance, some may have been injured in transit, though the results do not indicate this as probable.

*Steel.*—The steel used in construction was preferably in the form of bars of circular section and generally of the ordinary mild steel quality required by the Ship Registration Societies, having a tensile strength of 26 to 33 tons per square inch, and with a modulus of elasticity of 13,000 tons per square inch. Bars of 2 inches diameter have been used, but the general specification placed a limit of 1 inch on the diameter, unless special approval was obtained. The above requirements applied to bars over  $\frac{3}{8}$  inch diameter. Bars of smaller diameter were not usually tested, and such bars were sanctioned, when of shell discard steel, having a higher

tensile strength and elastic limit. Such steel was not sanctioned for the principal reinforcement, because of its unreliability, as it was desired not to introduce into the structure any material of importance known to possess unsatisfactory qualities.

In certain vessels a twisted bar with a section of triangular character was used, where a satisfactory supply could be obtained. In others a ribbed bar of square section, with circular ribs at frequent intervals, was adopted. Expanded metal sheeting was used for both main and slab reinforcement.

The load is certainly better maintained in the case of small than with large bars, and this fact, together with the supposed difficulty of hooking thick bars without furnacing, seemed sufficient reason for restricting the size of bars until further experience had been gained. Large 2-inch diameter bars were, however, successfully hooked cold to an internal radius of  $3\frac{3}{4}$  inches without much difficulty.

*Reinforced Concrete.*—Reinforced concrete owes its success to two important physical properties of cement and steel. These two materials have, for all practical purposes, the same coefficient of heat expansion, and, owing to the fineness of the cement particles and to slight contraction on setting, a very strong grip or adhesion of the concrete to the steel is obtained. This grip is believed to be mainly of a mechanical nature, and is necessarily dependent upon the surface area of the bars. The smaller the diameter of the bar, therefore, the greater the adhesion per unit area of cross section per unit of length. Provided the two materials expand or contract or change shape together, it is reasonable to assume that the bond will be maintained, but it will certainly fail when the steel contracts under tension more rapidly than the concrete. It may, therefore, be expected that when the elastic limit of the steel is reached, that is, when definite contraction takes place, the bond will fail, and smooth round bars will pull out from the concrete mass unless their ends are hooked or otherwise anchored. Even if the bars are anchored the bond will be destroyed and will not be renewed on relieving the stress. There is, therefore, a limiting stress—that corresponding to the elastic limit—beyond which round steel bars may not be used in reinforced-concrete structures, particularly in those subjected to alternating stresses.

In the design of land structures, on which the loading is usually fairly definite, a tensile stress in the steel of 16,000 lbs. per square inch is permitted, assuming the steel to take the whole of the tensile stress. Should this stress be developed in mild steel or other material with the same modulus of elasticity, the neighbouring concrete will be stressed beyond its ultimate stress, and will fail.

In a ship, taking the concrete as capable of resisting tension, as indeed it must during the initial application of a load, it will be found that the resulting stress in the concrete under the assumed loading may very well be less than that corresponding to rupture under tension. For example, in some reinforced-concrete tugs, neglecting concrete for tension, the estimated tensile stress in the hogging condition was 9,800 lbs. per square inch. Assuming a modular ratio of 12, and taking concrete into account for tension, the estimated stress in the concrete was 325 lbs. per square inch, and in the steel less than 4,000 lbs., or under 2 tons per square inch. The concrete is not likely to fail from tension at the stress estimated, and it would at first sight appear reasonable to include in design the possibility of concrete resisting tension. But concrete can only be of such use provided it is homogeneous and continuous. Immediately a crack occurs, due to loading or to shrinkage, or to temperature stresses, the resistance of the concrete to tension at the crack is lost. It is, therefore, not permissible to rely upon the concrete to take tension, to resist which sufficient steel must be provided. Admitting that cracks may occur, the steel then limits their magnitude.

There are clearly two distinct conditions of design :—

- (a) For a new ship which is everywhere homogeneous and intact.
- (b) For a ship already on service in which the concrete is not continuous.

An examination of the conditions previously stated leads to the following conclusions :—

- (1) Concrete of the kind used can resist tension up to about 325 lbs. per square inch.
- (2) Under this condition the steel will not be stressed to 16,000 lbs. per square inch (the maximum stress).
- (3) The steel must not be stressed to the elastic limit; and
- (4) The bond on a round bar will then be maintained, and with good design will be sufficient.
- (5) Artificial bond, other than hooked ends or overlaps, is not then necessary in ship work.

It will be obvious that in this case the steel is not economically used, and that to obtain a more effective structure as a whole, a material having a higher modulus of elasticity than steel is desirable.

Whilst these conclusions, after an examination of the problem, became almost self-evident, it was thought desirable to conduct a series of experiments which should bring out the behaviour of concrete used independently, and when combined with steel in a reinforced-concrete structure. The series of experiments comprised:—

- (1) Tests of the cement in direct tension.
- (2) Tests of the concrete in direct tension.
- (3) Tests of reinforced-concrete beams under a steady bending moment,
  - (a) Using wire rope as reinforcement.
  - (b) Using round steel bars as reinforcement.<sup>1</sup>
- (4) Tests of reinforced-concrete beams under alternating bending moment.

Particulars of (1) and (2) are given in Table II (Appendix) and have already been summarized (see pp. 229, *et seq.*)

The tests under (3) comprised tests of beams using two different types of steel wire-rope reinforcement for the purpose of comparison with beams having plain steel rods. It had been suggested that in the case of a vessel built mainly on the precast unit system, the use of wire rope would facilitate the fabrication of that part of the work to be formed in situ. Though the difficulties of securing a flexible rope in its correct position in a restricted space were realized, it was decided to put the proposal to the test.

The dimensions of the beams are shown in *Figs. 4*.

Three types of beams were made, the tensile reinforcement consisting of:—

- (1) Three  $\frac{1}{2}$ -inch diameter rods.
- (2) Three lengths of well-used  $1\frac{1}{2}$ -inch galvanized submarine cable of seven strands of seven wires, each 0·053 inch diameter.
- (3) Three lengths of 2-inch flexible steel wire rope consisting of six strands of twenty-four wires, each 0·035 inch diameter.

Four specimens were made of types 1 and 2 and three only of type 3. The curves of deflection are the mean of the results obtained with each type.

A two-point system of loading was adopted, to obtain uniform

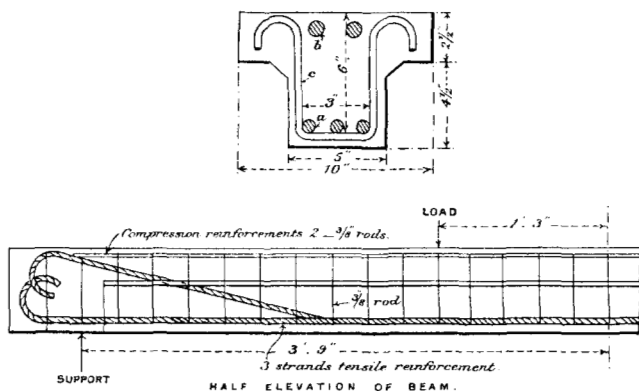
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<sup>1</sup> These tests were initiated by Mr. E. O. Williams, of Messrs. Hill, Richards and Company.

bending over mid-span. The load was applied in the horizontal plane, so that the weight of the beam could be neglected.

An analysis of the results appears to indicate that the point at which the concrete ceases to resist tension, and at which tensile stresses are taken wholly by the steel reinforcement, can be deter-

Figs. 4.

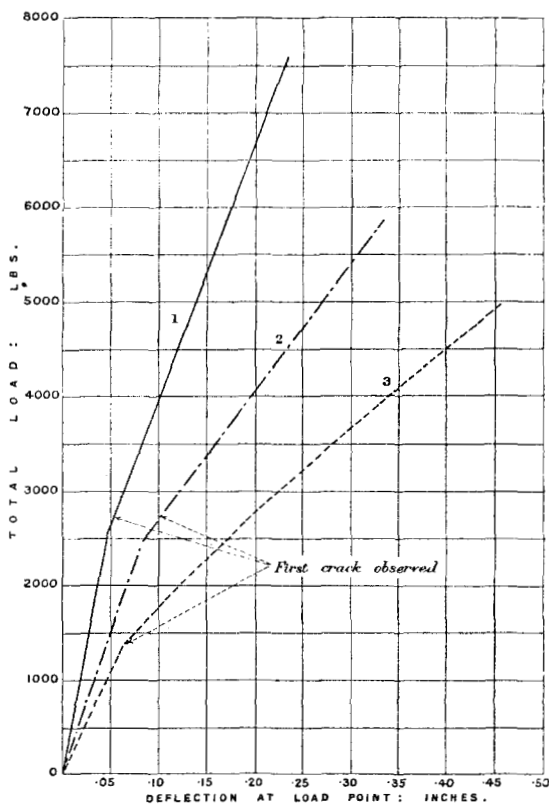


No. of Curve.	Particulars of Reinforcement.			Moment of Inertia.	Load at Failure of Concrete.		Estimated Tensile Stress in Concrete at Failure.
	a	b	c		Estimated	Cracks Observed at	
1	3- $\frac{1}{2}$ in. rods	2- $\frac{3}{8}$ in. rods	$\left\{ \begin{array}{l} \frac{3}{8} \text{ in. rods} \\ 3 \text{ c/c.} \end{array} \right\}$	306	2,800	2,800-4,000	514-735
2	3-1 $\frac{1}{2}$ in. ,, Submarine Cables.	,,	,,	274	2,400	2,800	515
3	3-2 in. ,, Flexible S.W.R.	,,	,,	288	1,400	1,200-1,400	285

mined closely from the load-strain diagrams (see *Fig. 5.*) The strain curve is closely represented by two straight lines whose point of intersection corresponds to the failure of the concrete (failure of the concrete commencing at the extreme fibres and extending towards the neutral axis). Taking account of the different moments of resistance of the different beams it appears that the stress in the concrete at failure was about the same in the beams reinforced with plain rod as with those reinforced with sub-

marine cable, with a slight advantage to the former, an advantage more pronounced in comparison with beams reinforced with flexible steel wire rope. In the latter each strand of wire has a hemp core, and it is probable that the bond between the wire and the concrete is more easily destroyed by reason of contraction under tension. The particular rope in question was quite new, though

Fig. 5.



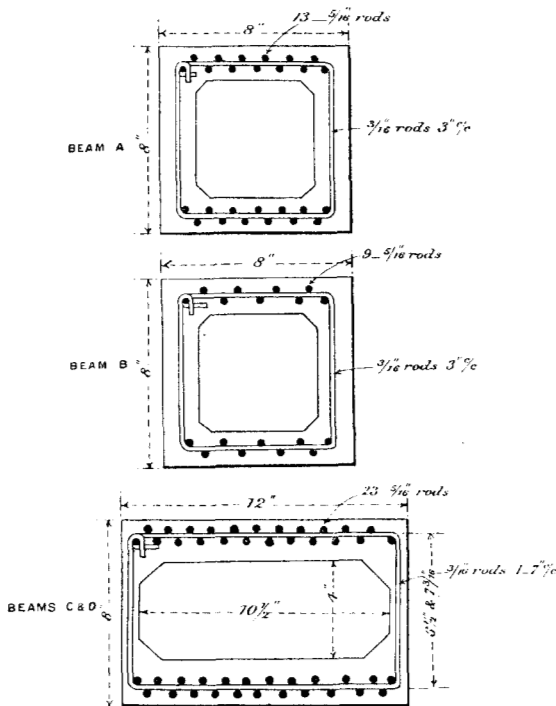
thoroughly cleaned, and the bond may not have been so effective as in the old and used submarine cable. The actual estimated stresses in the concrete were: 515 lbs. per square inch, rising in one or two cases to 735 lbs., in the case of plain-rod beams; 515 lbs. per square inch in the case of the submarine cable beams; and 285 lbs. in the case of the flexible steel wire rope reinforcements.

It is unfortunate that these stresses cannot be compared with the tensile strength of the cement, since no test-pieces were made for its determination.

The experiments indicate that wire rope not containing soft-cores can be successfully used, but that it is inferior to circular steel rods for reinforcement.

It should be remarked that the fractures on the tension side always

Figs. 6.



occurred at the stirrups and, so far as could be seen, not intermediately. This was to be expected, and is an indication that in estimating the moment of inertia and position of the neutral axis of a reinforced-concrete girder, in which the concrete can take tension, allowance must be made for the presence of transverse steel on the tension side.

Further tests upon beams were carried out in order to determine the behaviour of reinforced concrete when used for making hollow

girders of box section. The test beams were designed by Mr. E. O. Williams, of Messrs. Hill, Richards & Co., by whose courtesy the results are published here. The immediate purpose of the experiments was to get information upon the behaviour of concrete (1) when heavily reinforced with steel in the flanges of a beam in which precautions had been taken to ensure that the beam should not fail through shear; (2) when, the flanges still being heavily reinforced, the beam was designed to fail by shear in the webs; and (3) to obtain some idea of the watertightness of reinforced concrete under tension.

The beams were of two types, shown in *Figs. 6*. Those beams (A and B) designed to fail by tension were 8 inches square externally with  $1\frac{1}{2}$ -inch webs and flanges; those beams (C and D) designed to fail by shear were 12 inches by 8 inches externally with  $\frac{3}{4}$ -inch webs and 2-inch flanges. A central point load was applied in each case the span between supports being 10 feet and 4 feet respectively. Reckoning the percentage of steel on the tension side of the cross section of the beam, that of beam A worked out at  $8\frac{1}{2}$  per cent., that of B at  $5\frac{3}{4}$  per cent., and that of beams C and D at  $7\frac{1}{2}$  per cent. in both cases.

The beams were filled with water under slight pressure to give evidence of fractures. Load-deflection curves are shown for beams A and B in *Fig. 7*. Each curve appears to be represented by two straight lines, the point of intersection of which probably indicates the load around which failure of the concrete under tension occurs.

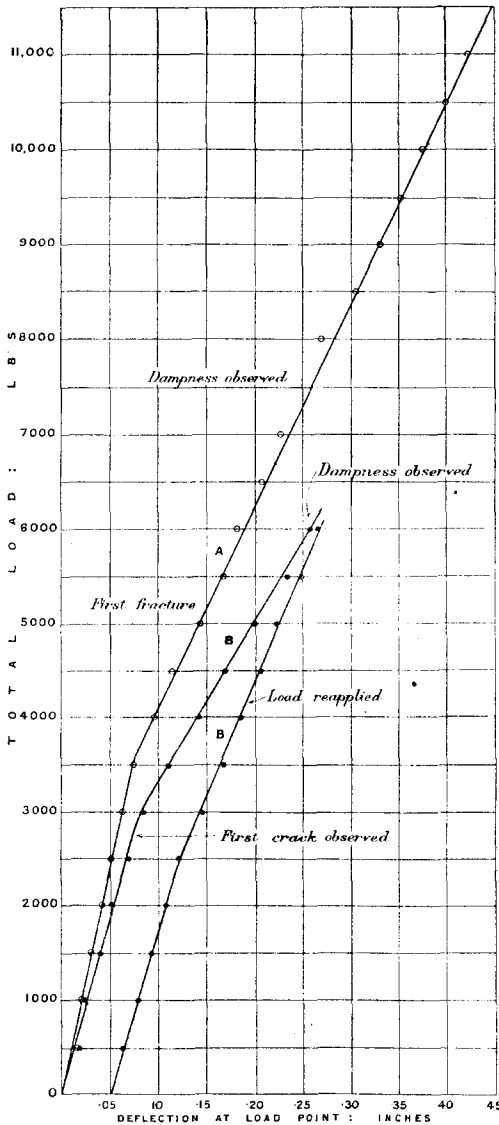
On the assumption that the modular ratio of steel to concrete is 12, and that the whole of the cross-sectional area of the girder is effective, the corresponding tensile stress in the concrete at the extreme fibre is 810 lbs. per square inch in beam A, and 800 lbs. per square inch in beam B. It is probable that actual fracture began at an appreciably lower stress than this, but far above the tensile strength of plain concrete.

It is not suggested that the presence of reinforcement has the effect of increasing the ultimate tensile strength of the concrete *qua* concrete. All that the reinforcement does is to reduce the probability of local failure throughout the mass by limiting the extension of the concrete, and by very gradually taking a greater and greater share of the tensile stress.

The loads corresponding to estimated and observed fractures are indicated in the figures, and also the load at which leakage occurred. It will be noticed that such leakages occur at some considerable interval after fractures are observed, indicating that fracture does not

take place simultaneously throughout the flange, and that the stress - distribution throughout the section does not change suddenly from the condition in which the concrete does resist tension, to that in which it does not resist it.

Fig. 7.



No attempt has been made to deduce the modular ratio of the steel and concrete from the deflection experiments.

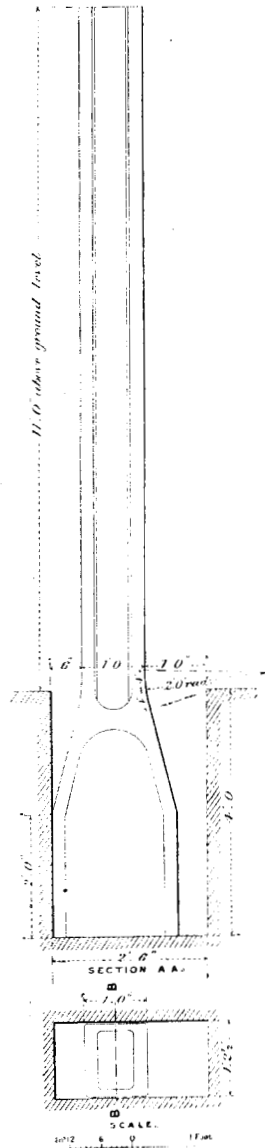
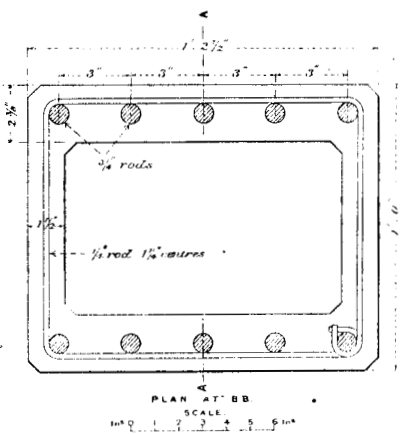
A ship girder is subjected to alternate and repeated bending stresses of varying magnitude. The behaviour of a reinforced - concrete girder under similar stresses was at least uncertain, and by some it was thought that, if the concrete had been fractured on the tension side, repetition and alternation of bending stresses might lead to disintegration of the concrete, particularly if, as in the case of a ship, the girder was at the same time subjected

to torsional stresses. To obtain some information on the point,

hollow reinforced-concrete columns (*Figs. 8*) were constructed of concrete, the qualities of which, when unreinforced, were known. The columns were erected vertically with their lower ends fixed rigidly in the ground, the lower end of the column being enlarged and shaped so that the position of maximum stress was above ground-level and in sight of the observer. The load was applied near the upper end by two opposed hydraulic cylinders, with coupled rams fitted with a self-acting reversing valve which impressed a reversal of load, with fixed deflection of the beam, from four to seven times per minute. The application of the load was interrupted occasionally to make adjustments to the valve, and was only applied during 10 hours of the day.

The columns were filled with water throughout the test, for the purpose of revealing cracks brought about by the loading. Before

*Figs. 8.*



applying the load a few cracks were revealed, principally in the  
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webs of the columns, and at the half width of the web face. These were probably shrinkage cracks, and did not extend to the flanges of the column. Under load several of these cracks developed, particularly the lower ones near the positions of maximum stress, and extended to the edge and ultimately to the flanges of the column. Others of these initial cracks remained unaltered. New cracks commenced at the flanges and gradually developed inwards across the web faces. The development of the cracks under a constant load or deflection was limited, increasing only on an increase of the load.

Four columns were constructed, but only two were tested, the armistice intervening and rendering it unnecessary to spend further money on the tests. The first column was subjected to 100,000 reversals at a load estimated to create a tensile stress of 180 lbs. per square inch in the concrete, on the assumption that the concrete was intact. During the early stages of the experiment the fine cracks in the web faces gradually developed and extended to the edges. After 8,000 reversals cracks began to develop on the flange faces, extending slowly from the edge to the middle of those faces. The cracks developed over a region some 3 to 5 feet from the position of maximum stress, at more or less regular intervals, corresponding to the spacing of the stirrups. Towards the end of the experiment the cracks became sealed by a whitish substance deposited in them. Each morning, at the commencement of the test, the column was quite dry and the cracks were sealed. On restarting the test the cracks generally opened, but ultimately they became quite sealed, and did not open even under the alternating load.

The load on the beam was then increased to produce an estimated tensile stress in the concrete of 360 lbs. per square inch, which exceeded the possible tensile strength of the concrete alone. The old cracks at once re-opened, and new and more extensive cracks appeared. These cracks after 30,000 reversals had not become sealed. The load was still further increased to give a deflection three times the original amount, to determine, if practicable, whether any signs of rapid disintegration of the concrete at the cracks would be disclosed. At this load movement was localized chiefly at the lowest crack, which dried under tension and became very wet under compression, the water being squeezed out from the crack which had become full when the flange was in tension. At the end of 50,000 reversals, or 200,000 in all, there were no signs of grinding away of the cement or the concrete.

The second beam was tested in a similar manner, but the reversals

at the smaller loads were limited to a comparatively small number. The maximum load corresponded to a deflection of 0.4 inch at the point of application of the load, four times that of the initial deflection corresponding to a concrete stress of 180 lbs. square inch. At this load 70,000 reversals were made, but here again there was no sign of disintegration. All movement was concentrated in the lowest cracks.

These experiments are of both interest and value, though not sufficiently extensive to enable general conclusions to be drawn. The column was thin and, though very carefully constructed, had cracks in the web of the girder before loading. These initial cracks became in some cases the ultimately important cracks. Under a small stress of about 1 ton per square inch in the steel the cracks became sealed, even under repeated bending, but with 2 to 3 tons per square inch stress in the steel it is almost certain that cracks would be formed in the concrete slabs of ships, and that they would not be sealed sufficiently to prevent interchange of water between the surfaces.

Particulars of the tests and observations are given in Table IV (Appendix).

The experiments were devised in conjunction with Dr. Gulliver, and were carried out under his supervision at Messrs. David Kirkaldy's laboratory in Southwark.

*Watertightness.*—If each particle of the aggregate, fine and coarse, can be coated with cement; if the voids can be filled; and if, in addition, the hydration of the cement be completed before disturbing the concrete, the resulting concrete will be watertight. There must, therefore, be a minimum of quantity cement for each particular type and size of aggregate used. The proportion of cement in the finished concrete should, provided proper workmanship be employed, be a guarantee of watertightness in the vessel. The specification provided that there was to be at least 35 per cent. by volume of cement in the finished concrete. This percentage ensures a probability that the concrete will prove watertight. Particulars of the mixtures used are given in Table III (Appendix).

Percolation tests were carried out to test the permeability of the mixture. The conditions under which concrete is placed in a ship differing so very much from those attending preparation of test specimens, this test was regarded rather as a test of the density or compactness of the mixture, than as a test of the watertightness *qua* watertightness. It is complementary to the crushing test.

In making the specimens no special treatment of the surface was

permitted. The slabs were generally 9 inches by 9 inches by 2 inches, and were cast in wood moulds with their larger surfaces vertical. Water-pressure at 30 lbs. per square inch was then applied to one of the surfaces. Some difficulties in regard to the permeability test were experienced, and, generally speaking, where the crushing-strength has been low the concrete has failed to pass the permeability test. Trowelling had a marked influence on watertightness. In one set of tests water under pressure applied to the trowelled surface failed to permeate a slab 2 inches thick at 200 lbs. per square inch, during an application of 2 hours. When applied to the untrowelled surface water passed out at the sides before escaping by the trowelled surface.

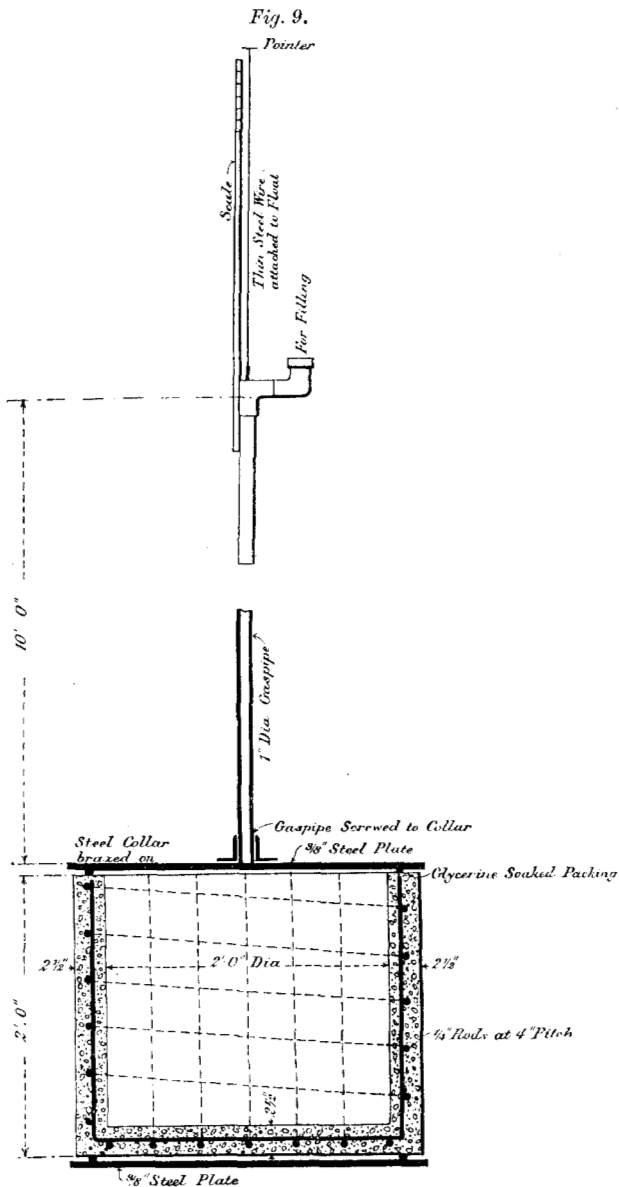
*Waterproofing Materials.*—The general view of the Department was that the concrete should be made watertight without the addition of special waterproofing materials. The result of tests on specimens, and experience to date with those vessels now in service, certainly justifies this view.

The question of using waterproofing compositions was not ignored, and tests of compositions put before the Department have been carried out. Generally speaking the compositions indicated an ability to reduce absorption without yielding better water-excluding results under pressure, and at the cost of a sacrifice in crushing-strength. The resulting concrete had a density sensibly less than the concrete of the same mixture gauged with water. There would appear to be some good reasons for using waterproofing compositions in cases where rich concretes are not essential from strength considerations, but there does not appear to be any need for their use in the construction of ships.

Surface treatment to secure watertightness in a concrete not otherwise watertight is considered inadmissible, since cement is so readily abraded.

Tests to determine the efficacy of waterproofing material consisted of pressure tests with a head of 10 feet of water in cylinders 2 feet in internal diameter and 2 feet high, with alternative thicknesses of 2 inches and 1 inch (*Fig. 9*), and of absorption tests and crushing tests on 6-inch cubes. The mixture used was 1 part of cement to 3 parts of Thames ballast, gauged with the proportion of water and of the waterproofing composition advised by the makers, and mixed in accordance with their recommendation. The cubes, after 28 days in water, were kept for 14 days in a dry place, having been weighed at 7, 14, and 28 days after immersion. The "water-mixed" specimens were saturated in 14 days, the "waterproof-mixed" in 28 days, the former absorbing rather more

than 4 per cent., and the latter rather less than 2 per cent. of the



dry weight of the cubes. The cylinders were in all cases quite

tight—illustrating the fact that non-waterproofed concrete, using rich mixtures, can be made water-excluding.

The crushing tests at 28 days showed a very marked defect of strength when the concrete was gauged with the waterproofing composition, and this defect of strength was more pronounced as time went on, up to the duration of the test, showing that the waterproofing mixture under trial delayed hydration of the cement. The water-gauged concrete was rather more than 4 per cent. the heavier.

*Permeability by Oil.*—Quite early in the building programme proposals were put forward to use concrete barges for the storage of oil, to be used at the Fleet bases for fuelling the smaller war vessels using oil fuel, and in order to release sea-going vessels which would otherwise be detained at the base. It was known that mineral oil, such as is used for oil fuel in marine boilers, had no appreciable disintegrating action upon cement, but it was not known whether it was possible to construct, under practical conditions, a vessel of comparatively small thickness of concrete which would exclude oil. Experiments were therefore initiated to determine the matter.

Cylinders, 2 feet in diameter and 2 feet high, having walls  $2\frac{1}{2}$  inches thick, were subjected to a head of 10 to 12 feet of oil. These cylinders were constructed by ordinary workmen exercising no special care, and using concrete of the proportions 1 of cement to 3 of an aggregate consisting of equal portions of sand and crushed Thames ballast. The cylinders were untreated in any way either on the inner or outer surface, but the surfaces were formed against sheet-metal moulds.

It was found that the cylinders retained the oil quite satisfactorily. There were one or two places at which oil appeared on the outer surface, but there was no flow. The experiments demonstrated in a satisfactory manner that with reasonable care very little risk would be involved in storing oil of high flash-point in a concrete vessel to be used mainly as a floating hulk. Accordingly it was decided to construct two barges for this purpose.

The storage of petrol was quite a different problem, because of its low viscosity and flash-point. Further tests were carried out in a similar manner with the same type of apparatus, but with new cylinders of the same general dimensions. In this case the percolation was very rapid with only 2 or 3 feet head. There were, however, patches in the walls of the cylinders which showed no permeation, indicating that it might be possible, with special care, to build a tank using ordinary Portland-cement concrete,

which would retain petrol; but taking into account the difficulties of placing concrete in a uniform manner on a large scale, it was decided not to use concrete vessels for this purpose, particularly as the vessels proposed might have been required for transport as well as storage.

Special types of cement which are petrol-proof are known to be on the market, but it was felt that, with the very limited knowledge of the behaviour of concrete vessels at sea, it would be inadvisable to take the risk, even with the better quality cement.

In addition to percolation tests, further tests were made to determine whether the petrol had any ill effect upon the crushing-strength of the concrete. These took the form of bending tests of the nature shown in *Figs. 1, 2 and 3*, using beams which were "over" reinforced for tension, so as to ensure that failure took place by crushing of the concrete. When the beams were 7 weeks old they were immersed in petrol for 9 weeks, to determine whether the petrol exercised any serious action in delaying the maturing of the concrete. No action of this kind was revealed, and generally speaking, so far as can be determined from a comparatively small number of tests, the concrete was slightly improved by maturing in the petrol. The mixture used was one part of cement to three parts of mixed aggregate, consisting of sand and Thames ballast. The use of water in a tank as the load enabled this to be very gradually applied, and readings of the deflection to be measured at frequent intervals.

*Protection of Concrete.*—One great fault with cement, or cement concrete, is its inability to withstand abrasion. Considerable attention was necessarily devoted to protecting the sides and decks of vessels where they were specially subject to abrading forces. Chafing by the anchor has been provided against by fitting steel protecting plates on the vessel's side in way of the hawsepipes. In the coaling-barges half-round cope irons, flat side downwards, have been embedded in the deck to take the heavy wear caused by dragging heavy coal-buckets along the deck. In the stoking flats the concrete has been reinforced by steel plates, or by steel bars spaced at intervals and securely anchored in the deck. Extensive fendering was provided in all the vessels, mainly to prevent abrasion. On the barges this consisted generally of a heavy fender rubber placed at or near the upper-deck level, and of one or more rubbers of slighter scantling distributed between the light and load lines. On the coaling- and oil-barges, which act as berths for vessels fuelling, both vertical and horizontal rubbers were provided. On the tugs a heavy fender was fitted at the upper-deck level, and, at

the forward end, short lengths of vertical fender were provided to take the heavy wear caused when the tug was being used for shouldering craft of low freeboard.

In some cases the fenders have been made of concrete, but in the majority of cases of wood. No extensive experience has yet been obtained with the concrete fenders, which were sanctioned mainly on account of the difficulty anticipated in making efficient attachments for the wood fenders, an anticipation justified by experience. The concrete fender is not so yielding, is heavy, is more expensive to construct and to fit, and in practice is liable to chip. On the other hand it can be securely attached to the hull, and can be readily repaired and protected.

The protection of reinforced concrete in a ship from the action of seawater is difficult. The two factors to be considered are protection against fouling by animal and vegetable growth, and, more important, protection against the corrosive action of the seawater upon the steel reinforcement. Experience with dock and harbour work indicates that no special covering to the under-water portion of the hull is needed to prevent growth. The fouling of concrete by weed and animal growth does not appear to be any more rapid than that of iron or wood, and since the mere adhesion of these growths does not appear to have any deteriorating or wasting effect on the concrete, it was decided not to coat the vessels with an anti-fouling paint.

The suggestion of coating the outside of the vessel to assist the concrete in excluding water was repeatedly pressed by the ship-builders, but after taking various opinions it was thought that on the whole the facts which experience disclosed suggested that it was not necessary to coat the exterior in any way. An examination of harbour works showed on the one hand that it was possible for very serious corrosion and deterioration to occur, but, on the other hand, that it was possible to prevent such corrosion. In harbour works heavy corrosion has been experienced in those portions of the structure which are in the neighbourhood of high-water level and especially a few feet above that level, whereas other portions, particularly those submerged, are quite unaffected if the concrete is of a rich and well-graded mixture. In the portions affected it would appear that the corrosion is due to a continual renewal of oxygen in the interior of the concrete by the alternate wetting and drying of the concrete by water carrying dissolved oxygen, and that where no such renewal takes place, as in the portions of the concrete always submerged, or at least always saturated in the neighbourhood of the reinforcement, corrosion does not occur. In a concrete ship,

on account of the pressure of the water on one side of the shell slab, there is an unbalanced pressure tending to force the water through the slab. Even if there be no cracks in the concrete, it is very probable that there will be some penetration, though the inner surface may by evaporation appear quite dry; and notwithstanding this apparent dryness there may be a continuous interchange of water in the body of the concrete, and a renewal of oxygen and of magnesium chloride which, under favourable conditions, has a very rapid corrosive effect upon steel. The first necessity, then, seemed to be to secure a rich and well-graded concrete in which there should be a surplus of cement, causing all the aggregate to be well coated, and the voids completely filled. Strength considerations fortunately ensured this condition being met. The second need seemed to be to prevent evaporation from the inner surface, so that when once the concrete had become saturated with seawater and the small amount of its contained oxygen had been used up by the steel, no further interchange of water and renewal of oxygen would take place. Coating the interior of the vessel with a suitable material, rather than the exterior, seemed to be the correct treatment to adopt, because the exterior was always more liable to abrasion than the interior. The interior, too, could always be made good at a time when it would not be possible to attend to the exterior.<sup>1</sup>

Arrangements were made to carry out a series of experiments to test a number of materials promising to meet these conditions and others which might arise in the self-propelled vessels, where it was feared that bilge-water might have some softening or corrosive effect upon the concrete. Bilge-water contains not only mineral but also vegetable oils, which are known to have a deleterious effect upon concrete. The materials chosen for experimental purposes were the inert substances paraffin wax and bitumen, but since experiments with them would involve a considerable lapse of time, it was decided to apply immediately to the bilges a coating of "supercement" (a Portland cement, in the manufacture of which the colloidal substance tannin is used in order to secure more uniform and complete hydration of the cement).

The preliminary tests were confined to coating the surfaces of concrete slabs, 9 inches by 9 inches by 2 inches thick, with paraffin wax and bitumen by various methods. These slabs were prepared, without any special care, from the concrete mixture used in the construction of one of the vessels, the surface to which the coating

<sup>1</sup> The Department was indebted to Mr. Arnold Philip, the Admiralty Chemist, for this explanation.

material was to be applied representing the surface of a concrete vessel constructed by the monolithic method. These slabs were tested for percolation by applying water-pressure over a treated surface 5 inches in diameter, for a period of 14 days, the pressure being increased in the following stages:—

30 lbs. per square inch for a period of 4 days.			
50	"	"	2 "
70	"	"	2 "
100	"	"	3 "
150	"	"	2 "
200	"	"	1 "

Eighteen slabs in all were made, in six groups, each of three specimens, one being an untreated concrete slab for comparative purposes.

The particulars of the tests are given in Table V (Appendix). The coatings applied were as follows:—

- (1) One coating of paraffin wax applied hot and subsequently melted with a blow-lamp.
- (2) One coating of mineral oil applied hot with an overcoating of paraffin wax subsequently melted with a blow-lamp.
- (3) Four coatings of a 10-per-cent. solution of paraffin in kerosene oil. After drying the waxy surface was heated by blow-lamp.
- (4) As (3) but a coating of melted paraffin wax was applied after the four coatings of the 10 per cent. solution. The wax coating was melted with a blow-lamp.
- (5) One coating with a solution of bitumen in coal-tar naphtha.
- (6) One coating with a solution of bitumen of another variety.

Of the five untreated slabs subjected to test (one of the six having proved defective) two satisfactorily resisted percolation at 200 lbs. per square inch, whilst the remainder failed at 30 lbs. per square inch. Of the twelve treated slabs all were successful in resisting the very high pressure of 200 lbs. per square inch, showing that the method of treatment of the surface would certainly be successful in preventing an interchange of oxygen-laden water with the interior of the reinforced-concrete structure. At the same time the experiments showed what high water-excluding powers can be realized from a concrete formed of a well-graded aggregate, and having a slight surplus of cement over that required to fill the voids. The second object of the experiments—that relating to evaporation from a surface—has not been attained, the experiments having been discontinued.

The majority of the tests of which particulars are given above were carried out by Messrs. David Kirkaldy and Son at their laboratories in Southwark Street. The Department had the assistance of the engineers of the various contracting firms and the Surveyors of the Classification Societies supervising the construction of the vessels.

The Paper is accompanied by three sheets of sun-prints, from which the illustrations in the text have been prepared.

## APPENDIX.

TABLE I.—COMPARISON OF CRUSHING STRENGTH USING WASHED AND UNWASHED AGGREGATE, COARSE AGGREGATE PASSES ½-INCH MESH.

No. of Specimen	Proportions by Volume.					Density, Lbs. per Cubic Foot.	Crushing Strength.		Remarks.
	Water.	Cement.	Coarse Sand.	Fine Sand.	Gravel.		Crushed Stone.	Individual.	
<i>(a) Natural Gravel Aggregate.</i>									
1	0.417	1.0	1.0	..	2.0	..	3,910	4,220	Washed
2							4,290		
3							4,470		
4	0.5	1.0	1.0	..	2.0	..	4,560	4,980	Unwashed
5							5,100		
6							5,270		
7							3,340	3,610	Washed
8	0.58	1.0	0.75	0.25	2.0	..	3,650		
9							3,850		
10							3,880	4,180	Unwashed
11	0.54	1.0	0.75	0.25	2.0	..	4,020		
12							4,650		
<i>(b) Natural Gravel and Crushed Stone Aggregate.</i>									
1	0.43	1.0	1.0	..	1.0	1.0	4,210	4,400	Washed (additional water decreases strength)
2							4,870		
3							4,180		
4	0.54	1.0	0.83	0.17	1.0	1.0	4,200	4,150	Unwashed (additional water decreases strength)
5							4,550		
6	0.5	1.0	1.0	..	1.0	1.0	4,280		
7							4,670		
8							3,900		
9	0.58	1.0	1.0	..	1.0	1.0	3,930		
10							3,980		

TABLE II.—PARTICULARS OF CEMENT AND CONCRETE USED IN CONSTRUCTION OF SPECIMENS FOR TENSILE TESTS OF CONCRETE.

*Cement.*

Fineness.	Setting Time with 24 Per Cent. Water.	Tensile Strength at 28 Days Gauged with 24 Per Cent. Water.
Residue on sieves, 76 × 76    180 × 180 0·1        10·9 per cent.   per cent.	“Initial.” 43. minutes Set hard. 285 minutes	Lbs. Per Square Inch. 795, 753, 798, 703, 788, 783, 795, 752, 772, 710, 725, 694. Average of 12 specimens :— 756 lbs. per square inch.

*Concrete.*

Mixture.	Water.	Age.	Cross Section of Specimen.	Ultimate Tensile Strength.	Remarks.		
By Volume.	Percentage Weight of Dry Materials.	Days.	Inches.	Lbs. Per Square Inch.			
1 cement, 1 sand, ½ inch downwards	13·8	36	3·1 × 5·86	199	176	Material <i>not</i> specially washed.	
			3·15 × 5·9	175			
			3·05 × 5·85	154			
1⅓ Bridport gravel ⅞ inch to ⅜ inch. Cement weighed on basis of 30 lbs. per cubic foot	13·8	31	3·00 × 6·90	186	151		
			3·00 × 5·85	122			
			3·00 × 5·85	144			
	13·3	31	3·00 × 5·95	316	290		Material specially washed.
			2·90 × 5·90	299			
			3·00 × 5·90	255			
	13·5	31	3·00 × 5·85	170	154		
			Specimen fractured in transit				
			3·00 × 5·95	138			
	13·4	31	3·00 × 5·90	208	209		
			3·00 × 5·95	178			
			2·95 × 5·85	242			
Same mixture but mixed independ- ently of above specimens	Not taken	42	..	282 285 292	286	Separately mixed. Same aggregate.	

Each group of three specimens were made from one mixing of concrete.

TABLE III.—PARTICULARS OF CONCRETE ACTUALLY USED IN THE CONSTRUCTION OF CONCRETE VESSELS.

	Materials.		Proportions.			Percentage of Voids.			Percentage of Cement by Volume.
	Course Aggregate.	Fine Aggregate.	Cement.	Fine Aggregate.	Course Aggregate.	Fine Aggregate.	Course Aggregate.	Mixture.	
1	Threefold granite, $\frac{1}{8}$ in.	Sand	1.8	2.0	4.0	47.0	33.0	21.0	31.4
2	Do., $\frac{1}{8}$ in.	"	1.8	1.9	4.1	42.5	33.0	24.0	31.4
3	Granite, $\frac{3}{8}$ in.	"	1.0	1.22	2.44	46.0	30.0	23.0	29.0
4	Beach shingle, $\frac{1}{16}$ - $\frac{1}{16}$ in.	"	1.0	1.0	2.0	39.8	27.4	23.0	31.8
5	Granite, $\frac{3}{8}$ in.	Granite sand	1.0	2.0	0.9	39.8	24.5	28.0	33.7
6	"	"	1.0	2.4	0.6	45.0	31.0	34.6	35.0
7	River ballast, $\frac{3}{8}$ in.	Beach sand, $\frac{1}{8}$ in.	1.0	1.125	2.25	38.25	26.0	24.25	30.0
8	"	River Sand	1.0	1.0	2.0	38.0	27.0	25.0	33.2
9	Beach gravel, $\frac{1}{16}$ - $\frac{3}{16}$ in.	Sand, $\frac{1}{8}$ in.	1.0	1.0	1.66	35.0	29.5	33.5	33.7
10	Beach gravel, $\frac{3}{8}$ in.	"	1.25	1.0	2.5	29.5	17.8	15.8	33.75
11	River ballast, $\frac{3}{8}$ in.	Crushed ballast, $\frac{1}{4}$ in.	1.0	1.33	1.6	38.0	28.5	27.0	37.0

TABLE IV.—SUMMARY OF RESULTS OF REPEATED AND ALTERNATING BENDING TESTS,

*Column No. 1.*

Deflection at Top of Column (with Variation).	Approximate Static Thrust at Top of Column.	Approximate Calculated Maximum Stress in Concrete.	Total Number of Double Bends.	Rate of Bending Reversals per Minute (with Variation).	Remarks.
Inch.	Tons.	Lbs. per Sq. In.			Column Marked No. 1. Cast 31/10/18.
0.1 ± 0.02	0.3	180	100,000	6.5 ± 1	After 1,000 reversals the existing cracks, which were originally confined to middle parts of faces, had extended towards edges of column. After 2,000 reversals some cracks had reached edges and joined with cracks on adjacent faces. After 8,000 reversals, cracks began to develop on flange faces. These cracks extended slowly from the edges to the middle of the faces. After 6,000 reversals the movement was chiefly localized at the crack in the position of maximum stress, but all cracks became ultimately filled with white material carried through by the water.
0.17 ± 0.02	0.5	300	50,000	7 ± 0.5	Old cracks re-opened almost at once and spread somewhat. After 35,000 reversals these new cracks appeared in tapered part of base, 12 to 15 inches below change of section, and these developed considerably during next 10,000 reversals.
0.3 ± 0.02	0.9	..	50,000	7 ± 0.5	After 15,000 reversals three new cracks developed at intervals between 3 and 5 feet from position of maximum stress; movement remained localized chiefly at the lower crack and its ramification into the base.
		Total	200,000		

TABLE IV—continued.

Column No. 2.

Deflection at Top of Column (with Variation).	Approximate Static Thrust at Top of Column.	Approximate Calculated Maximum Stress in Concrete.	Total Number of Double Bends.	Rate of Bending Reversals per Minute (with Variation).	Remarks.
Inch. 0.1 ± 0.01	Tons. 0.3	Lbs. per Sq. In. 180	3,000	4 ± 0.02	Column Cast 29/11/18. Existing cracks near base spread to edge of column and joined with cracks on adjacent faces. No new cracks appeared.
0.2 ± 0.02	0.6	360	3,000	4 ± 0.02	New crack appeared diagonally in tapered part of base after 400 reversals, another after 900, and another after 2,500 reversals.
0.3 ± 0.04	0.9	..	24,000	5 ± 0.5	Diagonal cracks in base developed. After 6,000 reversals several new cracks appeared at intervals above position of maximum stress, and gradually spread.
0.4 ± 0.04	1.2	..	70,000	6 ± 0.3	Movement became localized almost entirely at the two lower cracks. No new cracks observed.
		Total .	100,000		

TABLE V.—RESULTS OF TESTS FOR PERCOLATION OF EIGHTEEN CONCRETE SLABS RECEIVED FROM H.M. DOCKYARD, PORTSMOUTH, PER ADMIRALTY CHIEF CHEMIST'S DEPARTMENT.

Slabs 9 inches × 9 inches × 2 inches. Water pressure applied over surface, 5 inches diameter.

	30 Lbs. 4 Days.	50 Lbs. 2 Days.	70 Lbs. 2 Days.	100 Lbs. 3 Days.	150 Lbs. 2 Days.	200 Lbs. 1 Day.
1	Pressure per Square Inch . . . . . Time under Pressure . . . . . <i>Treatment.</i> One coating of paraffin wax applied hot, and subsequently melted with blow-lamp. Not treated.	Surface dry " Small damp spots on first day. One-third of surface damp on fourth day. Slabs saturated when broken.	dry " "	dry " "	dry " "	dry " { " cracked dry
2	One coating of mineral oil applied hot with overcoating of paraffin wax. Subsequently melted with blow-lamp. Not treated.	Surface dry " Slab found cracked on receipt	" " "	" " "	" " "	" " "
3	Four coatings of 10 per cent. solution of paraffin wax dissolved in kerosene oil, each coating being allowed to dry separately, and subsequently, after the drying of the last of these coatings, the surface heated by means of a blow-lamp, in order to melt the wax into the pores of the concrete. Not treated.	Small damp patch on second day. Surface dry "	(One-third of surface damp on second day) dry "	(Drops of water appeared after 3 hours. Half of surface wet on first day. Surface dried on second day.) dry "	" " "	" " { " Cracked at 190 lbs. dry

TABLE V.—continued.

	Pressure per Square Inch . . . . .	30 Lbs. 4 Days.	50 Lbs. 2 Days.	70 Lbs. 2 Days.	100 Lbs. 3 Days.	150 Lbs. 2 Days.	200 Lbs. 1 Day.
4	<p><i>Treatment.</i></p> <p>Four coatings of 10 per cent. solution of paraffin wax dissolved in kerosene oil, each coating being allowed to dry separately, and coating of melted paraffin wax then applied and subsequently melted with the blow-lamp. Not treated.</p>	Surface dry	dry	dry	dry	dry	dry
5	<p>One coating with solution of bitumen in coal tar naphtha, described as Wailes and Dove's bitumastic solution.</p> <p>Not treated.</p>	<p>"</p> <p>"</p> <p>(One-third of surface damp on second day. Half on third day. Surface completely damp on fourth day. Slab saturated when broken.)</p>	"	"	"	"	"
6	<p>One coating of Peacock and Buchanan's bitumen solution protective under-coat, A1 brand.</p> <p>Black No. 1 protective</p> <p>Not treated.</p>	<p>Surface dry</p> <p>"</p> <p>(Quarter of surface damp on fourth day. Slab saturated at damp place. Water penetrated 1½ ins. elsewhere.)</p>	"	"	"	"	"

The treated slabs were coated on both sides, but as arranged for the purpose of the tests the coating was removed from the outer side. The rubber joint rings blew out when the pressure was raised above 200 lbs. per square inch.