10TH FEBRUARY, 1887.

W. D. CRUICKSHANK, PRESIDENT, in the Chair.

THE following candidate was balloted for and duly elected as

MEMBER:

H. G. M'KINNEY.

Professor Warren then read the following paper:—

THE ADHESION OF CEMENT AND OF VARIOUS CEMENT MORTARS TO BRICKS,

And its application in the design of Retaining Walls, Arches, and similar structures.

BY PROFESSOR WARREN.

IN a paper entitled "Notes on Cement," which was recently read before this Association by Mr. A. C. Mountain, M.I.C.E., the various tests recommended by authorities on Portland Cement were fully considered and criticised. The tests described in Mr. Mountain's paper for ascertaining the value of a given cement, either for mixing with sand to form concrete, or with various aggregates to form mortar, are very satisfactory, and leave little else to be desired in so far as the cement itself is concerned. But while admitting the value of these tests, it must be conceded that it is at least as necessary to know the properties of the materials generally associated with cement in mortar and concrete, which, in conjunction with the cementing material, exercise an important influence in resisting the forces which are developed in the concrete or mortar in the uses to which they are applied by the engineer and architect.

Consider, for example, the behaviour of a mass of concrete formed of blue metal, sand, and cement, when subjected to a crushing force in the testing machine. Here the concrete will fail, not by the actual crushing of the material forming the aggregate, but by a separation of the pieces of blue metal from the cementing material which binds them together. So that while the mass, as a whole, is subjected to an externally applied crushing force, the interior is called upon to resist forces which develop to some extent the tensile strength of the cement, but which fully develop the adhesive strength of the cement mortar, and the materials forming the aggregate. If the resistance of the cementing material to be thus separated from the material with which it is united is less than its tenacity, it follows as a consequence that the adhesive strength of cement is at least as important as its resistance to simple tension. The adhesion of cement, and of various cement mortars to bricks forms the subject of this paper.

The only experiments known to the author on this subject are to be found in a work entitled "Strength of Cement," by Mr. John Grant, M.I.C.E. These were conducted as follows:—blocks of four bricks were cemented together with Portland cement and lime mortars of various degrees of richness; after twelve months the blocks were subjected to a tensile stress in a testing machine until they yielded at one of the joints, the force required to thus separate the bricks divided by the area of join gives the adhesive strength of the mortar. Mr. Grant's table of experiments is here reproduced (see Table I.). Several of the results recorded in this table appear inconsistent, and they have been put in bolder figures in order that they may be more easily noted. Mr. Grant says, that he considers many more experiments should be made before any trustworthy deductions could be made from them, and that there are considerable mechanical difficulties in making this class of experiments with any machine which combines the necessary strength and delicacy.

The experiments made by the author with the aid of the University Testing Machine were as follows:—

FIG. 1.

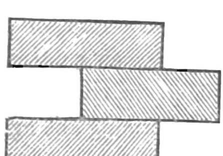
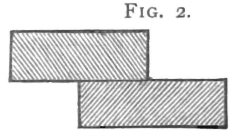


FIG. 2.



The bricks were set in two ways, which are shown in figs. 1 and 2. They were set in the cement room at the Town Hall, Sydney. The material used in forming the mortar, and the method of determining the exact proportions, and the mixing of the materials will be again referred to. The bricks, after being set in the manner described, were allowed to remain in the cement room for periods of 7 and 28 days respectively, after which they were carted to the University and tested. Every care was taken to ensure that the specimens were not damaged in carting, loading, and unloading, and only two specimens out of one hundred and fifty-six were damaged. The testing consisted in causing the middle brick in fig. 1 to slide between the two outside ones, thus overcoming the adhesion existing between the mortar and bricks on two surfaces. In fig. 2 one brick was made to slide upon the other, which developed the adhesion on one surface only. As might have been anticipated, it was found to be impossible to cause the force to be equally distributed over the two surfaces in Fig. 1, and in nearly every case one side failed before the other, so that the results obtained by testing as in Fig. 2 do not differ much from those obtained by testing as in Fig. 1. In future experiments on this subject the author proposes to arrange the specimens as in Fig. 2 only.

MATERIALS.—The bricks used were made by Messrs. Goodsell Bros., St. Peter's, three months before they were used in adhesive tests. They were thoroughly soaked in water before using, and the average absortion was found to be 7.6 per cent. They were subjected to a crushing test both on the bed and on end, and gave the following results: —

No.	Description.	Size.	Weight.	Area exposed to Crushing.	Total force required to crush brick.	Force per sq. inch.	Remarks.
			lbs.		lbs.	lbs.	
1	Pressed brick as used in adhesive tests.	8·7 x 4·2 x 2·3	8¼	36·54	98,000	2682	Tested on bed cracked at 40,000 lbs.
2	Do.	8·7 x 4·2 x 2·3	7½	9·66	27,000	2795	Tested on end.

The Cement used was the "Castle Brand," No. 67, manufactured by W. Levett & Co. The materials which were mixed with the Cement to form mortar consisted of Crushed Sandstone, Nepean River Sand, and Blue Stone dust. They were each passed through a sieve, having 400 meshes per square inch, and the residue rejected. The degree of fineness of the material which had passed through a sieve with 400 meshes per square inch was tested by passing it through a sieve having 900 meshes per square inch, and the percentage of fine stuff which was thus passed through was as follows :—

Sand derived from Crushed Sandstone	67·1	per cent.
Sand derived from the Nepean River..............	39·0	„
Blue Stone Dust	71·8	„

The materials which were fine enough to pass through the sieve of 400 meshes per square inch were each mixed with the Cement by hand, on a slate table, in the following proportions by bulk, 1 to 1, 2 to 1, 3 to 1 and 4 to 1.

Mixing.—In order to mix the materials in the required proportion, the following method was adopted :—

The weight per imperial bushel of the cement was first ascertained, and the weight of a cubic inch derived from it by dividing this weight by the number of cubic inches in an imperial bushel.

The weight of the materials used with the cement to form mortar was ascertained by filling a measure $\frac{1}{10}$ the volume of the imperial bushel with the material in question, and well shaking it down. The measure and its contents were then weighed. The same measure was again filled with a copper funnel and again weighed, the mean of the two weights thus obtained was taken, and the weight of the measure deducted, the result was then divided by the number of cubic inches in the measure, the weights thus formed were as follows :—

Neat Cement—No. 67, Castle Brand...	0·7411	oz. per cubic inch.	
Sand obtained from Crushed Sandstone	0·7787	„	„
Nepean River Sand	0·8509	„	„
Blue Stone Dust	0·9771	„	„

In order to mix the materials in the required proportions by bulk, it is only necessary to weigh out the material in accordance with these results. Thus, for example, to find out the quantities necessary for mixing Nepean river sand and cement in the proportion of 3 to 1, weigh out 0·7411 ounces or pounds of cement, and $3 \times 0{\cdot}8509$ ounces or pounds, as the case may be, of Nepean river sand.

The percentage of water used in mixing the materials was found to be as follows :—

Neat Cement	... ...	23·4 per cent.
Crushed Sandstone	1 to 1	21·1 ,,
	2 ,, 1	17·7 ,,
	3 ,, 1	19·2 ,,
	4 ,, 1	18·4 ,,
Nepean River Sand	1 ,, 1	18·2 ,,
	2 ,, 1	12·5 ,,
	3 ,, 1	11·6 ,,
	4 ,, 1	11·17 ,,
Blue Stone Dust	1 ,, 1	19·7 ,,
	2 ,, 1	16·8 ,,
	3 ,, 1	16·1 ,,
	4 ,, 1	16·5 ,,

The results of the experiments are recorded in Tables II., III., IV., V., and these are summarised in Table VI. Table VII. was prepared by Mr. Mountain, from experiments made with the same brand of cement as that used in the adhesive tests. The tensile strength of this cement was found to be—

At the end of 3 days,	... ...	472 lbs. per square inch.
,, ,, 7 ,,	... ...	609 ,, ,,
,, ,, 28 ,,	... ...	740 ,, ,,

By comparing these results with those given in Table VII., the relative adhesive strength of this cement to the materials enumerated in the Table may be inferred thus. When mixed with crushed sandstone in the proportion of 1 to 3, the tensile strength was found to be 191 lbs. per square inch at the end of 7 days, and 219 lbs. per square inch at the end of 28 days. Now, although a tensile force has been applied in this case, the internal resistances developed in the briquette were the adhesive strengths of the particles of cement to the particles of sand, and thus, from the experiment quoted, is 0·311 times that of the tensile strength of the neat cement at the end of 7 days, and 0·296 times at the end of 28 days, giving a mean value of 0·3035, which may be used as a co-efficient to calculate the adhesive strength of crushed sandstone to the cement when mixed in this proportion. In a similar manner other co-efficients may be derived which may be used in like manner. The adhesive strength of neat cement mortar to the bricks experimented upon may be found by multiplying the tensile strength of the neat cement by 0·275.

APPLICATIONS.—The foregoing facts have an important application in the design and construction of enclosure walls, retaining walls, piers, abutments, buttresses and arches. With regard to retaining walls the following conditions are usually accepted :—

a. When the wall is subjected to fluid pressure on one side only :

1. The centre of pressure when the water reaches its highest position must fall within the centre third of the thickness of the wall at every level.
2. The centre of pressure due to the weight of the wall itself must fall within the centre third of the thickness of the wall at every level. (Note.—This will happen in every case unless the wall or dam is exceptionally high.)
3. The intensity of the vertical pressure at the outer face must not exceed that which the material can safely bear.
4. The angle which the resultant pressure on any bed joint makes with the normal to that joint must not be greater than the angle of which $\frac{4}{5}$ of the co-efficient of friction of material is the tangent.

b. When the wall is subjected to earth pressure on one side only :

Here the same conditions apply, with the exception that in condition 1 we substitute the maximum earth for the maximum fluid pressure due to water. In all ordinary retaining walls which satisfy this condition, the intensity of vertical pressure on the outer edge will not generally exceed the safe limit with regard to crushing of material.

c. In dock and quay walls, which are subjected to both water and earth pressure, the walls must be designed to resist the maximum earth thrust when the dock is empty, and the maximum water pressure, less the minimum earth thrust, when the dock is full.

With regard to arches: The line of resistance is supposed not to pass without the centre third of the thickness of any voussoir, and its direction at any joint must not make with the normal to the joint an angle greater than the angle of friction of the materials. Similar conditions are accepted with regard to piers and abutments of bridges, &c.

In all such cases as the foregoing it has been the usual practice to work in accordance with the above conditions, for if the line of pressure in a retaining wall, or the line of resistance in an arch, passes outside the middle third of the thickness of the arch or wall, as the case may be, it is generally assumed that there will be an insufficient margin of stability, and that the intensity of pressure on the edge nearest the line of pressure may exceed the safe limit, and that the edge furthest from the line of pressure will be entirely relieved of pressure. These will undoubtedly be true if the joint in question is incapable of resisting tensile stress. If, however, the adhesive strength of the mortar in the joint is relied upon to resist the tensile stress, which will be developed at the joint by the deviation of the line of pressure from the middle third of the thickness, the distribution of pressure will be considerably modified, and a much thinner wall be found sufficient.

The following examples have been chosen to illustrate a method of dealing with such questions, and to show how much the adhesive strength of the mortar may increase the strength of such structures.

Example.—To determine the thickness of a retaining wall at the base, having given the thickness at the top and head of water, first, when there is no tension on the joint AB, and, secondly, when tension is developed at the corner A.

First, when there is no tension at A,

Let the thickness of the wall at top be ... ... 4′ 0″

,, ,, head of water ... ... 20′ 0″

,, ,, material of the wall be concrete weighing 140lb per cubic foot

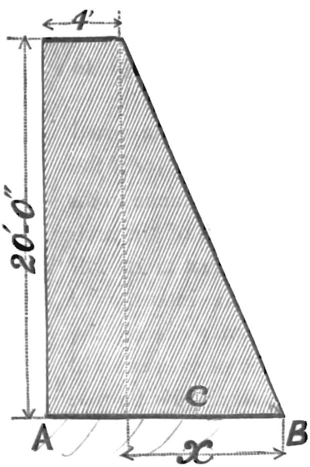
,, x be the extra thickness of the wall at the base

Then the area of the wall will equal ... ... $10\,(x+8)$

,, ,, weight ,, ,, ,, ... $1400\,(x+8)$

Let the distance of the centre of gravity of the wall from the edge B = X.

$$\text{Then } 10\,X\,(x+8) = 10x \times \frac{2x}{3} + 80\,(x+2)$$



$$X = \frac{\frac{20x^2}{3} + 80\,(x+2)}{10\,(x+8)}$$

The distance of the centre of gravity of the wall from C where BC = $\frac{1}{3}$ AB is

$$= \frac{\frac{20x^2}{3} + 80\,(x+2)}{10\,(x+8)} - \frac{x+4}{3} = \frac{10x^2 + 120x + 160}{30\,(x+8)}$$

Take moments about C, then moment of wall

$$1400(x+8)\left\{\frac{10x^2 + 120 + 160}{30\,(x+8)}\right\}$$

$$= 1400\,(x^2 + 12x + 16)$$

$$\text{Moment of water} = \tfrac{1}{6}wh^3 = \frac{62{\cdot}5 \times 8000}{6}$$

$$\therefore \frac{62{\cdot}5 \times 8000}{6} = 1400\,(x^2 + 12x + 16)$$

$x = \pm\, 14{\cdot}5 - 6$, taking the upper sign we find $x = 8{\cdot}5$. Hence the total thickness of the wall will be 12·5 feet at base.

Secondly, when there is tension at A.

Take the moments in this case about B instead of C. Then

$$1400(x+8)\left\{\frac{\frac{20x^2}{3} + 80\,(x+2)}{10\,(x+8)}\right\} = \frac{140}{3}\left\{20x^2 + 240\,(x+2)\right\} = \frac{62{\cdot}5 \times 8000}{6}$$

$$x^2 + 12x + 24 = \frac{62{\cdot}5 \times 8000 \times 3}{6 \times 2800} = 90$$

$x = -6 \pm 10$ = neglecting negative sign, 4 feet.

Hence the thickness of the wall will be 8′ instead of 12′ 6″.

We will now investigate the distribution of pressure and tension on the point AB.

Area of wall = 20 × 6 = 120 square feet.
Weight of wall = 140 × 120 = 16,800 ℔.

The distance of centre of gravity of the wall from A

$$= X = \frac{40 \times \frac{8}{3} + 80 \times 6}{120} = \frac{8}{9} + 4 = 5 \text{ nearly.}$$

Let N = normal pressure per lineal foot of length of wall = 16,800 ℔.
Let Y = distance of centre of gravity from B = 8 − 5 = 3 ft.
t = thickness of wall = 8 ft.
Let n = the intensity of pressure at A.
,, n' = ,, ,, ,, B.
Then it can be proved that

$$n = \frac{2t-3y}{t} \times \frac{2n}{t} = \frac{16-9}{8} \times \frac{33.600}{8} = 3675 \text{ ℔ per sq. ft.}$$

$$n' = \frac{3y-t}{t} \times \frac{2n}{t} = \frac{9-8}{8} \times \frac{33{,}600}{8} = 525 \text{ ℔ per sq. ft.}$$

Moment of flexure about the section AB $= \frac{1}{6}wh^3$
,, ,, resistance ,, ,, ,, $= \frac{1}{6}bd^2 f$

$$\therefore \quad wh^3 = bd^2 f \qquad \because \quad f = \frac{wh^3}{bd^2} = \frac{62 \cdot 5 \times 8000}{8 \times 8} = 7182 \cdot 5$$

Therefore the compression at B = 7812·5 + 525 = 8337·5 ℔ per ft.
,, ,, tension ,, A = 7812·5 − 3675 = 4137·5 ,, ,,

Compression at B = 57·8 ℔ per sq. in.
Tension at A = 28·7 ,, ,,

On referring to Table VI. it will be seen that this tension is not excessive with any of the mortars which consist of cement and sand in the proportion of one to one, and the crushing resistance of good concrete may be taken as 1000lbs. per square inch (see remarks given in discussion of Mr. Mountain's paper).

This system of construction is especially applicable to structures having a rock foundation, but it may be applied in many other cases if the footings be sufficiently spread out to prevent the pressure of the wall on the foundations exceeding the safe limit. The advantages in uniting the base of a wall built under water to a rock foundation with good cement mortar are obvious, as the water will be prevented from finding its way under the wall and exerting an upward pressure equal to the weight of the water displaced by the wall. Moreover since the adhesion of the cement to the rock will allow tensile stresses to be developed at the joint, it follows that the thickness of the wall usually adopted in such cases might be reduced without any risk of danger.

The author desires to thank Mr. A. C. Mountain, M.I.C.E., for co-operating with him in making the experiments described in the paper, and to Mr. Errey for his care and intelligent assistance, both in the preparation and testing of the specimens.

DISCUSSION.

MR. TREVOR JONES desired to signify his appreciation of Professor Warren's pains-taking experiments to deal with the very important question of retaining walls from some new points of view, as in the case under consideration involving the adhesiveness of mortar.

The question of retaining walls was one that, if approached in an incautious manner, was likely to lead its students into pitfalls; the consideration of the question embraced many features not to be hastily dealt with.

Cement mortar had been tested for its tensile resistance with great care and pains, but while that quality, if satisfactory, had proved a fair indication of its power to sustain pressure, nevertheless, direct experiments on its crushing, cross breaking and even shearing resistance had the most important value, in view of the many uses that cement was being put to in modern structures.

With reference to retaining walls generally, the adhesive property of cement had been all but ignored, and indeed he would not now advocate entire dependence to be placed on that quality. He was still of opinion that the inner toe of a retaining wall should not be subjected to tension.

Meantime the author had shown that a retaining wall may safely be designed showing a substantial reduction in substance by the use of cement in place of lime mortar.

One source of insecurity in building with lime mortar, especially if the wall was to sustain pressure within a short period of its being built, arose from the fact that lime mortar took months, to set, and therefore, instead of constituting an element of stability, it afforded a pasty lubricant (if rich in lime) for the stones to slide one on another.

Lime within the heart of a thick wall could not collect sufficient carbonic acid gas from the air for setting purposes, it was well known that if lime paste was kept in a box covered with water, it would not set in 100 years, because it could not collect its carbon to set with if not in contact with air.

In connection with the question of utilizing the cohesive property of cement for retaining walls, some time since he made some experiments in that direction and had conferred with Professor Warren on the subject.

The Professor had shown, that a wall to sustain a head of water of 20 feet must at least be 8 feet in thickness; it might at first glance surprise one that he had built a brick wall, to sustain the same head, only $4\frac{1}{2}$ inches in thickness, and it had sustained that load without any failure; moreover by calculation it could be raised to 30 feet.

The tank in question was an upright cylinder of $4\frac{1}{2}$ inches brick, 10 feet in diameter internally, built upon and accurately cemented to a rock foundation. This was rendered inside with $\frac{1}{2}$ inch of 1 to 1 cement mortar.

As the maximum bursting stress was on the bottom brick, the water pressure, computed as for pipe or boiler pressure, exerted a pressure at 20 feet depth, of $20 \times {\cdot}434 = 8{\cdot}7$ lbs per square inch and from $T = Pr$ or the tension in the enclosing wall = the pressure per square inch multiplied by the radius, all in inches, we had $T = 8{\cdot}7 \times 60 = 522$ lbs.

Well, the lower brick had to sustain a tension of 522 lbs., or to part from its fellows under that tension; here the tensile strength of the cement would be shown to be more than sufficient to obviate the latter event; moreover the lower brick gained a large access of strength from the superincumbent weight of the wall above.

A brick wall of $4\frac{1}{2}$ inches in thickness in cement would bear in tension a pull of $4\frac{1}{2} \times 290$ lbs. $= 1305$ lbs., hence without counting on the adventitious strength derived from the weight of wall and $\frac{1}{2}$ an inch of cement, the wall was $2\frac{1}{2}$ times the actual thickness necessary to burst the tank.

This tank had been built to be burst, if 20 feet should be found sufficient to do so, but having withstood the test it still remained to be shown what head would burst it; not that he would for a moment advocate the utilising of such tanks for any purpose, excepting that it demonstrated that the cohesive property had a certain appreciable value.

If we took for example a tank of 50 feet diameter, the strain on the bottom inch layer would be 5220 lbs., to sustain which, assuming brickwork to afford a resistance of 290 lbs. per square inch, a thickness of 18 inches would just sustain it, while a thickness of 4 feet 6 inches would give a factor of safety of 3.

Now if such a wall were to resist overturning as computed from standard methods, it had been shown that its minimum thickness should be 8 feet; was it not plain that if a 4 feet 6 inch wall was three times the strength to resist the strain, or if even this factor be thought too small there must be a thickness between the two extremes that would afford ample security with economy.

He had extended his remarks too much to enter on the consideration of the saving that might further be effected by a taper section, and concluded by saying that the profession could not have too much information on the subject treated of so ably by our valued colleague, Professor Warren.

Mr. SHELLSHEAR remarked that he thought the paper a most valuable addition to the proceedings of the Association. Up to the present there was a great want of proper experimental data to guide the engineer in the use of local materials, and the recent tests at the University by Professor Warren would do much to supply that want. With reference to the construction of retaining walls, no doubt where there was a really good foundation, considerable economy could be effected in the direction pointed out, but it often occurred that walls had to be built on anything but first-class foundations, in which case it would not be prudent to reduce the section of the wall. The very interesting experiment referred to by Mr. Trevor Jones showed how much could be done in the way of reducing the section of walls when the foundation was really good, but if a similar experiment had been tried on inferior ground the result would have been very different.

PROFESSOR WARREN, in reply, stated that it appeared to be generally admitted that cement mortar was superior to lime mortar for such structures as retaining walls, arches, abutments, &c., not only on account of the increased strength of the structure in consequence of the greater adhesive strength of the cement mortar, but from the fact that it would set equally well in the interior of a brick wall, under water, or when simply exposed to air. Lime mortar set by the absorption of carbon dioxide which formed small crystals of carbonate of calcium in the joints. It could only crystalise where it was exposed to the atmosphere, from whence it derived its carbon dioxide, and hence could never set in the interior of a thick wall. He saw a retaining wall the other day which had partly fallen, and he obtained from the interior a quantity of lime mortar which was quite soft.

Mr. Jones had stated "that he did not think the inner toe of a retaining wall should be subjected to tension." This was equivalent to ignoring the adhesive strength of cement mortar, but the interesting experiment described by him appeared to the author to be another example of adhesion, not of tension as stated by the author. The method of calculating tensile stress on a ring of brickwork from the formula $T=Pr$ was strictly true for a thin film subjected to internal pressure; it was generally accepted as true for a boiler shell, and he did not think there was any considerable error in applying it to such a case as the one under consideration. Although the weight of the hollow column of brickwork was neglected, as well as the strength of the inside rendering of cement, the former in a tank of 10 feet in diameter, and $4\frac{1}{2}$ inches thick, might be neglected, but when this same system was applied to a tank 50 feet in diameter, or 500 feet in diameter, it failed entirely, and the results obtained were absurd.

The exact treatment of circular reservoirs was much more complex, and would form a good subject for a separate paper.