CONSTRUCTION AND SUSTAINABLE MATERIALS

Aggregate Grading, Workability and Strength Development of Concrete and Mortar Made with Water-Resistant Cement and Portland Limestone Cement

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Abstract

While the performance of concrete and mortar is known to be influenced by the type of cement and aggregates, there are not many comparative studies concerning the characteristics of water-resistant commercial cement (WRC) that report on the characteristics of the aggregate. In this study, the properties of locally sourced aggregates were characterized and the workability, compressive strength and flexural strength of mortars and concrete prepared by a WRC and a PLC with same mix proportions were compared with the same water–cement ratio and water curing. The crushed granite was single sized 19–25 mm aggregate (absorption 0.55%) with medium sand (fineness modulus 2.79, uniformity coefficient 6.5 and curvature coefficient 0.98), resulting in a gap-graded grading. Workability of the WRC mixes was slightly reduced (concrete had a 8,2 % lower slump while mortar had 5,8 % lower slump, 3,9 % lower flow). As for compression strength, it was found that WRC concrete were stronger than the PLC concrete at all ages from 7 days, with a difference of up to 5.0% at 112 days; whereas PLC mortar were stronger than the WRC concrete at all ages from 28 days with a difference of up to 6.6%, at that age.For flexure it was observed that WRC concrete were stronger than PLC concrete by up to 1.7–5.0% at all ages, except at 28 days, at the same age, PLConcrete gave slightly stronger results at flexural strength, while WRC mortar gave slightly stronger flexural strength; PL.Concrete at 112 days were stronger by 3.6%. The 112-day strength was achieved between 85-96% at 28 days. Therefore, the effect of WRC is composite specific and it should be selected on the basis of application and workability requirements and aggregate grading.

Keywords: aggregate grading; concrete; mortar; water-resistant cement; workability

1 Introduction

The selection of the cement type is one of the first steps in a project and is significantly involved in the workability, strength and durability characteristics of cement and concrete. In Nigeria, portland limestone cement (PLC) is still the major constituent of binding materials but its hydrated paste is porous and permeable to water. In this regard, water-resistant cement (WRC) has been introduced, either by the addition of pore-refining supplementary materials, or by the addition of pore-blocking and hydrophobic materials [1]. Before these cements could be confidently specified it is necessary to know whether or not they would affect the fresh and mechanical properties of concrete and mortar.

There is some evidence already to date that the effect is not uniform. One waterproofed composite Portland cement (plain cement) achieved comparable strengths and strength gains with the addition of a permeability reducing admixture had minimal effect on workability [2], [3]. However, other wa-

ter-repellent compounds changed the hydration kinetics and other characteristics of mortar [4] and in some cases, the flexural strength of the mortars modified by the admixtures did not necessarily correspond to their compressive strength [5]. Comparisons are also sensitive to curing as well as to the water–cement ratio [6], [7] that affects the workability, as well as to the strength, of the materials.

One additional source of variability that is typically not considered is aggregate. Aggregates make up 70-80% of the volume of concrete, and their size distribution determines the volume of voids in the skeleton, the demand for paste and therefore workability, strength and permeability.

Variability in the strength of 1 : 2 : 4 concrete was noted by Mkpaidem et al. [8] and it was found that in Nigeria coarse aggregate are not often considered during selection, and that their grading is hardly considered in reporting on comparative cement studies.

This paper does characterise locally sourced aggregates and also compares a commercial version of the WRC and PLC version used in concrete and mortar. The objectives are to describe the grading and packing of the aggregates, compare the workability of fresh concrete and mortar, compare compressive strength (concrete and mortar) and flexural strength (mortar) at 7, 14, 28, 56 days and 112 days. The block and water-resistance results of the same programme are reported separately.

2 Materials and methods

2.1 Materials and aggregate tests

Lafarge EcoPlanet 32.5N (PLC) and Lafarge Water Shield (WRC), both from Lafarge Africa Plc, were bought from one retail outlet at the same time, stored dry and used as supplied without chemical analysis. The fine aggregate was natural river sand and the coarse aggregate crushed granite, each from a single source. Potable water complying with BS 3148 was used [9].

Sieve analysis followed BS EN 933-1 [10] on 500 g of sand and 5000 g of granite, and the results were compared with BS EN 12620 [11]. The fineness modulus (FM) was taken as the sum of the cumulative percentages retained on the 4.75, 2.00, 0.850, 0.425, 0.212 and 0.150 mm sieves divided by 100 (Equation (1)). The diameters D_{10}, D_{30} and D_{60} were interpolated from the grading curve, and the coefficients of uniformity C_u and curvature C_c were calculated using Equations (2) and (3). Moisture content of the sand was found by oven-drying at 105 ± 5°C [12]. The specific gravity of sand was determined by the pycnometer method and that of granite, with its water absorption, by the wire-basket method [13].

$$\mathrm{FM} = \frac{\sum (\text{cumulative \% retained})}{100} \tag{1}$$

$$C_u = \frac{D_{60}}{D_{10}} \tag{2}$$

$$C_c = \frac{D_{30}^2}{D_{10} D_{60}} \tag{3}$$

Packing was assessed by comparing the combined grading of the concrete aggregate with the Fuller–Thompson curve (n = 0.50) and the maximum-density curve (n = 0.45) given by Equation (4), where P is the percentage passing a sieve of size d and D = 25 mm is the maximum size. The combined grading was computed from the individual gradings and the aggregate fractions in the mix (sand 35.3%, granite 64.7%), and its closeness to the ideal curve was expressed as the root-mean-square (RMS) deviation in percentage points.

$$P = 100\left(\frac{d}{D}\right)^{n} \tag{4}$$

2.2 Mixes, specimens and curing

Concrete was proportioned by the Department of the Environment method [14] at 1 : 1.2 : 2.2 and a free water–cement ratio of 0.36. Mortar was made at 1 : 2.48 (cement : sand) and a water–cement ratio of 0.45 (Table 1). Both cements used identical proportions, aggregates and curing within each composite. Mixing water was corrected for the moisture of the sand, materials were batched by mass and mixed mechanically, and specimens were cast in layers and compacted according to BS EN 12390-2 [15]. They were demoulded after 24 h and water-cured until testing.

Table 1. Mix proportions and specimens.

Composite	Mix ratio	w/c	Specimen (mm)
Concrete	1 : 1.2 : 2.2	0.36	Cube, 150 × 150 × 150
Mortar	1 : 2.48	0.45	Cube, 50 × 50 × 50
Mortar	1 : 2.48	0.45	Prism, 40 × 40 × 160

Three specimens per cement per age (7–112 days).

2.3 Fresh and hardened tests

Workability of each fresh mix was measured by the slump test [16] and, for mortar, also by the flow table, in triplicate with the mean reported. Density and compressive strength of concrete followed BS EN 12390-7 and BS EN 12390-3 [17], [18], and compressive strength of 50 mm mortar cubes followed ASTM C109 [19]. Flexural strength was obtained by central loading of prisms over a 100 mm span [20]. Strength gain between two ages and the difference between cements were calculated with Equations (5) and (6), so a positive difference means a higher value for WRC. Results are means ± standard deviation (SD) of three specimens, and differences comparable to the SD are treated as tentative.

$$\text{Gain } (\%) = \frac{f_2 - f_1}{f_1} \times 100 \tag{5}$$

$$\text{Difference } (\%) = \frac{\text{WRC} - \text{PLC}}{\text{PLC}} \times 100 \tag{6}$$

3 Results and discussion

3.1 Grading and properties of the aggregates

The sieve analysis of the sand is given in Table 2. The fineness modulus was 2.79 and 54.63% passed the 0.6 mm sieve, so the sand is medium and lies within the 35–59% band of grading zone 2 of British and Nigerian practice. The diameters D_{10}, D_{30} and D_{60} were 0.114, 0.289 and 0.742 mm, giving C_u = 6.5 and C_c = 0.98. A uniformity coefficient above 6 indicates a wide size range, and a curvature coefficient of 0.98 lies at the lower limit of 1–3 associated with well-graded sand. The sand is therefore medium and nearly well-graded, with a slight deficiency in the 0.425–2.00 mm fractions.

Table 2. Sieve analysis of the fine aggregate.

Sieve (mm)	Retained (g)	Cum. retained (%)	Cum. passing (%)
4.75	50.86	10.17	89.83
2.00	24.14	15.00	85.00
0.850	104.52	35.90	64.10
0.425	80.48	52.00	48.00
0.212	140.91	80.18	19.82
0.150	25.67	85.32	14.68
0.075	49.22	95.16	4.84
Pan	24.20	100.00	0.00

Sample mass 500 g.

The granite was narrowly graded: 68.84% of the 5000 g sample was retained on the 19 mm sieve, 28.00% on the 9.5 mm sieve and 2.10% above 25 mm, and only 1.06% was finer than 9.5 mm. It is thus a nominally single-sized material of 19–25 mm and coarser than the 9.5 mm single size that gave the highest strength in [8]. The properties in Table 3 are typical of sound aggregates. The dense granite (specific gravity 2.62–2.66, absorption 0.55%) will contribute little to water uptake, so differences in absorption between mixes can be attributed mainly to the paste, and sand and granite have similar mineral densities, which suits proportioning by mass. The absorption of the sand was not determined because the pycnometer procedure gives specific gravity only.

Table 3. Physical properties of the aggregates.

Property	Fine	Coarse
Type	River sand	Crushed granite
Fineness modulus	2.79	–
Passing 0.6 mm (%)	54.63	–
C_u, C_c	6.5, 0.98	–
Nominal size (mm)	–	19–25
Moisture content (%)	3.55	–
Specific gravity	2.60	2.62 (OD), 2.64 (SSD), 2.66 (app.)
Absorption (%)	n.d.	0.55

n.d. = not determined; OD = oven-dry; SSD = saturated surface-dry.

3.2 Particle packing of the combined aggregate

Figure 1 compares the combined grading of the concrete aggregate with the ideal curves. It follows them closely between 0.425 and 2.00 mm, where the sand controls the distribution, but falls well below them from 4.75 to 19 mm. At 9.5 mm only 36.0% of the combined aggregate passed, against 61.6% on the Fuller–Thompson curve. The single-sized granite leaves sizes of about 5–19 mm almost unrepresented, making the blend gap-graded. The RMS deviation from the Fuller–Thompson curve was 14.0 percentage points for the adopted 35 : 65 blend, and a sand fraction of about 50% would reduce it only to 10.8 points, so the gap cannot be closed by proportioning alone.

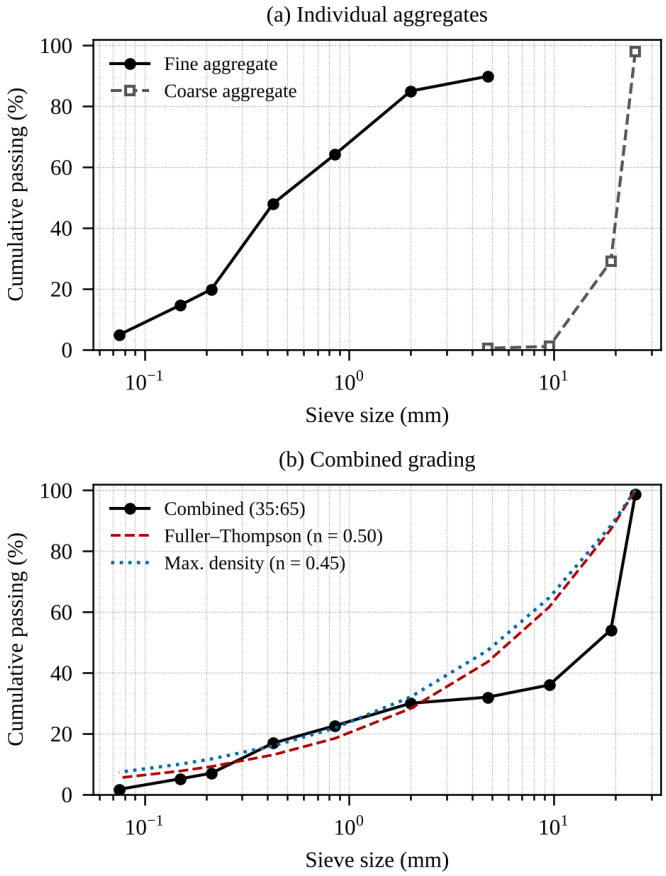


Figure 1. Grading of the aggregates: (a) individual gradings and (b) combined grading of the concrete compared with ideal packing curves.

Two implications follow. The voids in the granite skeleton were filled by paste and mortar rather than by intermediate aggregate, consistent with the cement-rich proportions and the low water–cement ratio of 0.36. Because the same blend was used with both cements, the limitation affects PLC and WRC concretes equally and does not compromise their comparison. The strengths reported here should not be regarded as the maximum attainable, and adding an intermediate size such as 9.5 mm would be expected to improve packing.

3.3 Workability

At equal water–cement ratio the WRC mixes were less workable than the PLC mixes in both composites (Table 4). Concrete slump fell from 85 to 78 mm (8.2%), mortar slump from 104 to 98 mm (5.8%) and mortar flow from 155 to 149 mm (3.9%). The same direction in composites with different aggregates, water–cement ratios and test methods suggests that the reduction is a property of the WRC itself, plausibly through the effect of its water-repellent or pore-blocking constituents on paste rheology. The effect is modest: both concretes stayed within consistence class S2 (50–90 mm) and all mixes were placed and compacted without difficulty. The result differs partly from the largely unchanged workability found with a permeability-reducing admixture [3], so a small penalty cannot be excluded for commercial water-resistant cements. Where higher workability is required, trial mixes with a slightly higher water content or a compatible water-reducing admixture [7] are appropriate. Only the mean of each triplicate was available, so the spread is unknown.

Table 4. Workability of fresh concrete and mortar.

Mix	w/c	Cement	Slump (mm)	Flow (mm)	Change (%)
Concrete	0.36	PLC	85	–	–
Concrete	0.36	WRC	78	–	−8.2
Mortar	0.45	PLC	104	155	–
Mortar	0.45	WRC	98	149	−5.8

Change in slump relative to PLC; WRC flow was 3.9% lower.

3.4 Compressive strength

Under both concretes it has been extremely found that the early gain is rapid and then the rate is rather tapering (Table 5, Figure 2) and cube strength is within 40 MPa and even above at 28 days in view of very low W/C ratio with concrete as expected. WRC concrete was stronger at all ages, with difference between means of 1.7% at 14 days and 5.0% at 28 days, whereas the difference between SDs was less than this difference between the means at most ages. At 28D, the advantage is not quite as certain as the mean value of the seven cubes would indicate, but the WRC mean (43.07 MPa) has a large SD (2.06 MPa) due to the outlier test cube which failed at 40.70 MPa and the other two test cubes failed at 44.02 MPa and 44.47 MPa. Its non-varying direction, however, suggests a marginal strength benefit for water resistance, while still maintaining no strength trade-off, which aligns with [2]. It can be seen that the strength difference is not due to a difference in density; the density increased for 7 days from PLC 2227 to 112 days to 2296 kg/m^3 corresponding to a 0.3% difference; for WRC, it increased from 2234 to 2301 kg/m^3 corresponding to 0.3%.

Table 5. Compressive strength of concrete cubes (MPa).

Age (days)	PLC	WRC	Diff. (%)
7	29.96 ± 0.86	30.58 ± 0.39	+2.1
14	34.66 ± 0.02	35.25 ± 0.28	+1.7
28	41.02 ± 0.14	43.07 ± 2.06	+5.0
56	44.56 ± 0.46	45.55 ± 0.27	+2.2
112	47.04 ± 1.27	48.54 ± 0.31	+3.2

Mean ± SD of three cubes.

Table 6. Compressive strength of mortar cubes (MPa).

Age (days)	PLC	WRC	Diff. (%)
7	7.46 ± 0.17	7.92 ± 0.32	+6.2
14	8.45 ± 0.18	8.33 ± 0.48	−1.4
28	9.27 ± 0.36	8.71 ± 0.19	−6.0
56	9.73 ± 0.30	9.09 ± 0.69	−6.6
112	9.67 ± 0.27	9.29 ± 0.21	−3.9

Mean ± SD of three cubes.

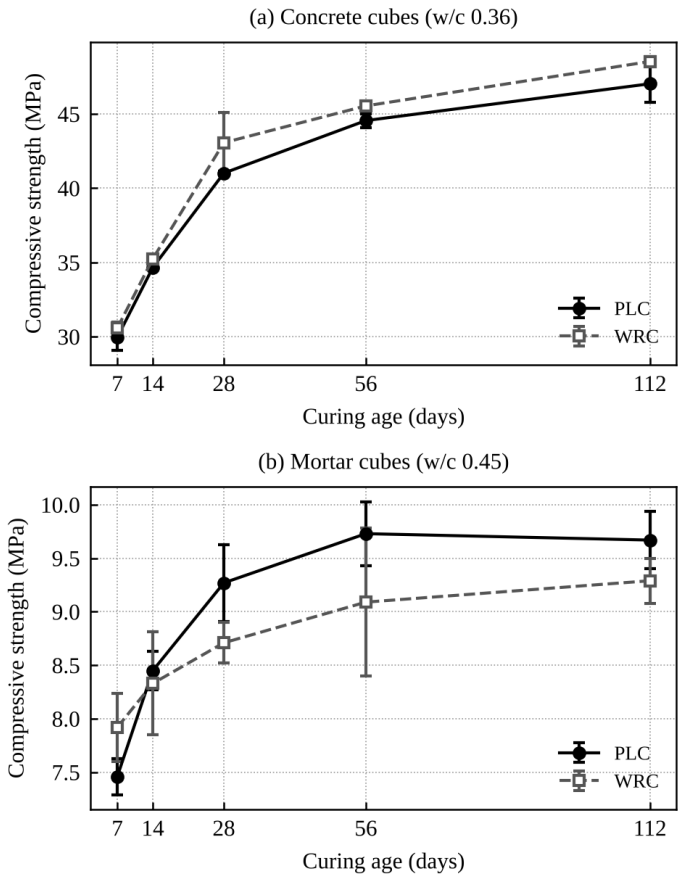


Figure 2. Compressive strength development of (a) concrete cubes and (b) mortar cubes (error bars: SD).

In the case of the mortar a pattern was used that was different (Table 6). WRC mortar was stronger only at 7 days (+6.2%), the two were practically equal at 14 days (−1.4%), and PLC mortar was stronger at 28, 56 and 112 days by 6.0, 6.6 and 3.9%. This is because of the rate of gain, at which PLC mortar increased by 24.3% between 7 and 28 days of the process, a rate almost double that of WRC mortar (which increased by 10.0% over the same period), and WRC mortar gained slightly more later (6.7% increase between 28 and 112 days of the process, compared to 4.3% for PLC). The differences at 14 and 112 days are not significantly different to the SDs (0.18-0.48 MPa), therefore it is not certain that PLC mortar is marginally superior on compression after 14 days, as a concrete. In comparison with concrete, which has strengths in the range of 30–49 MPa, the strength of the mortars (7–10 MPa) was small, not surprising given that it has a higher w/c ratio (0.45 versus 0.36) and because the mortar does not contain coarse aggregate and is tested with a small cube. The action of the two composites has proved to be opposite, meaning that the effect of a cement that repels water may not be also reflected in all composites, and this is why they must be tested individually.

3.5 Flexural strength of mortar

WRC prisms were stronger than PLC prisms at 7, 28, 56 and 112 days (by 2.0, 2.5, 3.4 and 1.9%) while PLC was higher at 14 days (by 5.6%), a result influenced by a large SD (0.46 MPa) probably caused by one weak prism (Table 7, Figure 3). The differences were generally similar to SDs (0.01–0.11 MPa), so that WRC mortar has the same strength level or exceeds as a bending strength and is slightly inferior in compression at later ages compared with PLC mortar. This is in the direction indicated by Choi et al. [5] and verifies the beneficial aspect of testing flexure independently of

compression. These ratios increased with age for both cements, being more gradual for the PLC. At 28 days, the ratio of flexural to compressive strength of the WRC was 38.0, compared with 34.8% for the PLC while at 112 days the ratio was 41.4 against 39.1%, respectively. Some of this is because the compressive strength of the WRC mortar is lower, therefore this represents a matrix that is more flexure tolerant, not stronger.

Table 7. Flexural strength of mortar prisms.

Age (days)	PLC (MPa)	WRC (MPa)	Ratio PLC (%)	Ratio WRC (%)
7	2.52 ± 0.07	2.57 ± 0.11	33.8	32.4
14	3.02 ± 0.46	2.85 ± 0.05	35.7	34.2
28	3.23 ± 0.06	3.31 ± 0.05	34.8	38.0
56	3.51 ± 0.05	3.63 ± 0.01	36.1	39.9
112	3.78 ± 0.04	3.85 ± 0.06	39.1	41.4

Ratio = flexural / compressive strength at the same age.

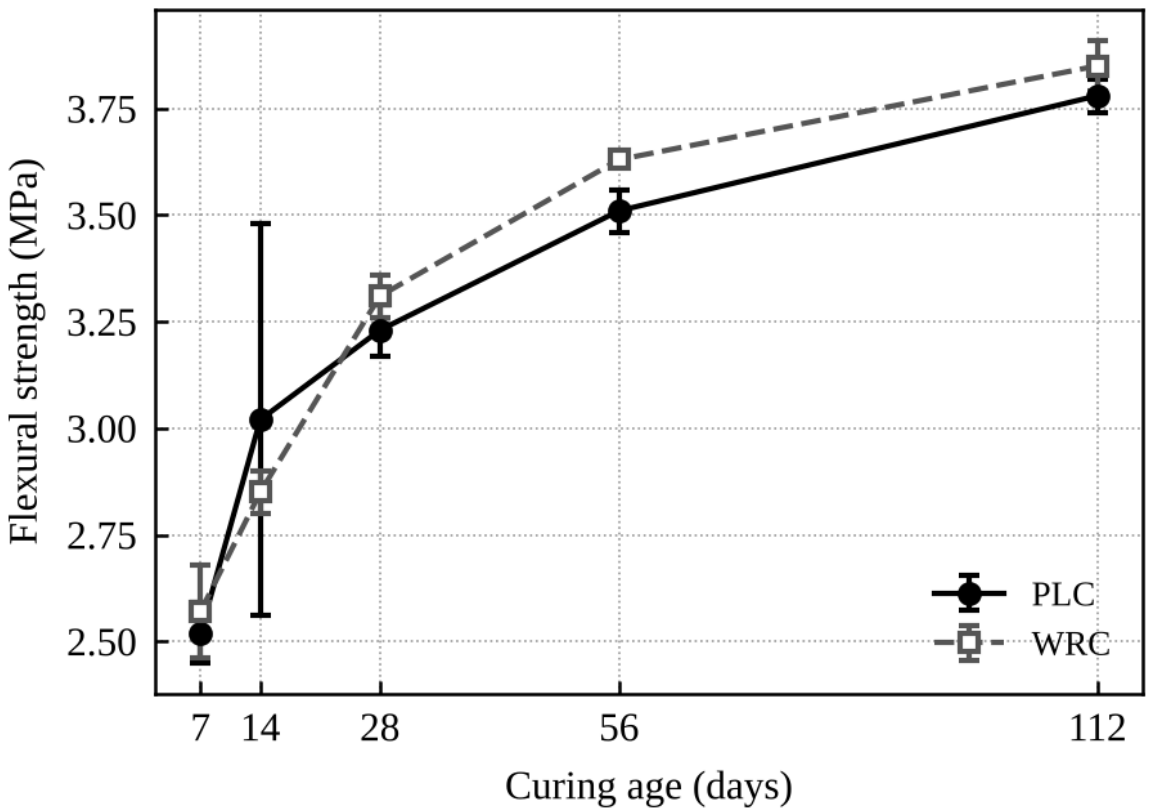


Figure 3. Flexural strength development of mortar prisms (error bars: SD).

3.6 Strength development with age

In concrete, WRC gained more strength early (40.8% against 36.9% from 7 to 28 days) and PLC more later (14.7% against 12.7% from 28 to 112 days), so total gains converged to 57.0% and 58.7% (Table 8). The advantage of PLC in mortar cubes was countered at 28 days while flexural strength of prisms showed very similar behaviour for both cements. The concretes had gained 85-96% of their strength

after 28 days, whilst the mortar cubes and prisms had gained 87.2-88.7% of their strength. It is therefore reasonable to assume that the usual 28-day criterion reflects much but not all of the strength gained during continuous water curing and testing at 56 and 112 days will supply additional knowledge.

Table 8. Strength gain between curing ages (%).

Property	Interval (d)	PLC	WRC
Concrete, compr.	7–28	36.9	40.8
Concrete, compr.	28–112	14.7	12.7
Mortar, compr.	7–28	24.3	10.0
Mortar, compr.	28–112	4.3	6.7
Mortar, flexural	7–28	28.2	28.8
Mortar, flexural	28–112	17.0	16.3

The study is limited to a single brand of each cement, one source of each aggregate, three specimens per condition and laboratory curing to 112 days. The cements were not analysed, so the differences cannot be attributed to a specific mechanism.

4 Conclusion

Different composites exhibit different effects of the water-resistant cement. In concrete it resulted in a slight reduction in workability (slump 8.2 % smaller) but with an increase in the strength at all ages (1.7 – 5 %); thus the water resistance was provided without compromising strength. In mortar, PLC tended to be stronger in compression from 28 days (by up to 6.6%) while WRC was equal or slightly higher in flexure. This implies that 85–96% of 112-day strength are obtained at 28-day time, so that 28-day strength gives the maximum value of stresses reached in continuous curing.

Aggregate characterisation indicates the importance of reporting grading in such studies; the sand was found to be medium and almost wastely graded (FM 2.79, Cu 6.5, Cc 0.98) while the single sized granite (19–25mm) led to gap-graded and limited packing packing characteristics. Where a single size course aggregate is being used, an intermediate should be used, and where high workability is required with WRC, trial mixing is recommended. Several brands, mixing of intermediate aggregate size, and various workability and longer curing regimens with admixtures, should be tested in further work.

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