

No. 1586.—“Portland Cement Concrete in Arches, and Portland Cement Mortar.” By CHARLES COLSON, Assoc. Inst. C.E.

THIS communication embraces a record of the mean results of experiments on the tensile strength of coarse and fine cement, gauged neat, and with an admixture of sand.

The course adopted in carrying out the experiments was to take from each cargo of cement, after being discharged into store, 1 bushel as delivered and 1 bushel screened through each of the following screens, viz., $34 \times 34 = 1,156$ meshes, and $58 \times 58 = 3,364$ meshes per square inch. A few samples were also screened through $65 \times 65 = 4,225$ meshes per square inch. The proportions were taken by measure, the weight being also taken as a check, inasmuch as it is possible, by allowing the cement or sand to fall too rapidly or too slowly into the measure, to have a bulk of varying density, an error immediately detected if the precaution of taking the weight is followed. Of the cement as delivered on the works, the average percentage of coarse, when screened through 1,156 meshes per square inch, was about 11 per cent.

Table 1 contains a summary of experiments, showing the mean breaking tensile strain on 2.25 square inches, and also per square inch of sectional area after being one month in water; the ratios of the strength of the fine cement, as compared with the coarse; and the ratio of strength when gauged neat, and when mixed with sand in the proportions of 1 to 1 and 2 to 1. The results show the advantages of extreme fineness. That it is necessary under all circumstances to screen the cement to the extreme degree of fineness, as adopted in these experiments, is by no means advanced; for special purposes, however, it might be desirable to do so, and possibly to exceed it. It is, however, submitted that, for all ordinary purposes, the degree of fineness adopted in specifications should in no case be less than 1,000 meshes per square inch, and not that any given percentage of the quantity should pass through, but that all should do so; and that the weight of the cement of this degree of fineness should not be less than 85 lbs. per cubic foot. The mean breaking tensile strain of the thirty-nine samples referred to in Table 1, after seven days' immersion in water, gauged neat as delivered on the works, was 665 lbs. on 2.25 square inches, = 295.50 lbs. per square inch.

TABLE 1.—COMPARATIVE TENSILE STRENGTH OF PORTLAND CEMENT ONE MONTH OLD, SCREENED AND UNSCREENED, GAUGED NEAT and MIXED with SAND in the PROPORTIONS of 1 to 1 and 2 to 1.

Neat Cement.										1 Sand to 1 Cement.						2 Sand to 2 Cement.																			
As Delivered.	Number of Tests.	Screened through 34 X 34 Inch. = 1,156 Meshes per sq.	Number of Tests.	Screened through 58 X 58 Inch. = 3,364 Meshes per sq.	Number of Tests.	Screened through 65 X 65 Inch. = 4,225 Meshes per sq.	Number of Tests.	As Delivered.	Number of Tests.	Screened through 34 X 34 Inch. = 1,156 Meshes per sq.	Number of Tests.	Screened through 58 X 58 Inch. = 3,364 Meshes per sq.	Number of Tests.	Screened through 65 X 65 Inch. = 4,225 Meshes per sq.	Number of Tests.	As Delivered.	Number of Tests.	Screened through 34 X 34 Inch. = 1,156 Meshes per sq.	Number of Tests.	Screened through 58 X 58 Inch. = 3,364 Meshes per sq.	Number of Tests.	Screened through 65 X 65 Inch. = 4,225 Meshes per sq.	Number of Tests.	As Delivered.	Number of Tests.	Screened through 34 X 34 Inch. = 1,156 Meshes per sq.	Number of Tests.	Screened through 58 X 58 Inch. = 3,364 Meshes per sq.	Number of Tests.	Screened through 65 X 65 Inch. = 4,225 Meshes per sq.	Number of Tests.				
39 839-346	263	873	265	271	824	159	270	777	190	42	463	855	270	300	218	256	549	973	264	569	342	37	206	241	265	338	917	255	377	096	250	415	856	28	
417-287		388	118	366	203	345	418				206	160		226	319	244	432		253	033		131	663		150	630		167	598		184	525 ²			
1-00		0-929		0-877		0-827					1-00		1-097		1-183		1-227		1-227		1-00		0-315		1-144		1-272		1-403 ³		1-403 ³		1-403 ³		
1-00		0-493	0-315
..		1-00	..	..	1-00	..	..	..	..	..	..	..	0-585	..	0-667	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
..	

3 Ratios.

2 Mean breaking strain per square inch.

1 Mean breaking strain on 2-25 square inches.

Table 2 shows the relative weight of the same samples of cement as delivered, and when screened through the various descriptions of sieves used throughout these experiments.

TABLE 2.—COMPARATIVE WEIGHT OF COARSE AND FINE PORTLAND CEMENT.

Number of Samples Tested.	As Delivered.	Screened through $34 \times 34 = 1156$ Meshes per square inch.	Screened through $58 \times 58 = 3364$ Meshes per square inch.	Screened through $65 \times 65 = 4225$ Meshes per square inch.	Remarks.
40	112·15	104·850	98·300	94·750	lbs. per bushel.
	87·61	81·910	76·790	74·020	lbs. per cubic foot.
	1·00	0·934	0·876	0·844	Ratios.

The results shown in the Table bear upon a point before referred to,¹ namely, that the weight of Portland cement, taken alone, is no true indication of its quality. A weight of 104 lbs., compared with 112 lbs. per bushel, would be considered exceedingly low, and would be sufficient, if taken alone, to condemn the sample as not complying with the specification; whereas the cement might be of equal, if not superior, quality to a sample of greater weight, but being ground or screened finer, would give a less result, both when weighed and when tested neat.

Table 3 shows the comparative results of experiments on

TABLE 3.—COMPARATIVE BREAKING TENSILE STRAIN ON PORTLAND CEMENT GAUGED NEAT, AND MIXED WITH DIFFERENT MATERIALS in the PROPORTION of 1 to 1 TESTED when ONE MONTH OLD.

Number of Tests to each.	Neat.	Sand.	Crushed Granite.	Crushed Brick.	Crushed Portland Stone.	Remarks.
56	985·75	542·75	594·07	671·85	700·87	lbs. on 2·25 sq. in.
	438·11	241·22	264·03	298·60	311·50	lbs. per square inch.
	1·00	0·55	0·60	0·68	0·71	Ratios.

cement gauged neat, and mixed with porous and non-porous materials in the proportion of 1 to 1, sand and crushed granite

¹ *Vide* Minutes of Proceedings Inst. C.E., vol. xli., p. 127.

representing the non-porous, and crushed brick and Portland stone the porous. Exactly the same proportions by measure were taken of each. It was, however, necessary to increase the quantity of water in the case of the brick and Portland stone, in consequence of the porous nature of the materials. It will be seen that the resulting tensile strain obtained from the admixture of porous material considerably exceeded that obtained from the non-porous.

COMPARATIVE TENSILE STRENGTH OF GREY LIME AND PORTLAND CEMENT MORTAR.

The object of these experiments was to ascertain what proportions of Portland cement and sand would produce a mortar equal in strength and as convenient to work as grey lime mortar, the proportions ordinarily adopted for constructive purposes. The mortar was mixed to a workable consistency, equal, in fact, to the condition in which it would be used in the work. The mass was then moulded in the frames used for testing Portland cement, where it remained until sufficiently hard to admit of removal. At the expiration of six months the blocks were tested for tensile strength, the results being shown in Table 5, Nos. 1, 2, 3, and 4. With regard to the lime mortar (No. 1), the fractured blocks showed that induration, or the chemical action of setting, had penetrated only to the extent of from $\frac{1}{8}$ inch to $\frac{3}{16}$ inch, but in the majority of instances to only $\frac{1}{8}$ inch. The remainder of the area, although dry and moderately hard, had become so mainly from the evaporation of the moisture originally contained in the mass, and in no sense from the absorption of carbonic acid. It was possible, moreover, to crush it in the hand without any great exertion of force. The cement mortar, mixed in the proportions shown in No. 2, was of such a raw, harsh character, particularly that having the greater proportion of sand, that it would be practically impossible to use it in a satisfactory manner. In order, therefore, to render it somewhat more convenient for working, a small quantity of lime or yellow loam was added, thus rendering the mortar more plastic and tenacious. The results of further experiments (Nos. 3 and 4) show that the addition of lime and loam reduces the initial strength of cement mortar considerably, the reduction due to the addition of loam being more marked than by the addition of lime. The quantity of un-slacked lime or loam, viz., $\frac{1}{2}$ the bulk of sand, was found to be as small a proportion as could be used, to give the necessary tenacity.

TABLE 4.—COMPARATIVE STRENGTH OF GREY LIME and PORTLAND CEMENT MORTAR; also PORTLAND CEMENT MORTAR with the ADDITION of LIME and LOAM.

No. 1.—GREY LIME MORTAR.

No.	No. of Tests.	Proportions.			Breaking Strain on 2·25 sq. ins. in lbs.	Breaking Strain per sq. inch in lbs.	Remarks.
		Sand.	Lime.	Water.			
1	17	2·00	1·00	1·33	61·06	27·13	Three samples.
2	27	2·00	1·00	1·33	106·07	47·09	Grey lime.
3	27	2·00	1·00	1·33	82·00	36·44	Water includes that required for slacking the lime.
Means	..	2·00	1·00	1·33	83·04	36·88	

No. 2.—PORTLAND CEMENT MORTAR.

No.	No. of Tests.	Proportions.			Breaking strain on 2·25 sq. ins. in lbs.	Breaking Strain per sq. inch in lbs.	Ratio compared with Lime Mortar.	Remarks.
		Sand.	Cement.	Water.				
1	15	6·00	1·00	1·25	233·53	103·79	2·81 to 1	Cement taken from bulk in store.
2	20	8·00	1·00	1·66	154·80	68·80	1·86 „ 1	
3	35	10·00	1·00	2·00	112·88	50·16	1·36 „ 1	

No. 3.—PORTLAND CEMENT and LIME MORTAR.

No.	No. of Tests.	Proportions.				Breaking Strain on 2·25 sq. ins. in lbs.	Breaking Strain per sq. inch in lbs.	Ratio as compared with Lime Mortar.	Ratio as compared with Cement Mortar.	Remarks.
		Sand.	Cement.	Lime.	Water.					
1	70	6·00	1·00	0·50	1·50	165·31	73·47	2·00 to 1	0·70 to 1	Water includes that required for slacking the lime.
2	74	8·00	1·00	0·66	2·00	132·62	58·94	1·60 „	1·0·85 „ 1	
3	85	10·00	1·00	0·83	2·50	95·27	42·34	1·14 „	1·0·84 „ 1	

No. 4.—PORTLAND CEMENT and LOAM MORTAR.

No.	No. of Tests.	Proportions.				Breaking Strain on 2·25 sq. ins. in lbs.	Breaking Strain per sq. inch in lbs.	Ratio as compared with Lime Mortar.	Ratio as compared with Cement Mortar.	Remarks.
		Sand.	Cement.	Loam.	Water.					
1	21	6·00	1·00	0·50	1·00	136·80	60·80	1·64 to 1	1·0·58 to 1	Yellow loam fresh dug and rather damp.
2	25	8·00	1·00	0·66	1·33	86·48	38·43	1·04 „	1·0·55 „ 1	
3	19	10·00	1·00	0·83	2·00	64·50	28·66	0·77 „	1·0·57 „ 1	

As regards the comparative adhesive power of these mortars, experiments made with the view of ascertaining the force required to separate bricks, joined with the several descriptions of mortar, were not altogether satisfactory, inasmuch as the appliances at hand were not sufficiently accurate and delicate to justify a ratio of comparison. It may, however, be stated that the general result went to prove that the adhesive power of mortar, mixed in the proportions of 8 of sand to 1 of cement, with the addition of loam, was superior to grey lime mortar mixed in the proportions of 2 of sand to 1 of lime.

Another point for consideration is the comparative cost of the different descriptions of mortar. Such estimates must, however, be received with caution, because difference of locality would exert a great influence upon the cost of production. The following statement, however, is a close approximation to the cost of the several descriptions of mortar; the charge for labour and water, and also the bulk of mortar produced, being in each case the mean results of experiments:—

TABLE 5.—STATEMENT OF APPROXIMATE COST.

Description.	Proportions in cubic yards.				Cost of Materials.	Cost of Labour and Water.	Total Cost.	Produce of Mortar in cubic yards.	Cost per cubic yard.
	Portland Cement at 45s. 8d. per cubic yard.	Grey Lime at 14s. 6d. per cubic yard.	Loam at 2s. 9d. per cubic yard.	Sand at 7s. 9d. per cubic yard.					
Grey lime mortar .	..	1·00	..	2·00	20·00	6·62	26·62	2·25	11·83
Portland cement mortar, No. 1	1·00	..	..	6·00	62·19	6·84	68·23	5·90	11·56
Ditto, „ 2	1·00	..	..	8·00	67·69	7·80	75·49	7·60	9·93
Ditto, „ 3	1·00	..	..	10·00	73·19	9·57	82·76	9·30	8·88
Portland cement & lime mortar, No. 1	1·00	0·50	..	6·00	69·44	8·68	78·12	6·40	12·20
Ditto, „ 2	1·00	0·66	..	8·00	77·27	11·20	88·46	8·25	10·72
Ditto, „ 3	1·00	0·83	..	10·00	85·22	13·78	99·00	10·15	9·75
Portland cement & loam mortar, No. 1	1·00	..	0·50	6·00	63·56	6·23	69·79	6·10	11·44
Ditto, „ 2	1·00	..	0·66	8·00	69·53	8·05	77·58	7·90	9·82
Ditto, „ 3	1·00	..	0·83	10·00	75·47	9·97	85·44	9·75	8·76

EXPERIMENTS ON THE STRENGTH OF PORTLAND CEMENT CONCRETE ARCHES AND BEAMS. (Plate 11.)

The object of these experiments was to ascertain, if possible, the relative supporting power of masses of concrete equal in quality and practically so in bulk, but differently disposed. It was also

desired to show the relative supporting power of arches of the same span, rise, and thickness at the crown, composed of porous and non-porous material respectively, such as shingle and broken bricks, but mixed in the same proportions. The proportions, in the experiments in which shingle was used, were 6 of screened harbour shingle, 3 of sand, and 1 of Portland cement. The proportion of sand was determined by the measurement of the quantity of water required to fill the interstices of the shingle when placed in a known cubic measure. In mixing the concrete as little water as possible was used consistent with thorough manipulation; and in depositing upon the centre great care was taken that there should be no horizontal beds or laminations, but that the whole should form a thoroughly homogeneous mass.

No. 1 experiment consisted simply of a beam of concrete, mixed in the proportions as before explained, 9 feet long, 1 foot 9 inches wide, and 9 inches deep; the distance between the supports was 8 feet 3 inches, with a bearing of $4\frac{1}{2}$ inches at each end. Fourteen days after mixing the supports were removed, when the beam suddenly gave way near the centre. The fracture showed that the concrete was perfectly sound, there being no vacuities whatever to cause a diminution of effective sectional area.

No. 2 experiment consisted of a concrete beam similar in all respects to No. 1 (Plate 11, Fig. 1), being made in fact from the same mass and deposited at the same time. In consequence, however, of No. 1 having failed on the removal of the supports at fourteen days, the supports were not removed in this case till twenty-one days after mixing. At this interval the beam stood perfectly sound, and remained unsupported for a further period of seven days, when it was tested, and broke under a central load of 5 cwt.

No. 3 experiment consisted of a portion of No. 1 beam (Fig. 1) 4 feet 6 inches long, placed on supports 3 feet 9 inches apart (Fig. 2). This beam supported a load of 7.50 cwt. for seven days, when the load was increased to 13.75 cwt., under which load the beam failed twenty-eight days after mixing.

No. 4 (Fig. 3) consisted of a portion of No. 2 beam, 3 feet 9 inches clear of the supports, and tested immediately after No. 2, viz., at twenty-eight days after mixing. This beam failed under a load of 1.044 ton placed at the centre.

In each of these experiments the beams broke suddenly, without the least evidence, either by gradual cracking or otherwise, that the limit of load had been reached. One point, with regard to Nos. 3 and 4, deserving notice, is the difference in the load borne by

each before fracture took place, the interval of time being the same. It is possible that in the case of No. 3, which consisted of a part of No. 1 beam, the portion appropriated may have been slightly strained at the time of the first fracture on the removal of the supports at the expiration of fourteen days. The concrete for Nos. 1 and 2 beams having been mixed in one mass and deposited at the same time, there can be no doubt as to their being of the same quality.

The foregoing experiments being upon beams resting simply on vertical supports, it was desired to know what increase of resistance to fracture would be derived from the ends of the beam being blocked in such a manner as to secure perfect rigidity. Sufficient concrete was therefore mixed in the proportions before described to form two beams. One, No. 5, was formed with the ends resting on piers, as in the case of the previous experiments (Fig. 1). The second, No. 6, was formed between two counterforts of the wall, in which bearings $4\frac{1}{2}$ inches deep had been cut (Fig. 4). After an interval of fourteen days the supports were removed, when No. 5 beam broke with its own weight in exactly the same way as No. 1. Having in view the first failure, additional precautions were taken in removing the supports, the folding wedges and bearers being all planed true in order to reduce the friction to a minimum. The circumstances attending the failure of these two beams being precisely the same lead to the conclusion that the strength of the concrete as used, at fourteen days' interval, was not sufficient to withstand the tensile strain at the centre due to its own weight. The supports were removed from No. 6 beam at the same time, no sign whatever of weakness being observed. After remaining unsupported for a further period of sixteen days the beam was tested by placing weights on the centre as before (Fig. 4). Under 0.25 ton a faint crack was observed at the centre through the whole width of the beam; with 0.635 ton it had increased as nearly as could be determined to half the depth, viz., $4\frac{1}{2}$ inches, and opened to about $\frac{1}{16}$ inch at the lower surface. The full extent of the fracture probably exceeded this, although not apparent on the surface. No perceptible upward extension of the fracture could however be detected after the imposition of the weight last referred to. The load at the centre was ultimately increased to 1.292 ton, when the beam broke. This experiment shows the necessity of guarding against the possibility of lateral movement, in the slightest degree, in the supporting girders of a floor; in this case by so doing the supporting power of the beam was materially increased. It also shows that the mass within the

dotted line *a b c* (Fig. 4) adds nothing to the strength of the beam when confined at the ends, as proved by the crack appearing so soon after the commencement of the loading.

Experiments Nos. 7 and 8 were made to compare the gain in strength derived from a different disposition of the same bulk of concrete. The same proportions and dimensions were preserved, but the mass was deposited in the form of an arch with a rise of 9 inches at the centre (Fig. 5). The supports were removed from both arches at the expiration of sixteen days; there was, however, no necessity for their remaining supported for so long a time, as shown by subsequent experiments on arches of nearly double the span.

No. 7 (Figs. 5 and 6). Testing was commenced when the concrete was twenty-three days old. When loaded with 1.75 ton, a pig of iron, weighing 2.85 cwt., fell on one of the haunches, carrying away a portion, as shown in Figs. 5 and 6. The arch then stood for two days with a load of 3 tons on the centre. Under a load of 4.50 tons slight evidence of distress was observed at the crown, and with a load of 5.50 tons the arch failed by the complete crushing of the material at the centre.

No. 8 (Fig. 7). The testing of this arch commenced at twenty-eight days after mixing the concrete. When loaded with 5 tons, the testing was suspended for three days; it was then resumed, and with a load of 6.75 tons the arch failed. The slight indications of distress observed in the previous experiment appeared in this case, only immediately before the fracture of the arch.

No. 9 (Fig. 8). In this experiment the arch was 13 feet 9 inches between the abutments, 1 foot 9 inches wide, and 9 inches thick at the crown, with a rise of 9 inches. Exactly the same proportions of shingle, sand, and cement were used as before described. The centering was removed at seven days from the date of mixing the concrete, and the arch was tested at twenty-one days. A gauge was fixed in order to ascertain the amount of deflection due to the imposed load, which consisted of pig-iron ballast applied at the centre of the arch. With a load of 4 tons slight signs of distress were observed at the crown, when the gauge registered a deflection of $\frac{1}{8}$ inch. With an additional load of $\frac{1}{2}$ ton, = 4.50 tons, the arch suddenly failed, with no greater indication of distress than was previously observed. The greatest deflection registered was $\frac{3}{16}$ inch.

No. 10 (Fig. 9) consisted of an arch of the same span and dimensions, constructed and the centering removed on the same dates as No. 9, but tested after one month. With 3.14 tons at

the centre this arch failed, without even the slight warning observed in the previous experiments.

The concrete for the last two experiments was mixed in one mass as regards proportions of cement, sand, and shingle. No. 10 was, however, made much wetter than No. 9, to ascertain the effect of an excess of water upon the concrete. Judging from the results of these experiments the effect was to materially reduce the strength of the concrete. This was also found to be the case when concrete blocks were subjected to compression in the hydraulic press. These blocks, 6 inches \times 6 inches \times 6 inches, were composed of the same proportions of cement, sand, and shingle as used in the arches. An equal number was mixed with a maximum and minimum of water and tested when six months old. The same effect was also observed when broken bricks and broken Portland stone were used for the cement. The results of these experiments are shown in Table 6, Nos. 1, 2, and 3.

TABLE 6.—COMPARATIVE STRENGTH of CONCRETE when MIXED with a MAXIMUM and MINIMUM of WATER.

Materials—Broken brick, harbour shingle, and Portland stone.

Proportions—Broken brick or stone 2·00

Sand 1·00

Portland cement 0·33

Age when tested:—Six months.

No. 1.—BROKEN BRICK.

Number of Tests.	Size of Blocks.	Weight of Blocks in lbs.		Load in Tons.		Remarks.
		In Air.	In Salt Water.	At Com- mencement of Fracture.	At Com- pletion of Fracture.	
Maximum of water.						{ All blocks kept in water till tested.
12	Inches. 6 × 6 × 6	16·20	8·00	24·00	25·08	
Minimum of water.						
11	6 × 6 × 6	16·27	8·31	27·11	28·09	Ratio 1·13 to 1.

No. 2.—PORTLAND STONE.

Maximum of water.						{ Blocks kept in water till tested.
24	Inches. 6 × 6 × 6	17·39	9·22	19·91	21·67	
Minimum of water.						
24	6 × 6 × 6	16·97	8·97	22·52	23·51	Ratio 1·13 to 1.

No. 3.—HARBOUR SHINGLE.

Maximum of water.						{Blocks kept in water till tested.
24	Inches. 6 × 6 × 6	18·05	10·07	17·17	19·69	
Minimum of water.						
14	6 × 6 × 6	17·61	9·79	22·83	25·09	Ratio 1·33 to 1.

NOTE.—The above ratios refer to the first appearance of weakness as being in fact the measure of the strength of the concrete.

In all the foregoing experiments ordinary shingle dredged from Portsmouth harbour, water-worn and rounded to a great extent, was employed. Although the expression, crushing of the concrete, has been used in describing the results observed, it is to be understood, not that the stone or shingle in the mass was crushed or fractured, but that the strain to which it had been subjected had in all cases overcome the adhesive power of the cementing material for the rounded, smooth, and non-absorbent surface of the shingle.

The concrete for Nos. 11 and 12 experiments was composed of broken bricks, mixed in the same proportions as used for the shingle arches, viz., 2 to 1 of broken brick and sand and 3 to 1 of sand and cement; before mixing, the broken material was well damped. The necessary bulk of concrete for both arches was mixed in one mass and deposited in position at the same time. The centerings were removed in both cases seven days after mixing, and the arches tested at twenty-eight days. In No. 11 experiment (Fig. 10), slight evidence of distress at the crown became apparent under a load of 6 tons on the centre, and with 6.77 tons the arch failed.

No. 12 (Fig. 11) was tested on the same day as No. 11 arch, and supported a load of 6.50 tons before any indication of distress was observed; the load was then gradually increased to 7.064 tons, under which the arch failed.

The superior strength of the arches in the last two experiments is evidently due to the more absorbent and angular character of the material. The appearance of the fractures in the two cases, *i.e.*, shingle and broken brick, showed a marked difference. In the first case, the strain destroyed the adhesive power existing between the shingle and the matrix; in no instance was a stone observed to be fractured, the casts being, as a rule, clearly defined in the cement. In the second case, the superior adhesive power existing between the broken brick and cement matrix was manifest; in but few instances had the cement left the surface of the brick, the general characteristic being that of complete disintegration of both brick and matrix.

This communication is accompanied by several diagrams, from which Plate 11 has been compiled.

