III.

*(Paper No. 2373.)***“The Influence of Sea-Water upon Portland Cement Mortar and Concrete.”**

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THE object of this Paper is to place on record investigations made in connection with the deterioration of some of the concrete work at Aberdeen Harbour, which have more than a local or transitory interest. In the correspondence on “Concrete Work for Harbours” the Author mentioned among the destructive influences bearing on the south breakwater at Aberdeen Harbour since its construction in 1872 “the disintegration of the surface of the concrete by the chemical action of the salt-water on the Portland cement.”¹ The softening of the concrete face of the wing walls at the entrance to the graving dock led to a thorough investigation of the chemical nature of this disintegration.

The graving dock was built on a site reclaimed from the Albert basin, by the erection in it of 1,000 lineal feet of quay walls, made of plastic concrete, surmounted by concrete deposited *in situ* and faced with granite ashlar. With a view to economy, Portland cement concrete was adopted for the whole of the works, with rubble stone added to still further reduce the cost. The concrete for the entrance works, caisson chamber, dock-bottom, and the head of the dock, was composed of 1 part of cement, 3 of sand, and 3 of stones, with rubble added; the concrete for the side walls, 13 feet thick, consisted of 1 part of cement, 4 of sand, and 4 of stones, with rubble; that for the foundations of the wing walls, of 1 part of cement, 3 of sand, and 4 of stones; for the fine concrete facing, from $3\frac{1}{2}$ feet to 12 feet above datum, the proportions were 2 parts of cement, 3 of sand, and 4 of stones; and for the concrete backing of the wing walls, 1 part of cement, 3 of sand, and 6 of stones. The altar steps, and the upper part of the wing walls were faced with granite ashlar. The plastic concrete composing the lower part of the quay walls, was specified somewhat similarly to the wing walls, with a fine concrete facing; but experience of this method of deposit at Provost

¹ Minutes of Proceedings Inst. C.E., vol. lxxxvii. p. 224.

Jamieson's Quay showed that the water fluxed the slightly set concrete, and spread the contents of the skips of fine facing concrete throughout the frame. To prevent the formation of horizontal layers of fine and coarse concrete, the specification for both walls was altered to "a homogeneous mass of concrete deposited inside frames, composed of 1 of cement, 2 of sand, and 3 of stone for one-third of the depth of the frame, and of 1 of cement, 3 of sand, and 4 of stone in the upper two-thirds." The order for this alteration, which consisted essentially of an addition to the strength of the concrete in the foundation of the wall, to compensate for waste of cement in commencing to fill the frame, was erroneously supposed by the Inspector of Works to be applicable also to the wing walls, which were thus by mistake built without the fine concrete facing. The alteration involved the use of a larger quantity of cement than would have been required by the specified arrangement; and immediately on being built, the surface was plastered. The length of the wing walls is 94 feet. The whole area of the bottom and top of the floor, and the back of the side walls up to the level of the surface of the floor, were specified to have a "watertight" lining composed of 3 parts of clean, rough, sharp sand to 1 of Portland cement, and to be 4 inches thick. This was adhered to for the underside of the bottom; but the upper surface of the floor, and the back of the walls were made much stronger, and covered with a really watertight mixture.

When the dock was opened, it was found that the leakage amounted to the flow through one safety-valve in the culvert commanded by about four hours' pumping of an 8-inch centrifugal pump per 24 hours. The leakage gradually increased, however, coming through the mortar of the concrete walls, and the entrance walls began to swell, opening the joints of the sill stones, and cracking the plaster. In June, 1887, about two years after the opening of the dock, the Author reported "that the Portland cement concrete entrance walls have expanded $2\frac{3}{4}$ inches on the height of the walls, their surfaces have cracked and bulged, and the joints of the caisson quoin stones have opened up, causing considerable leakage." As the damage appeared to be due to chemical action on the Portland cement, Professor Brazier, of Aberdeen University, was consulted on the subject. He reported to the Author, in June, 1887, that

"the analyses of the series of decomposed cements show a remarkable difference to the original cement, inasmuch as that in all these samples there is found a large quantity of magnesia, and a large proportion of the lime in the form of carbonate. I believe this alteration is brought about entirely by the

action of sea-water upon the cement. There is no other source for either the magnesia or the carbonic acid."¹

Tables are given in Appendix I showing the constitution of the original cement, and of the decomposed cements, as analyzed by Professor Brazier. The results of a further series of experiments obtained by digesting Portland cement in a variety of solutions are given by Professor Brazier in a letter to the Author, dated 19th November, 1887 (Appendix II).

When the matter was reported to the commissioners in May, 1887, no damage or decomposition was observable at low water on the north wing wall of the dock. Even in July, the damage, so far as it was noticeable at low water, was confined to the south wing wall, the caisson chamber, and the entrance walls. It was then reported by the Author that,

"the rapidity of the chemical action of the sea-water on the south wing wall, as compared with the north wing wall, was due to the unbalanced pressure of the water on the south wing wall when the dock is emptied of water. This caused a current of sea-water through the porous concrete structure, which continually washed the decomposed cement into the dock, and brought new particles of concrete and sea-water into contact."²

In July, 1887, Mr. Philip J. Messent, M. Inst. C.E., was requested to visit Aberdeen and report as to the cause of the damage, and the steps to be taken for remedying the defects. Mr. Messent reported on the 24th of November, 1887, that "it appeared that the deterioration was chiefly confined (so far as could be ascertained by examination) to the concrete which contained the largest proportion of sand, viz., three to one and upwards. The plaster composed of one of cement to one-and-a-half of sand was generally hard, as were the lower portions of the wing walls, as well as the portions of the culverts above mentioned" (composed of 1 of cement, 2 of sand, and 3 of stones).

The report and analyses made by Mr. Pattinson, public analyst of Newcastle-upon-Tyne, of samples of concrete and plaster, from the Aberdeen graving dock, sent to him by Mr. Messent, are given in an Appendix to Mr. Messent's report, and substantially confirm those by Professor Brazier. The conclusions arrived at by Mr.

¹ Details of this report are given in Mr. P. J. Messent's Report as to "The Cause of Damage to the Aberdeen Graving Dock," dated November 24, 1887, a copy of which is in the Library of the Institution.

² Report by the Author to the Aberdeen Harbour Commissioners, 19th July, 1887.

Pattinson will be found in Appendix III. Mr. Messent remarks with reference to these analyses that,

"In their examination of the deteriorated concrete, both agree that the presence of too much magnesia in the cement is the cause of the deterioration ; and that, as the same proportion or quantity was not found in the briquettes made of the neat cement used, the additional quantity found in the spoiled concrete must have been supplied by the sea-water, in contact with the cement portion of the concrete, which sea-water, whilst precipitating the magnesia that it contains, takes away in an altered form a portion of the lime from the cement."

Mr. Messent made experiments as to the quantity of sea-water absorbed by briquettes of neat cement, and by briquettes made of cement mortar of 1 part of cement to 3 of sand, and found that, by repeated absorption and drying, the solids contained in the sea-water were left in the briquettes, and the strength of the cement diminished in the neat cement briquette 69·64 per cent., and in the 1 to 3 mortar briquette 36·8 per cent. He also made the following experiments, with the view of ascertaining the effect and relative extent of the percolation of sea-water through cement mortar.

"I took two briquettes, one of neat cement and one mixed one to three, and having procured two 1-gallon glass bottles with mouth and neck of about 1½ inches internal diameter, I secured over the mouth of each bottle one-half of each briquette in such a manner that any water entering the bottles must pass through the half-briquettes. They were then loaded and suspended by lines from a craft afloat in Shields harbour ; the depth of their immersion being about 18 feet, giving a pressure on the briquettes of about 8 lbs. per square inch. They were raised several times to allow the compressed air (if any) to escape, and after actual immersion for about eighty-seven hours they were taken up, and it was found that about 94 ozs. of water had passed through the mixed, one to three, half-briquette into the bottle, and only 1 oz. had passed through the neat cement half-briquette."

The analyses by Mr. Pattinson of the two halves of the 3 to 1 briquette, and of the sea-water in the bottle and in the sea, are given in one of the Appendixes to Mr. Messent's report, and they are summed up in the following words :

"A distinct amount of lime has been removed from the briquette through which the 94½ ozs. of sea-water had passed, and a very marked increase in the amount of magnesia is found in the same briquette, about two-and-a-half times more than is found in the original briquette which had not been brought into contact with sea-water. These results show that the chemical action between sea-water and cement indicated in my last report to you actually takes place ; that is, that the lime of the cement precipitates, as hydrate, the magnesia of the magnesium chloride and sulphate contained in sea-water, with the consequent formation of calcium chloride and sulphate. If the cement or concrete is con-

tinually brought into contact throughout its substance with fresh portions of sea-water there will be a continued deposition of hydrate of magnesia and probably sulphate of lime, and removal of lime, necessarily resulting in the disintegration and destruction of the concrete."

Mr. Messent observes, with reference to the results of the analyses, that,

"The effect of the percolation was thus to increase the percentage of magnesia in the mixed briquette by 1·05, equal to an increase on the cement portion (one-fourth of the whole briquette) of over 4 per cent. in eighty-seven hours of forced percolation."

In a subsequent paragraph of his Report Mr. Messent states,

"I am of opinion that the cause of the damage referred to is the injurious effect of sea-water, which entered through holes in the plaster,...percolated the concrete of the intermediate portion of the wing walls, and of the mass behind the altars of the dock walls, and in so percolating extracted lime from, and deposited magnesia in, the cement portion of the concrete, causing it to deteriorate and expand; and that the injurious percolation was facilitated by the inappropriate relative proportions of the cement, sand, and stones, or the insufficient quantity of cement in the original composition of the deteriorated concrete."

Mr. Messent's experimental investigations not only confirm the Author's opinion that the damage to the graving dock, by the chemical action of sea-water on the Portland cement, has been accelerated by the pressure of the water on the porous concrete of the dock, but they also suggest the obvious remedy and prevention of that action, in such works, by the formation of impermeable concrete or masonry. The whole of the specimens investigated, both at the south breakwater and the graving dock, were taken from concrete blocks, which had been made in Messent's mixers, deposited in the usual manner above water, and allowed to set over six months before immersion.

To test the permeability of concrete made of various proportions of materials, the Author constructed a pair of cast-iron boxes (*Fig. 1*) to mould and contain each a cubic foot of concrete. The boxes are cast with a conical bottom terminating in a square pipe, and are fitted with watertight covers with shoes to receive the ends of vertical pipes. These pipes lead up to a cistern placed 24 feet above the top of the block, and containing sea-water which filters through the concrete and is collected at the bottom of the box. The results of these experiments, which are given in Appendix IV, show that to obtain an impermeable concrete, (1) the cement must be finely ground; (2) it should not be weaker than 1 of cement to 6 of sand and stones; and (3) the concrete

should have sufficient time, at least three months, to set before the application of the pressure. If any of these conditions are

Fig. 1.

APPARATUS FOR TESTING THE PERMEABILITY OF CONCRETE.

lessened, a corresponding increase must be made upon the others. The 1 to 6 experimental blocks being made of selected materials carefully mixed, the concrete required to give equal results in the works had to be stronger, generally 1 to 5. The apparent inconsistency of the results, where all the experiments were made carefully with no leakage past the sides of the concrete, point to the conclusion that only the worst results, in the cases of finely-ground and coarsely-ground cement respectively, should be relied upon. The principal defect of concrete work in general is the irregularity of the results in mixtures that are nominally alike; and a considerable margin of strength is therefore required even in carefully made experiments, and much more in actual work. The anomalous result of No. 7, which,

although it had been kept three times as long, and was made of finer cement, was worse than No. 1, may be due to the greater porosity of the concretes as distinguished from the permeability of the mortars. The porosity of the concrete, including accidental voids between stones and mortar, as well as the permeability of the mortar, is the property against which provision must be made in actual concrete work.

According to Professor Brazier, the cause of the expansion of concrete when subjected to the chemical action of sea-water, appears to be the formation of a more bulky compound of magnesia and lime with carbonic acid, and especially with sulphuric acid and water, in place of the lime of the cement. The chemical equations for the action of the lime in the cement upon the magnesian salts in sea-water are:—

Magnesium chloride + Calcium hydrate = Magnesium hydrate
+ Calcium chloride.

Magnesium sulphate + Calcium hydrate = Calcium sulphate
+ Magnesium hydrate,

the sulphate of lime crystallizing with water as—

Calcium sulphate + Water = Hydrated calcium sulphate,

a substance of great bulk compared with the lime base.

The lime of the cement takes up the free carbonic acid from the sea-water, forming carbonate of lime; the sulphate, carbonate, and hydrate of magnesia in the sea-water react with the lime, forming a deposit of magnesia and hydrated sulphate of lime, which, being bulkier than the lime base, causes swelling and disintegration of the concrete, while the magnesia destroys the adhesive power of the cement. It is very improbable that magnesia is present in the Portland cement, and causes swelling of the concrete by the absorption of water; for where the cement is subjected to the ordinary mechanical tests, a large proportion of magnesia would betray its presence by reducing the adhesive strength. Magnesia, in a minute state of subdivision, could not escape hydration on the mixture of the cement with water. There is no doubt that, in permeable concrete, the whole of the lime forms a base on which carbonic acid and the salts contained in the sea-water act chemically; that the resulting deposit occupies a larger space than the lime base; and that the force of chemical action exceeds the adhesive power of the cement, thus effecting the rupture of the mortar and expansion of the mass of concrete. In concrete made with a small proportion of sand, the stones are united by a cement mortar of great adhesive strength; and the voids left by the absence of mortar in interstitial spaces are filled with a creamy white substance, formed chiefly by the action of free carbonic acid and magnesia from the sea-water on the walls of the cells. Where the voids do not communicate with the sea through a very permeable mortar, or under unbalanced pressure, the first filling is not renewed, and chemical action ceases. It is possible that where the mortar is of good strength, its adhesive power may balance the chemical force for a time. The sudden access of water under pressure to concrete containing voids, reveals the presence of decomposed cement by white clouds of magnesia and carbonate of lime in the escaping liquid. The immediate cause of swelling in concrete is the want of adhesive strength in the mortar to resist the disruptive force of the chemical action of sea-water on the Portland cement.

Setting of Cement.—It is evident, from the certainty and readiness with which chemical action is set up between the lime contained in Portland cement and certain constituents of sea-water, that the union of the lime with the silica, or silicates, which was supposed to take place on the addition of cold water, if a chemical combination, is exceedingly feeble. It is more probable that slaked lime develops the adhesive property of cement when minutely subdivided with silica, alumina, and iron, than that it should require the destruction of a silicate of potash or soda, the formation of silicate of lime, the partial decomposition of silicate of alumina and iron, and the formation of double or treble hydrated silicates of lime, alumina, and iron, to cause setting. But the absorption of water is not confined to the lime in the cement; and probably the adhesive property of Portland cement is due simply to the restoration of the water of crystallization to the lime and alumina.

The degree to which cement clinker should be burned appears still undecided by chemical investigation, and is determined by experience. The driving off of carbonic acid and water are the essential objects of burning both natural and artificial cements; the decarbonization of the lime, and the dehydration of the lime and alumina may be verified by analysis as essential to the formation of cement. The decomposition of the clay, to separate the alumina from the silica and make the latter soluble in water, is said to be another object of burning; but what "those combinations of silica, alumina, and lime, which require a very high temperature for their production,"¹ may be, has not been defined. The decomposition of the clay appears to be the essential object of high burning below 2,000° Fahrenheit, to set the alumina free from the silica so that it may crystallize freely with the lime on the addition of the water of crystallization. In a low-burned cement, the lime is probably the only constituent free to crystallize with water, which is shown by the under-burnt cement flying in cracks and blisters like a mixture of lime and brick-dust. The under-burning of cement clinker does not appear to be discoverable by analysis, but it may be detected with certainty by the usual mechanical tests. The sieve for fineness, twenty-eight day mortar tests for strength, and the "thin pat on plate" tests for heat or under-burning, appear sufficient to ascertain the quality of cement, for none that is bad or adulterated, or unsuitable for sea works, can pass these tests.

¹ Dent's Cantor Lectures, 1887.

Detrimental Constituents in Cement.—The presence of hydrate of magnesia in disintegrated Portland cement concrete leads naturally to the conclusion that magnesia is a very undesirable constituent. It does not necessarily follow, however, that it cannot be present innocuously; nor can it be argued that the presence of magnesia originally in the cement is likely to cause disintegration. Hydrate of magnesia, or mixtures of hydrate of magnesia with lime or carbonate of lime, are not cementitious substances; and the presence of magnesia diminishes the adhesive property of cement. The tendency of magnesia and its compounds in solution, on a glass slide, is to roll off like quicksilver; while their precipitates have a hard gritty feeling when touched, which is the antithesis of the satiny feeling of cements. The latter appear to be of a sticky nature on a microscopic slide, and present a simple crystalline structure, very different from the amorphous grains of magnesia and its compounds separated out of disintegrated concrete. But notwithstanding the repellent nature of magnesia and its affinity for water, the magnesian hydrate found in concrete could not have affected the strength had it been originally present. All the chief constituents of cement dehydrated in the kiln reabsorb water greedily, first from the water in the air in slaking, and afterwards on admixture with water. Calcined magnesia finely ground, or in the precipitate powder, absorbs water as freely as lime or alumina; and having taken up its equivalent, becomes inert. That hydration should commence again after the setting of the cement is only probable on the assumption of the magnesia having less affinity for water than the lime and alumina, which would thus dehydrate it during the process of setting. From experiments made by Mr. Henry Thomas Jones, of Aberdeen University, the rate of absorption of water by the oxide of magnesium is as follows:—

100 parts magnesium oxide, Mg O, absorbed—

(a) In twenty-four hours	36·00
(b) In forty-eight hours	38·74
(c) In nine days	44·30
Theoretical maximum	45·00

the hydration of magnesium oxide being in these experiments more rapid than that of Portland cement. The Author mixed dehydrated oxide of magnesium with Portland cement in the proportion of 5 per cent. by weight. The briquette, broken at nine days, showed a tensile strength of 277 lbs. per square inch, indicating a loss of strength of about 20 per cent. due to the presence of the magnesia. Briquettes of 1 to 3 mortar, with the same proportion of magnesia in the cement, broken at

twenty-eight days, gave 162 lbs. on the square inch. There was no appearance of subsequent hydration, or softening, on the re-immersion of the briquettes.

The presence of sulphuric acid in cement which has been calcined in the course of manufacture, may be injurious. The formation of "dead-burnt gypsum" takes place at a temperature ranging between 200° and 500° Fahrenheit.

"The gypsum is burnt dead at the temperature employed in making the cement, and does not combine with water until after the rest of the mass has hardened; and then, as it slowly takes up water and expands, it causes the whole to crumble. After it has been heated to 500° Fahrenheit, it also combines with water very slowly, the combination going on for several weeks; but the product is a hard mass, which is translucent like alabaster, and more dense than ordinary gypsum.¹ If it is then heated to 150°, it passes into the condition of ordinary burnt gypsum."²

The temperature to which the cement clinker is raised is generally far above that of the "dead burning" of gypsum; and the temperature to which it is afterwards raised in the process of grinding is no doubt sufficient to make the calcium sulphate pass from the highly-burned condition, into the state of ordinary gypsum. Thus the theory of injury accruing to Portland and Roman cement concrete from the presence of sulphuric acid, or rather of dead-burnt gypsum, is far from being established, either by chemical science or the practical observation and experiments of engineers.

The Roman cement used for repairing the south breakwater at Aberdeen, under water, contains a large proportion of sulphuric acid, without detriment so far as four years' experience shows. The analysis of this cement, made by Professor Brazier, is as follows:—

Constituents.	Percentage.	Deducting last Item.
Alumina and oxide of iron	22·20	24·66
Silica	23·63	26·35
Lime.	41·24	45·82
Magnesia	0·63	0·70
Sulphuric acid	2·23	2·47
Moisture, carbonic acid, &c.	10·07	..
	100·00	100·00

¹ "Dingl. Polyt. Journ." vol. cci. p. 254.

² *Ibid.* vol. ccii. pp. 52 and 355.

Particulars of the sand and stones used for concrete work at Aberdeen are given in Appendix V.

Remedial and Preventive Measures.—The coating of carbonate of lime formed on the surface of concrete blocks or masses of concrete, on exposure to the air, has been supposed to protect them from the chemical action of sea-water. It was noticed that until the water passed through the skin of the concrete, no swelling or serious damage took place; and the formation of the coating of carbonate of lime, either in the air or in sea-water, was connected with this fact. Some authorities even recommend the exposure of the blocks to the air for several months previous to immersion, to allow of the formation of a film of carbonate of lime; and in case the progress of the building should not allow sufficient time for the natural process, they suggest that a film might be formed by washing the block with a solution of commercial carbonate of ammonia (sesqui-carbonate of ammonia). The fact that the cause of the chemical action of sea-water on concrete is the forcing of the sea-water through permeable mortar by an external force, demonstrates the futility of the carbonate of lime film, which is itself more permeable than the mortar on which it is formed. The mistake arose from the formation of the deposit being only observable on an approximately watertight skin of mortar or plaster. The free carbon dioxide in sea-water (which amounts to 0·0479 gramme in 1 litre of water, or 0·005 per cent.)¹ forms a film of carbonate of lime on the skin of all immersed concrete, and ultimately destroys it. Mechanical attrition assists this kind of chemical action, by the repeated exposure of fresh surfaces to the sea-water; but the thickness of the film, increasing with the time of exposure, shows that the coating of carbonate of lime is in itself no protection to the concrete from chemical action.

The exclusion of sea-water by a coat of Portland cement mortar plaster, practically watertight, cannot be regarded as a permanent or a certain protection. The fracture of any portion of such a covering, or the penetration of sea-water to the body of the concrete from any part accidentally omitted in plastering, or through adjacent blocks, permitting a slight degree of chemical action in the mass, although the softening may not be apparent, swells the concrete, parting the surface of the plaster in hair-cracks, which, though scarcely perceptible, admit more water to the body of the concrete and hasten its disintegration. The practical difficulty of making concrete walls watertight by

¹ "The Voyage of the 'Challenger,'" by Sir C. Wyville Thomson.

plastering can only be appreciated by experience, quick-setting cement being unsuitable for this description of work, owing to its tendency to part on the surface in hair-cracks under the float used for smoothing it; while a slow-setting cement is inapplicable to vertical walls. A lining of fine concrete, 2 or 3 feet thick, is more satisfactory when carried under the foundations and up the back and front of the wall, the internal porous mass being filled in simply as hearting. But the penetration of sea-water by accidental openings through adjacent masses of concrete, as in the case of the graving dock side walls, by causing the hearting to swell, cracks the fine concrete or masonry lining, the chemical force overcoming the resistance of a considerable thickness of fine concrete or ashlar masonry.

The works recommended by Mr. Messent for the repair and protection of the graving dock were as follows:—

“If the water is prevented from entering from the front, further damage or deterioration would be prevented, and I have no doubt that a very large proportion of the concrete is as yet uninjured, whilst much of what is partially deteriorated is still strong enough for its required purpose, so long as it is protected from the effect of further sea-water percolation. With this object, the works of repair and protection that I recommend are chiefly confined to the outside entrance and wing walls. They consist of an additional apron, made of concrete, composed of one Portland cement, one-and-a-half sand, and four-and-a-half gravel, enclosed by sheet piling at least 10 inches thick, 18 feet long, with outside waling, tied to the present apron and wing walls by wrought-iron bolts at 5 feet intervals. The facing of the wing walls should be taken down, probably for a depth of $2\frac{1}{2}$ feet from the face, so as to remove the deteriorated portions of the concrete, and be refaced from the foundation to the under side of present granite facing, by coursed granite rubble, backed with random rubble, set in Roman cement mortar. The coursed rubble to consist of two stretchers to one header, and to average in depth $1\frac{1}{2}$ feet, whilst the average of the coursed and random rubble should be $2\frac{1}{2}$ feet deep, to be properly stepped and bonded to the existing concrete, and returned for the whole thickness of the walls at the ends next the harbour quay walls. The present ashlar facing of the upper portion of the wing walls to be rebuilt with Roman cement mortar, any deteriorated concrete behind to be taken out and replaced by random rubble in Roman cement mortar. . . . The sides of the caisson chamber to be faced with granite coursed rubble, 9 inches thick, with random backing, stepped and bonded into the concrete, after the removal of the deteriorated portions. Those portions of the culverts that pass through the entrance and wing walls should be faced by coursed granite arch, side, and invert stones, averaging 1 foot in thickness, replacing the deteriorated concrete previously removed. The present outside apron, with the proposed addition to the apron, to be covered with a paving of granite sets, 9 inches thick, set, bedded, and jointed in Roman cement mortar. The outer sill between the granite quoins to be similarly paved, any defective concrete found being removed and replaced by rubble in cement.”

These recommendations were carried out, Portland cement being

substituted for Roman during the course of the work, with Mr. Messent's concurrence, on seeing the dry state of the walls when enclosed within the cofferdam.

The only certain and permanent method of building large masses of concrete or masonry for immersion in sea-water under variable pressure, is to make the entire mass impermeable. It thus becomes a question of comparative expense, whether Portland cement concrete may be more suitable for any work in sea-water than masonry. It is evident that a large margin in the proportion of the more expensive materials must be allowed, in concrete building, for imperfect mixing and distribution, and that the weakest proportion of cement to ballast which can be considered permanently safe, under the pressure of sea-water, is 1 to 4, or say 1 part of cement, $1\frac{1}{2}$ of sand, and $2\frac{1}{2}$ of stones. The same mortar used in building blocks of rubble masonry would only amount to one-third, instead of one-half of the mass, the proportion being 1 part of cement, $1\frac{1}{2}$ of sand, and 5 of stone, or 1 of cement to $6\frac{1}{2}$ of sand and stone.

The prices of these materials and labour will vary with the locality. At Aberdeen they compare as follows:—

PORTLAND CEMENT CONCRETE 1 to 4.

	Per Ton.	Per Cubic Yard.
	s. d.	£ s. d.
Cement.	35 0	0 9 4
Sand	2 0	0 0 11½
Screened gravel	3 8	0 3 0
Labour and framing		0 6 10½
		<hr/> £1 0 2

RUBBLE MASONRY 1 + $1\frac{1}{2}$ + 5.

	Per Ton.	Per Cubic Yard.
	s. d.	£ s. d.
Cement	35 0	0 6 2½
Sand	2 0	0 0 7½
Rubble	3 0	0 3 3
Labourers, $1\frac{1}{4}$ day at 3s. 4d. =		0 4 2
Mason, 1 day at 5s. 5d. =		0 5 5
		<hr/> £0 19 8

Whether made of concrete or of masonry, the blocks should be bonded and built as headers and stretchers like ordinary ashlar masonry; then the water and air should be excluded by caulking the face joints, and filling the whole of them with cement grout,

made with either Roman cement or equal measures of Roman and Portland cement for work under water, and Portland cement, lime, and sand for work above water. There should be no flat or concave horizontal surfaces where sea-water may lodge; for no mortar, however strong or impermeable, appears to withstand the chemical action of sea-water when exposed to soaking and evaporation in the sun.

The practice during the last thirty years in sea works has tended towards increasing the size and weight of concrete blocks, trusting to the stability of individual blocks for the durability of the structure. Bond has in many cases been ignored, and even avoided, on the plea of allowing for unequal settlement. At Aberdeen Harbour there are two kinds of dry ashlar work in the north pier, the older part by Smeaton laid in horizontal courses, and that more recently constructed on Telford's design in inclined courses. The walls in both cases are backed with rubble and ballast hearting, liable to be swept away by the water flowing in and out through the joints of the ashlar face during the passage of waves along the pier. The voids left behind the ashlar appear to be dangerous, chiefly because the sudden compression of the air in them blows out the ashlar facing stones, a frequent occurrence in the horizontal coursed wall, but rare in the inclined courses. The same effect of the sudden compression of air occurs in the south breakwater, as described by the Author,¹ where the concrete blocks, eight times the weight and ten times the bulk of the ashlar stones in the north pier, proved more liable to removal from this cause.

While examining three cavities in the surface of the south breakwater, in June, 1887, the Author was struck by the fact that each of them was opposite the vacancy left by the eating away of a pile by sea-worm, and that they were each formed, entirely under low water, by the fracture and blowing out of blocks in two or three courses (*Fig. 2*). He tried the remaining parts of the fractured blocks with a pick, and found them quite sound, and only sufficiently softened to admit the point of the pick about an inch at a blow. Thus, although the concrete blocks had softened considerably by chemical action, they were still sufficiently hard to require an enormous and suddenly-applied force for their fracture. The volume of air confined in the upper part of the cavity left by the pile could not have exceeded 12 to 14 cubic feet. The pressure per square inch of this volume of air, however, was trans-

¹ Minutes of Proceedings Inst. C.E., vol. lxxxvii. p. 224.

mitted by the water to the backs of the blocks adjacent to the tube; the total pressure being increased in the proportion of the area of the surface of the blocks to that of the water. The accumulated pressure in the cavity, although tending to expel the water by the fissures at which it entered, would attain its maximum before this was effected to a material extent, and the blocks would be blown out. The spaces left in the interior of the breakwater, by the eating away of the piles, thus formed a series of hydro-pneumatic accumulators which, as the blocks became weakened by chemical action, were exposed to the bursting out of their sides under the action of storm-waves. During the summer of 1886, the portion of the breakwater which had sustained the greatest damage from this action was grouted up solid, through

Fig. 2.

sixteen holes bored down through the superstructure of concrete *in situ*, since which no further damage has been sustained at this part. During the summer of 1887, forty holes were bored, and filled up with 212 tons of grout, the joints in the face of the breakwater being first caulked by divers.

Thus no apparent advantage has been gained by the increase of the size of the blocks in constructing the south breakwater. The destructive force at work on the small ones in the north pier was not excluded from the south breakwater; and whilst the weight of each block was increased, from a little over 1 ton on the north pier, to 12 or 18 tons, the size was increased in a greater ratio; and the air received accommodation specially adapted for destructive compression, and was assisted by the chemical action of

the sea-water upon the Portland cement concrete blocks. Where the ashlar facing of the north pier has been rebuilt with Portland and Roman cement mortar, it has not given way again.

The increase in the size of blocks used in the construction of sea works has become almost fanciful. Heavy plant for handling and building large blocks is not available for small harbour works; and while the heavy block system may be economical for great sea works, it is unfortunate for smaller harbours that the stability of these sea works should be considered due to the use of blocks weighing 45 tons and upwards, if it really depends on the perfect homogeneity of the whole structure obtained by bond and grout. The chemical action of sea-water has proved injurious to the concrete blocks at the south breakwater in other ways besides softening them. Within a year or two after the completion of the structure, some of them were observed to be chipped on the face by the vertical cleavage of a triangular section off a corner, or of the whole face to a depth of about a foot. It was evident that there was some strain on the blocks in the plane of cleavage, but it was not understood why the giving way should be deferred for several years, and fresh cases occur every year. The unequal swelling of the blocks, from varying degrees of deterioration by the chemical action of sea-water is sufficient to account for this result. The swelling being greater near the sea face of a block, or greater in one block than in those adjacent, brings a greater pressure to bear on the part which yields to cleavage. That the face of a concrete wall tends to swell more rapidly than the interior, is seen on the roadway of the breakwater, which was built with a convex camber, but has now become slightly concave in cross section along its whole length. Cracks in the upper portions of homolithic concrete structures are due also to the swelling of the portion under water by the chemical action of sea-water on the Portland cement. They have generally been ascribed to changes of temperature, or to unequal subsidence of foundations; but the swelling of the lower part of the structure is, as a rule, the only possible cause of the unsightly cracks which open up in the lines of least resistance. Thus the defects observed in concrete structures, and the chief cause of their destruction, arise from the chemical action of sea-water, and the sudden compression of air within the interstices. The same remedy applies to both evils, namely, the formation of an impermeable homogeneous mass.

It is hardly possible to compare the durability of one description of masonry or concrete work, exposed to the action of the sea, with that of another under a different exposure. The concrete bag

work forming the north pier extension is only exposed to seas striking the point of the pier, and running along its two sides at nearly equal heights, so that very little difference of pressure is produced between them. On the other hand, the concrete blocks of the south breakwater are sometimes subjected to a head of water on the sea face of 20 feet, the seas coming nearly broadside on to the breakwater during south-easterly storms, and the waves flowing over it at low water.

Mr. Messent reports that:—

“The blocks on the north side of the south breakwater, from which the specimens 9 and 10, Table II, were taken, furnish an illustration of the slowness of the deterioration of concrete, although of injudicious proportions, where there is no regular forced percolation. The blocks from which these specimens were taken were made of concrete, in which the cement and sand were as one to four, or similarly proportioned as the deteriorated concrete of the graving dock walls, and were placed in their present position (about 4½ feet above low water) about sixteen years ago. The block from which No. 9 was taken, had on its surface the original hard skin that usually forms on the surface of concrete built on land and afterwards exposed to air. This skin was absent from No. 10. The magnesia found in the cement is shown to be 3·32 per cent. in No. 9, and 5·49 per cent. in No. 10. The original cement probably contained about 1 per cent. of magnesia, so the addition amounts to 2·32 per cent., and 4·49 per cent., in sixteen years.”

Although an addition of 4 per cent. of magnesia to the cement is required to cause the complete softening of the concrete, the partial deterioration in hardness due to a smaller increment exposes it to great danger of destruction by other forces. A slight expansion by chemical action may cause cleavage; this opens up the concrete to the reception of more water, which dissolves and removes cement, besides depositing more magnesia; and the partial softening renders it liable to rupture by compressed air, or to wear by attrition. While it is a simple matter to prevent the deterioration of Portland cement concrete in this way, by constructing all new work so as to be impermeable to sea-water, and the additional cost of so doing would be rapidly counterbalanced by the diminished cost of maintenance; the stoppage of this action on existing sea works, and its prevention in the permeable concretes, of which many of them have been constructed, is more difficult. The formation of an impermeable skin, by facing the old concrete work with strong mortar or masonry, is the plan adopted at Aberdeen; and the work done has proved more durable than the original structure. The chief difficulty consists in securing the permanent adhesion of the old work and the new. The precautions taken are, the use under water of Roman cement exclusively; the

clearing away of all decayed concrete, and of sufficient sound concrete to leave room for a thick patch; washing the surface of the old concrete, where it is above water, with a strong solution of caustic soda; and fixing iron ties between the old and new work. It is found advantageous to make the new masonry or concrete liner sufficiently heavy to stand by itself independently of adhesion to the old work. The great source of danger to these patches lies in the sea-water continuing to obtain access, through some other place, to the old work at the back of them, when the continued deterioration and swelling of the old concrete severs the connection with the new face, which it bulges and cracks.

The expenditure on maintenance of the south breakwater, refacing the surface with granite chips in Roman cement under water, and with granite ashlar in Portland cement above water, grouting and building up cavities, and depositing an apron, has amounted, since its completion in 1873, to £11,000. The cost of refacing the wing walls and entrance works of the graving dock with granite ashlar in Portland cement mortar, and depositing an apron, including a temporary cofferdam, amounted to £5,000.

The Paper is accompanied by three tracings in illustration, from two of which the Figs. in the text have been produced.

APPENDIXES.

APPENDIX I.

ANALYSIS OF ORIGINAL DRY CEMENT.¹

Alumina and oxide of iron	13·10
Silica	20·92
Carbonate of lime	8·18
Hydrate of lime	11·26
Caustic lime	45·39
Magnesia	0·33
Sulphuric acid	0·82
	<hr/> 100·00

ANALYSIS OF SAMPLES OF DECOMPOSED CEMENTS.

Constituents.	No. 1A.—Taken from corner of Wing Wall on South Side of Entrance, built dry inside of Cofferdam—Plaster.	No. 1B.—Taken from corner of Wing Wall on South Side of Entrance, built dry inside of Cofferdam—back of plaster skin.	No. 2A.—Taken from Entrance Wall above Culverts inside Dock.	No. 2B.—Taken from Entrance Wall above Culverts inside Dock, 1 rippings.	No. 3.—Taken from Outlet Culvert.
Alumina and oxide of iron	26·76	28·42	1·05	1·53	5·60
Silica	18·04	19·55	1·33	1·31	10·87
Carbonate of lime	6·61	15·78	45·72	35·42	38·37
Hydrate of lime	30·54	16·94	27·85	17·17	19·21
Hydrate of magnesia	13·57	15·08	21·03	39·96	22·30
Sulphuric acid	2·98	4·23	1·31	0·90	0·85
Soluble in water	1·50	..	1·71	3·71	2·80
	<hr/> 100·00	<hr/> 100·00	<hr/> 100·00	<hr/> 100·00	<hr/> 100·00

A sample of decomposed concrete taken from a block on the west side of the south breakwater was analyzed by Professor Brazier, in order to compare it with the disintegrations at the graving dock, with the following results:—

Alumina and oxide of iron	21·60
Silica	17·81
Carbonate of lime	33·08
Carbonate of magnesia	12·68
Hydrate of magnesia	9·94
Sulphuric acid	4·89
	<hr/> 100·00

¹ In a letter dated 24th Feb., 1892, Mr. Smith explained that, instead of "original dry cement," the heading should have been "original cement of test briquette," the original cement having been all used up before an analysis was considered expedient.—SEC. INST. C.E.

APPENDIX II.

RESULTS OF DIGESTING PORTLAND CEMENT IN VARIOUS SOLUTIONS.

The cement employed was obtained by breaking down a briquette, sifting out and rejecting the fine powder, and reserving pieces about the size of large-grained shot. Two hundred grains of the cement were taken for each experiment, and after being tied in a small muslin bag were suspended in 20 ozs. (one imperial pint) of the undermentioned fluids:—

1. Distilled water. 2. Solution containing 31 grains of chloride of magnesium per imperial pint (equivalent to 13·05 grains of magnesia, being the average proportion of this salt in sea-water). 3. Solution of 62 grains of chloride of magnesium per imperial pint (equivalent to 26·10 grains of magnesia) being double the strength of the former solution. 4. Solution of sulphate of magnesia, containing the same equivalent of magnesia as solution No. 2. 5. Solution of sulphate of magnesia, containing the same equivalency of magnesia as solution No. 3. 6. Sea-water—specific gravity 1·026, containing magnesium salts (chloride and sulphate) equivalent to 18·37 grains of magnesia per imperial pint. 7. Sea-water—duplicate of above. 8. Solution of chloride of sodium—250 grains per imperial pint.

The whole of these digestions were started at various times between the 13th and 20th of July, and remained until the 14th of October, when the solutions were disturbed for the purpose of examination.

No. 1, *Distilled Water*.—On removing the muslin bag in which the cement had been suspended, it was found to be very much incrustated on the outside; and a considerable deposit of a white material had formed at the bottom of the jar. On opening the muslin bag, the cement itself appeared quite firm, and no incrustation was visible on its surface. The incrustation on the outside of the muslin bag, and the material at the bottom of the jar proved to be carbonate of lime. The solution was found to contain 0·75 grain of lime per pint.

No. 2, *Chloride of Magnesium Solution (No. 1)*.—The fluid contained a considerable amount both of suspended and deposited matter, which resembled in appearance what has been termed in a former report a “creamy white substance,” and was found to be a mixture of hydrate of magnesia and carbonate of lime. On opening the muslin bag in which the cement had been suspended, a still larger quantity of the same insoluble material was found. The clear fluid contained 14·62 grains per pint of lime, and 0·07 grain per pint of magnesia, thus showing that nearly all the magnesia had been removed by the process.

No. 3, *Chloride of Magnesium Solution (No. 2)*.—The appearances in this instance were very similar to those described in the above experiment, except that they were more marked. The clear fluid was found to contain 26·04 grains per pint of lime, and of magnesia 2·06 grains per pint, showing that in this case, although the solution of the magnesium salt was much stronger, nearly all of the magnesia had been removed.

No. 4, *Sulphate of Magnesium Solution (No. 1)*.—In this case considerable action had evidently occurred. The solution was turbid, and there was a large deposit at the bottom of the jar, which was proved to contain carbonate and sulphate of lime, along with hydrate of magnesia. Both upon the outside and inside of the muslin bag in which the cement had been suspended, the incrustation had a somewhat crystalline appearance, evidently owing to the presence of sulphate of lime (gypsum). The clear fluid contained 9·10 grains per pint of lime, and of magnesia 0·10 grain per pint.

No. 5, *Sulphate of Magnesium Solution* (No. 2).—In this instance again the appearance of chemical action was similar to that described in the last experiment, excepting that with the stronger solution the appearance was more marked. The clear fluid contained 5·40 grains of lime per pint, and of magnesia 4·55 grains per pint. The proportion of magnesia in solutions No. 2 and No. 4 was the same, and also in solutions No. 3 and No. 5; and by a comparison of the first experiment in each case, that is to say of Nos. 2 and 4, the chemical action seems as rapid in the one instance as in the other. With chloride of magnesium, all the magnesia is removed except 0·07 grain per pint; with sulphate of magnesium, all the magnesia is removed excepting 0·1 grain per pint.

Nos. 6 and 7, *Sea-water*.—In each case there was evidence of considerable action having taken place. On opening the muslin bags in which the granules of cement had been suspended, abundance of the white creamy-looking substance was observable. The clear fluid in experiment No. 6 was found to contain a proportion of 4·21 grains of magnesia per pint, thus showing a precipitation of 14·16 grains from the original sea-water. The clear fluid in experiment No. 7 contained equivalent to 3·65 grains of magnesia per pint, thus showing that 14·72 grains had been precipitated from the original pint of sea-water. The results of these two experiments are strongly confirmatory of those obtained in the experiment detailed in my report of June 9, 1887.

No. 8, *Chloride of Sodium*.—This experiment agreed closely with the results obtained in experiment No. 1 (distilled water)—a proportion of lime amounting to 1·60 grain per pint seems to have been dissolved.

An additional experiment was also arranged, in which two pieces of solid cement (from a briquette), weighing together 2,400 grains, were suspended in 2 pints of sea-water of similar character to that mentioned in experiments Nos. 6 and 7, and the whole was allowed to remain at rest for the same period as the other digestions. At the end of the time there was no very marked appearance, except that here and there a few white spots were discernible. The sea-water originally contained a proportion of 18·37 grains per pint of magnesia; and after the digestion, 15·73 grains per pint, thus showing a loss of 2·64 grains per pint during the experiment.

APPENDIX III.

EXTRACT FROM MR. PATTINSON'S REPORT OF OCT. 25TH, 1887, GIVING HIS CONCLUSIONS FROM THE RESULTS OF HIS ANALYSES.

On comparing the analyses of the concrete used in the work with those of the original briquettes, Nos. 1, 2, and 3, it is evident that very considerable changes have occurred in the composition of the cement used in the concrete. First—much of the lime has disappeared from samples Nos. 6, 6b, 7, 8, 10, and 11. Second—a great increase of the magnesia has taken place in the same samples. Third—an increase in the amount of sulphuric acid has taken place in the same samples. This sulphuric acid exists as hydrated sulphate of lime.

These samples of concrete, which show a diminished amount of lime and increased amounts of magnesia and sulphuric acid, are just the samples which show, by their crumbling and friable nature, that the concrete has become disintegrated and deteriorated.

There can be no doubt, I think, that this deterioration is caused by the action of the sea-water with which the cement has come into contact. According to Thorpe and Morton's analysis (Chem. Soc. Journal, xxiv. 506), 1,000 grains of

sea-water contain 3.151 grains of chloride of magnesium, and 2.066 grains of sulphate of magnesia. The magnesia of both these salts in solution is precipitated as hydrate of magnesia on coming into contact with lime, with the simultaneous formation of soluble chloride of calcium and partially soluble sulphate of lime. This chemical action of sea-water has evidently taken place in the cement used in the samples of concrete marked Nos. 6, 6B, 7, 8, 10, and 11, and notably in No. 6 sample, from which about two-thirds of the lime has been removed, and in which about twenty times the original quantity of magnesia, and more than three times the original quantity of sulphate of lime, have been deposited, thereby causing the friable and disintegrated condition which marked this sample. The same result in a lesser degree is observable in the other samples.¹

APPENDIX IV.

TABLE OF FILTRATION OF SEA-WATER THROUGH PORTLAND CEMENT CONCRETE BLOCKS, 28 DAYS OLD, UNDER 24 FEET HEAD.

—	No. 1.	No. 2.	No. 3.	No. 4.	No. 5.	No. 6.
Proportion . .	1 : 1 : 4	1 : 4 : 1	1 : 2 : 3	1 : 1½ : 4½	7 Days. 1 : 3 : 4	1 : 1½ : 5½
Time from putting on pressure to appearance of water through block	9 hours.	35 minutes.	13 hours, 50 minutes.	3 hours, 15 minutes.	5 minutes.	35 minutes.
1st Day. . .	Ounces. 6	Ounces. 282	Ounces. 25½	Ounces. 46½	Ounces. 719½	Ounces. 385
2nd „ . . .	6	210½	21	41	386½	200
3rd „ . . .	2½	126	18	30	258	125
4th „ . . .	..	..	14¾	22	184½	76
5th „ . . .	..	..	..	..	137	53½
6th „ . . .	..	..	..	..	103	41½
7th „ . . .	..	..	..	..	83	24
8th „ . . .	..	..	..	..	70	23½
9th „ . . .	..	..	..	..	..	24½
10th „ . . .	..	..	..	..	Unreliable, being kept only 7 days — when taken out was found to be swelled and decomposed.	15
11th „ . . .	..	..	..	..		12½
12th „ . . .	..	..	..	..		21
13th „ . . .	..	..	..	..		12
14th „ . . .	..	..	..	..		10
15th „ . . .	..	..	..	..		10

¹ Published as Appendix II of Mr. Messent's Report on the Aberdeen Graving Dock, November 24th, 1887.

TABLE OF FILTRATION OF SEA-WATER THROUGH PORTLAND CEMENT CONCRETE BLOCKS, 3 MONTHS OLD, UNDER 24 FEET HEAD.

—	No. 7.	No. 8.	No. 9.	No. 10.	Apron Blocks for Works.	
					No. 11.	No. 12.
Proportion . .	1 : 1 : 4	1 : 4 : 1	1 : 2 : 3	1 : 1½ : 4½	1 to 5	1 to 5
Time from putting on pressure to appearance of water through block	5 minutes.	1 hour, 15 minutes.	64 hours, 30 minutes.	13 hours, 30 minutes.	20 minutes.	5 minutes.
1st Day . .	5½ oz.	44 oz.	1 oz.	⅛ oz.	20 oz.	1¾ oz.
2nd „ . .	9 „	32 „	1¼ „	..	3½ „	1 „
3rd „ . .	6 „	24 „	1¼ „	..	4 „	¾ „
4th „ . .	3 „	16½ „	1 „	..	3 „	1 „
5th . . .	2¾ „	12 „	1 „	..	2¾ „	½ „
6th „ . .	1 oz. nearly	6 „	1 „	..	2 „	½ „
7th „ . .	½ oz.	5 „	¾ „	..	2 „	½ „
8th „ . .	½ „	4 „	½ „	..	2 „	½ „
9th „ . .	1½ „	3 „	¼ „	..	1½ „	few drops
10th „ . .	1 „	2½ „	½ „	..	1½ „	..
11th „ . .	1 „	1 „	⅛ „	..	1½ „	½ oz.
12th „ . .	¾ „	1 nearly	⅛ „	..	1¼ „	½ „
13th „ . .	¾ „	¼ oz.	few drops	..	1¼ „	¼ „
14th „ . .	¾ „	1 „	⅛ oz.	..	¼ „	few drops
15th „ . .	few drops	¾ „	¾ „	..	¼ „	½ oz.
16th „ . .	⅛ oz.	½ „	few drops	..	½ „	⅛ „
17th „ . .	½ „	¼ „	damp	..	¼ „	⅛ „
18th „ . .	..	⅛ „	..	..	¼ „	⅛ „

TABLE OF FILTRATION OF SEA-WATER THROUGH ROMAN CEMENT CONCRETE BLOCKS, ONE MONTH OLD, UNDER 24 FEET HEAD.

—	No. 13.	No. 14.	No. 15.
Proportion . .	1 : 1 : 4	1 : 2 : 3	1 : 2 : 3
Time from putting on pressure to appearance of water through blocks	1 hour, 5 minutes.	Block did not become hard enough to come out of mould.	Moulded and hardened, but not tried under pressure.
1st Day . .	223 oz.		
2nd „ . .	201 „		
3rd „ . .	189 „		
4th „ . .	173 „		
5th „ . .	173 „		

The cement used for the first six experiments was not finely ground, leaving 10 per cent. on a 2,500-mesh sieve; the cement for the experiments, numbered 7 to 12 inclusive, was ground to a fineness of $2\frac{1}{2}$ per cent. residue on a 5,800-mesh sieve. The Roman cement referred to in experiments 13 to 15 was very coarse, leaving 26 per cent. residue on a 2,500-mesh sieve.

APPENDIX V.

SAND AND STONES USED FOR CONCRETE WORK AT ABERDEEN.

Sand.—The sand used for the concrete works at Aberdeen Harbour is clean, sharp, quartzose sand, screened through a sieve of 40 meshes to the inch, and contains a small proportion of minute water-worn pebbles. It has no sea-shells, clay, or impurities considered detrimental to concrete. From experiments made with it on the shrinkage of hydraulic mortars, it appears that the shrinkage is wholly due to the fluxing and packing of the sand; that the cement brings no new element for filling interstitial spaces in the mass of sand, but is all used in coating the grains and filling in the extra space between the grains of sand due to this coating. The sand has thus the variety of size of grain requisite for the formation of impermeable mortar on the addition of a sufficient proportion of cement. A similar quality of sand is collected from the beach of the Bay of Nigg on the south side of the harbour. That forming the beach to the north of the harbour, extending a distance of 15 miles, is considered too fine for concrete work; it consists of flat micaceous grains, so fine as to be blown by a light freeze when dry, but when fluxed in water is much heavier than the large-trained quartzose sand, the specific gravity of which when wetted is as 1.5 to 2.

Similar sand, dredged from the channel at the harbour entrance, contains a proportion of sea-shells and has a specific gravity of 1.75.

Stones.—The nature and size of the stones used for the formation of concrete has a considerable influence upon its ultimate strength. Smooth, water-worn pebbles are used at Aberdeen, also road-metal of broken granite, trap, or whinstone, and granite chips. The strongest concrete is that made with granite chips or broken granite, and the weakest that made with water-worn pebbles of quartzite or whinstone. Concrete carefully made of granite chips and mortar has twice the strength of concrete similarly proportioned made with water-worn pebbles. The Author observed that concrete made with sandstone at Nairn was more tenacious than similarly proportioned concrete of granite chips, a homogeneous wall being obtained with a poorer mortar than could be used in building with granite. The most advantageous quality to be sought for in the stones next to durability, is that they should form a good base for the crystallization of the cement, a quality which may be easily ascertained by experiment.

Brick forms an exceedingly good base for crystallization; and broken brick is a favourite material with concrete builders. It is, however, very unsuitable for work exposed to sea-water, disintegration setting in from chemical action much more rapidly in contact with brick than with stone.

[DISCUSSION.

[THE INST. C.E. VOL. CVII.]

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