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Investigations of Chemical and Physical Properties of White Cement Concrete

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To address questions concerning the behavior and performance of white cement concrete, a research program was designed to conduct comparative studies of type I gray and white portland cements. Different properties of cement paste and cement mortar, made with the two different cements, were measured and compared. Test results indicated shorter setting time of white cement paste and greater ultimate tensile and compressive strength for its mortars than the corresponding values for the gray cement.

Results of tests on samples of fresh concrete indicated greater slump and shorter times of initial and final set of mixes prepared with the white cement. Tests conducted on samples of hardened concrete indicated greater ultimate compressive strength of the white cement cylinders. Finally, full-scale companion reinforced concrete beams, identical except for the type of cement, were designed to fail in shear or in flexure. Test results indicated no difference that could be attributed to the type of cement used. Advanced Cement Based Materials 1995, 2, 161–167

KEY WORDS: Beam tests, Compression tests, Portland cement, Time of set, Tricalcium aluminate (C_3A), White cement

Different types of portland cement are manufactured to meet various normal physical and chemical requirements for specific purposes. In 1983, 87% of the total cement shipments in the United States belonged to the ASTM types I and II portland cements, 3.2% to the ASTM type III, 0.6% to the ASTM type IV, and the rest to special cements [1]. Special cements include oil-well cement, masonry cement, expansive cement, high-alumina cement, and white cement.

Cement color reflects chemical composition and processing conditions. Cement colors can vary widely, with shades of lighter or darker gray being common and more rarely shades of brown or buff. The common gray and brownish colors of commercial cements are primarily due to the iron compounds in them and the burning and quenching of the clinker. Small quantities of other transition metals like manganese, chromium, and vanadium also affect the color.

White cement is often used in architectural concrete, both precast and cast-in-place. Applications include precast curtain walls and facing panels, terrazzo surfaces, stucco, cement paint, tile grout, and decorative concrete. It is especially suitable for exposed aggregate finishes and for making colored cements with pigment additions. White cement is a portland cement typically made to conform to the specifications of ASTM C150 for type I or type III cements, but the manufacturing process is controlled so that the finished product is white in color. This is achieved by a careful selection of raw materials containing negligible amounts of iron oxide (not more than 0.5% by weight) and manganese oxide, the substances that give cement its gray color [2]. Suitable raw materials are chalks and limestones having low iron contents and white iron-free clay (kaolinite or china clay) [3,4]. Bauxite (aluminum oxide) is often needed to achieve the required alumina content. As the iron oxide acts as a flux in the burning process, sodium aluminum fluoride (cryolite) is sometimes added to perform this function in the manufacturing process of white cement. Moreover, oil fuel is often used in place of pulverized coal in the burning process to avoid contamination by coal ash. Special ball mills must be used to prevent iron contamination during the process of grinding the cement clinker. The higher cost of raw materials and changes in manufacturing procedures make the price of white cement considerably higher than that of ordinary portland cement. In 1983,

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white cement made up 0.35% of the total cement production in the United States [1].

Objective

The properties of portland cements are governed by the fineness of grinding and by the relative proportions of four principal chemical compounds that make up around 90% of cement by weight. The compounds are tricalcium silicate (C_3S), dicalcium silicate (C_2S), tricalcium aluminate (C_3A), and tetracalcium aluminoferrite (C_4AF). White portland cement is a type I or type III cement with a high tricalcium aluminate content and almost no tetracalcium aluminoferrite. The general impression is that certain white cements are usually not quite as strong as ordinary portland cements [3]. The objective of the research program reported in this paper was to conduct comparative studies of type I gray and white portland cements to assess the effect of white cement on concrete properties. Type III gray cement was not included in the study because its fineness was found to be much greater than the other two cements. The white cement used in the study is typical of white cements used in the Middle East region. Samples of the type I gray and white cements used throughout the research program were purchased from a cement plant in Chekka, North Lebanon, and conform to the specifications of ASTM C150.

Chemical Composition

A routine chemical analysis was performed by the manufacturer on samples of the gray and white cements to determine the proportions of the major oxides. Results are listed in Table 1. The white cement used has more silicon dioxide and calcium oxide than the type I cement. The percent by weight of ferric oxide in the white cement is 0.25 as compared with 3.0 in the gray cement. It is primary due to the presence of iron that portland cement derives its characteristic gray color [2].

The potential compound compositions of the two cements were computed using the Bogue equations [5]. Results are shown in Table 2. The silicates, C_3S and C_2S, play the dominant role in the strength development of portland cement. The total percentage of the silicates is 71 in the gray cement and 79 in the white cement. Also, the white cement has a much higher percentage of C_2S than the gray cement (30.5 compared with 18.8). Therefore, it is expected that concretes made with the white cement will have higher late-age strength. Although similar reaction products (calcium silicate hydrate and calcium hydroxide) are formed upon hydration of both calcium silicates, stoichiometric calculations show that using an optimum water:cement ratio the hydration of C_3S would produce 61% calcium silicate hydrate and 39% calcium hydroxide, whereas the hydration of C_2S would produce 82% calcium silicate hydrate and 18% calcium hydroxide. Therefore, it is expected that the ultimate strength of a high-C_2S portland cement would be greater than a high-C_3S cement (more $C_3S_2H_3$ or C-S-H and less calcium hydroxide, which may be strength-limiting because of its tendency to cleave under shear) [4,6]. The percentage of the ferrite compound C_4AF is 9.1 in the gray cement and only 0.8 in the white cement. The C_4AF compound is comparatively inactive and contributes little to the strength or heat of hydration of cement.

TABLE 1. Chemical analysis

Oxide	Percent by Weight	
	Gray	White
Silicon dioxide (SiO_2)	20.3	23.4
Aluminum oxide (Al_2O_3)	6.0	5.2
Ferric oxide (Fe_2O_3	3.0	0.25
Calcium oxide (CaO)	63.5	65.8
Magnesium oxide (MgO)	1.8	0.5
Sulfur trioxide (SO_3)	2.6	2.2
Sodium oxide (Na_2O)	0.2	0.1
Potassium oxide (K_2O)	0.6	0.5
Calcium oxide (free)	0.5	0.5

TABLE 2. Potential compound composition

Compound	Abbreviation	Percent by Weight	
		Gray	White
$3CaO.SiO_2$	C_3S	52.2	48.5
$2CaO.SiO_2$	C_2S	18.8	30.5
$3CaO.Al_2O_3$	C_3A	10.8	13.4
$4Cao.Al_2O_3.Fe_2O_3$	C_4AF	9.1	0.8

Tests on Cement, Cement Paste, and Cement Mortar

Two standard ASTM tests, namely the density and fineness of hydraulic cement, were carried out on the two types of cement (see Table 3). Density values were 3.15 g/cm^3 for the gray cement and 3.14 g/cm^3 for the white cement. The two values are very close and within the range set by ASTM C150 (3.05 to 3.2 g/cm^3). The average fineness of the gray cement was 3,900 cm^2/g and the white cement was 3,400 cm^2/g. The values are within the ASTM range (2000–6000 cm^2/g). The gray cement that was used was finer than the white cement by around 15%.

Tests were conducted on cement pastes made with the two cements to determine and compare normal consistency, time of setting, and soundness. Results are listed in Table 3. Normal consistencies of the gray and white cements were 24% and 24.6%, respectively. Results indicate no effect of the cement type on normal consistency. The initial setting time for the white cement paste was shorter than that for the gray cement. This is due to the larger C_3A (the most reactive compound) content and much smaller C_4AF (the least reactive compound) content in the white cement. Unsoundness due to excessive free lime was determined using Le Chatelier accelerated test procedure. An amount of expansion in excess of 10 mm as measured by Le Chatelier's test indicates unsoundness. Measured values for the gray and white cement pastes were small (0.45 and 1.1 mm, respectively) indicating very small percentages of free lime in both cement types (0.5%).

Compressive and tensile strength tests were conducted on hydraulic cement mortars prepared with the two types of cement at three ages: 3, 7, and 28 days. The tensile tests were made on mortar briquets, and the compression tests were performed on cube specimens. Results are shown in Table 4. The 3-day tensile and compression strengths were greater for the white cement mortars than the gray cement mortars. This is due to the greater percentage of C_3A in the white cement. The difference was more pronounced for the compression tests (43%) than the tensile tests (12%). The 7-day mortar tensile and compressive strengths were comparable for both cement types. At 28 days, the white cement mortars showed 7% greater tensile strength and 25% greater compression strength than the gray cement mortars. This is basically due to the higher percentage of C_2S and the higher total percentage of the silicates in the white cement.

Tests on Fresh Concrete

Two companion non-air-entrained concrete mixes, identical except for the type of cement, were prepared for each of three nominal concrete strengths: 20, 40, and 60 MPa (3, 6, and 9 ksi). Batching weights for the three mixes are shown in Table 5. The superplasticizer used to achieve the nominal concrete strengths of 40 and 60 MPa is produced by the German company Fosroc. The product name is Conplast 430, and it satisfies ASTM C494 type F and BS 5075 part 3. The proposed dosage of the producer is 0.6 to 2 L per 100 kg cement.

Tests were conducted to determine and to compare slump, air content, and time of setting of the companion concrete mixes. Test results are shown in Table 6. The slump of the mix made with the gray cement was smaller than the slump of the companion mix made with the coarser white cement for the 20- and 40-MPa (3 and 6 ksi) strength designs. An increase in cement fineness implies larger surface area per unit weight, and hence the cement will react more rapidly with water leading to faster loss of consistency. For the 60-MPa mix design, the use of a high dosage of the superplasticizer (2 L per 100 kg cement) led to a very wet fresh concrete mix regardless of the cement type.

The pressure method was used to determine the amount of entrapped air in fresh concrete. The apparatus used was the Air Entrainment Meter. The air content (entrapped air) was around 2 to 2.5% for all six concrete mixes (see Table 6). The type of cement used and the strength of the mix had no effect on the amount of entrapped air in fresh concrete.

Penetration resistance measurements were performed on mortars sieved from different concrete mixtures to determine and to compare times of initial and final set. Results of tests performed on the two companion concrete mixes for the 20-MPa (3 ksi) strength

TABLE 3. Tests on cement and cement paste

Test	Units	Gray	White
Cement density	g/cm³	3.15	3.14
Cement fineness	cm²/g	3900	3400
Normal consistency	%	24	24.6
Initial set	minutes	166	129
Final set	minutes	250	245
Soundness (Le Chatelier)	mm	0.45	1.1

TABLE 4. Strength tests of cement mortars

Age (days)	Tensile Strength (MPa)		Compressive Strength (MPa)	
	Gray	White	Gray	White
3	1.43	1.60	7.76	11.12
7	1.69	1.76	16.20	15.52
28	1.98	2.11	19.18	24.05

TABLE 5. Concrete mix proportions

Ingredients	Nominal Compression Strength		
	20 MPa	40 MPa	60 MPa
Cement (kg)	294	430	630
Water (kg)	217	205	193
Water:cement ratio	0.74	0.48	0.31
Sand (kg)	730	722	594
Coarse aggregate (kg)	1041	960	1007
Superplasticizer (L/100 kg cement)	—	1	2

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TABLE 6. Tests on fresh concrete

	Nominal Compression Strength					
	20 MPa		40 MPa		60 MPa	
Test	Gray	White	Gray	White	Gray	White
Slump (cm)	5	8.5	15	25	25	25
Air Content (%)	2.33	2.35	2.5	2.1	2.4	2.5
Initial set (minutes)	256	155	189	180	—	—
Final set (minutes)	470	230	279	240	—	—

indicate much shorter initial and final setting times when white cement was the type of cement used (refer to Table 6). The shorter setting times are due to the higher percentage of C_3A, the most reactive compound in cement that affects the course of events during the early stages of the hydration process most significantly. On the other hand, when a superplasticizer was used to achieve a nominal concrete strength of 40 MPa (6 ksi), the setting times were only slightly shorter for the white cement mortars.

Tests on Hardened Concrete

Ten 150 × 300 mm (6 × 12 inch) cylinders were cast from each of the six concrete mixtures according to ASTM C31. At each of five different ages: 1, 3, 7, 14, and 28 days, two cylinders were tested in compression. Results are shown in Figure 1. Each plotted value is the average of two test results. The compressive strength of the white cement concrete cylinders was greater at 1 day and 28 days than the companion gray cement cylinders regardless of the nominal concrete strength and of whether superplasticizers were used or not. For the 1-day age, this is explained by the higher percentage of C_3A in the white cement than in the gray cement (13.4 compared with 10.8). C_3A is the first compound to hydrate and hence it contributes most to the 1-day strength. As for the 28-day age, the greater strength of the white cement concrete cylinders is attributed to the higher percentage of the total silicates (79 compared with 71 in the gray cement) and the higher percentage of dicalcium silicate (30.5 compared with 18.8 in the gray cement), leading to more C-S-H

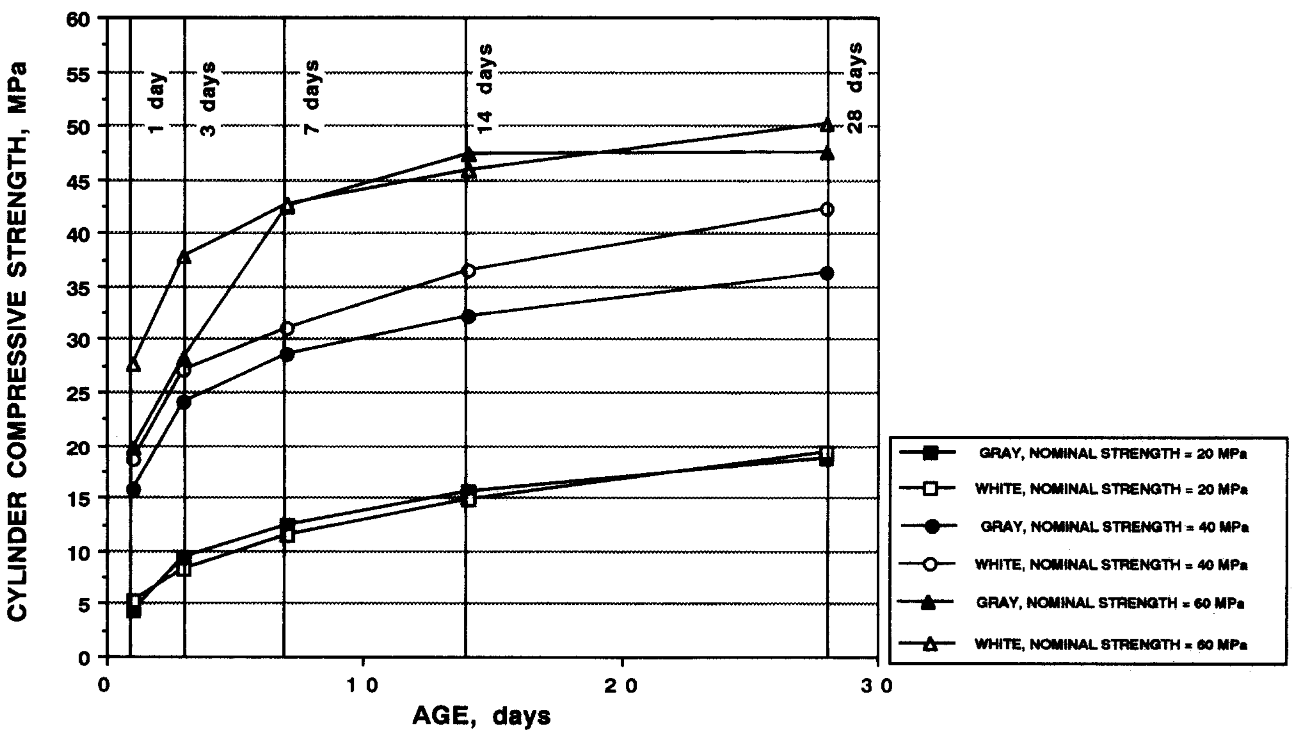

FIGURE 1. Variation of cylinder compressive strength with age.

TABLE 7. Tensile strength tests at 28 days

Nominal Compression Strength (MPa)	Type of Cement	Splitting Tensile Strength (MPa)	Flexural Strength (MPa)
20	Gray	2.10	3.20
	White	1.81	3.28
40	Gray	2.71	5.72
	White	2.61	5.83
60	Gray	3.34	7.44
	White	2.97	8.26

and less calcium hydroxide in the white cement concrete.

The compressive strength at the intermediate early ages of 3, 7, and 14 days was greater by around 10% for the gray cement concrete cylinders than for the companion white cement cylinders when the nominal concrete strength was 20 MPa. However, the intermediate early age strength was around 10% greater for the white cement cylinders when the nominal strength was 40 MPa (6 ksi). When the nominal strength was 60 MPa (9 ksi), the compressive strengths at 3, 7, and 14

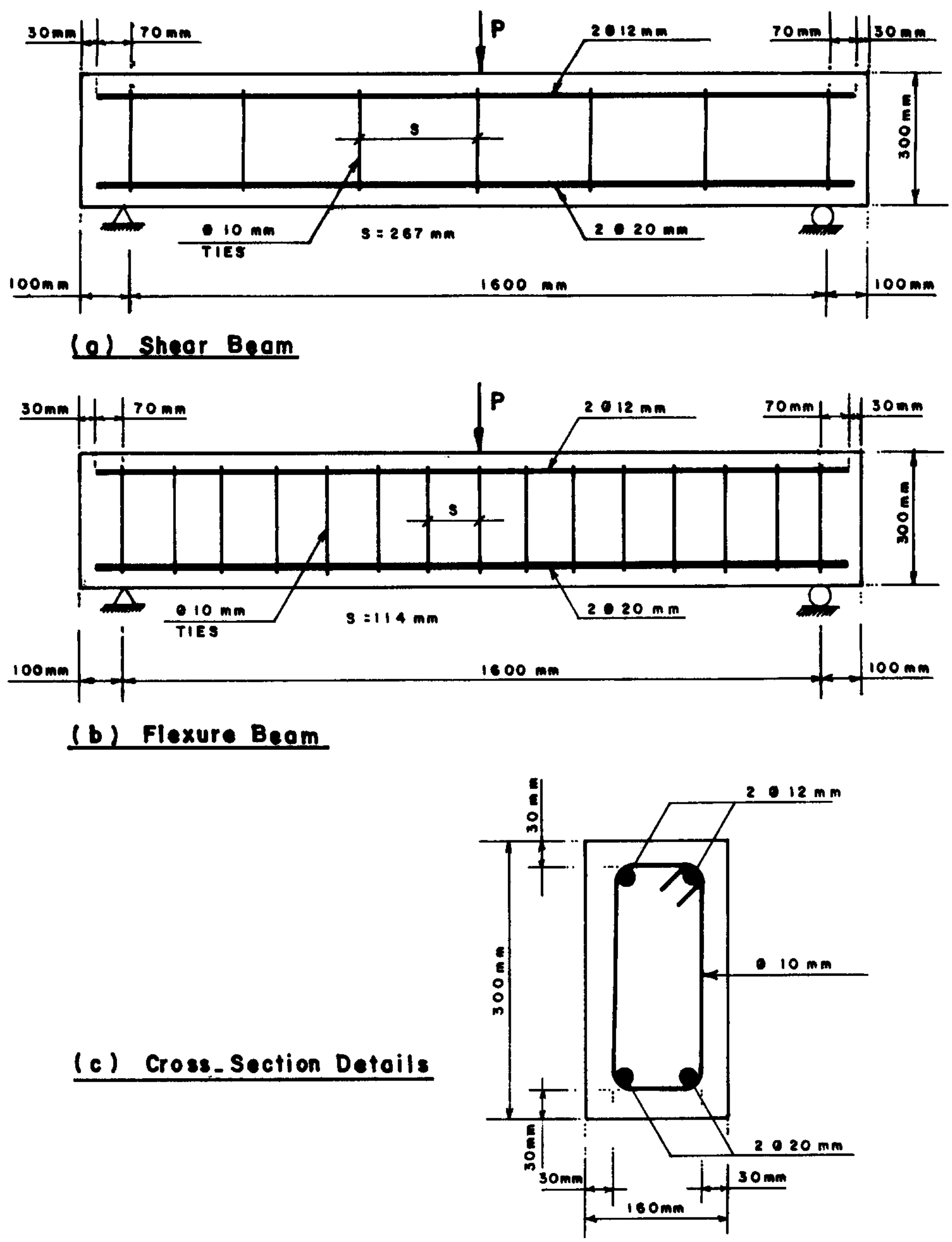

FIGURE 2. Details of the beam specimens.

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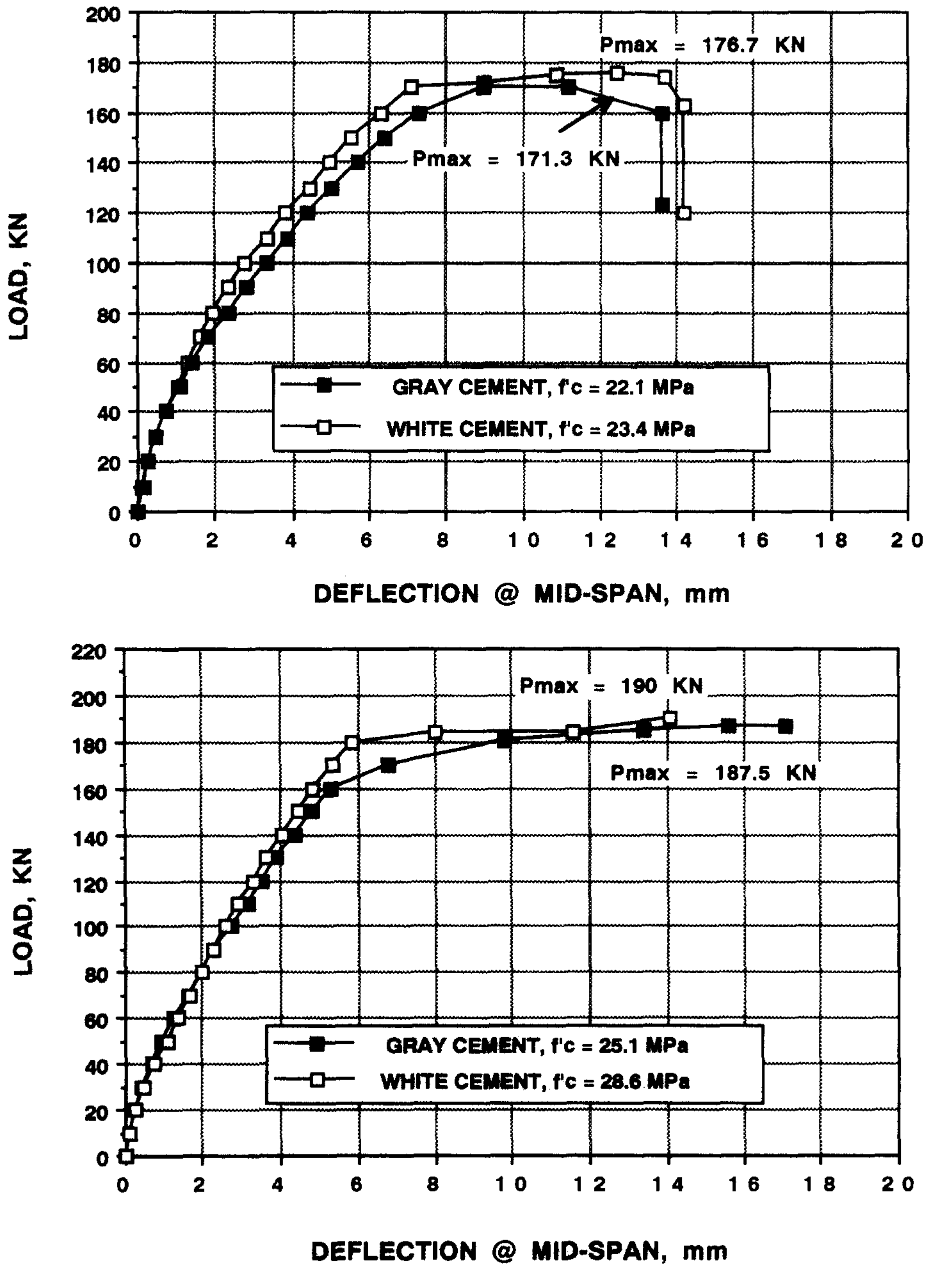

FIGURE 3. Load-deflection curves for the beam specimens.

days of the gray and the companion white cement cylinders were comparable.

For each of the three nominal concrete strengths considered, two 150 × 300 mm (6 × 12 inch) cylinders and two 150 × 150 × 500 mm (6 × 6 × 20 inch) beams for each cement type were tested at 28 days to determine the average splitting tensile strength and the average third-point flexure strength, respectively. Test results are shown in Table 7. The splitting tensile strength of the gray cement cylinders was slightly greater than the companion white cement cylinders. On the other hand, the flexural strength of the white cement beams, which is the more generally used index of tensile strength, was slightly greater than the companion gray cement beams for the three nominal concrete strengths. It could be concluded that the type of cement studied had no major effect on the measured tensile strength of concrete.

Tests on Reinforced Concrete Beams

To study the effect of white cement on the structural behavior of reinforced concrete members, two companion beam specimens, one prepared with the gray cement and the other with the white cement, were designed and detailed to fail in flexure. The beams are referred to as the "flexure beams." Two more companion beams, referred to as the "shear beams," were designed to fail in shear. All beams were tested in positive bending. The loading system consisted of a single concentrated load applied at midspan of a simply supported beam. The beams were 1800-mm (71 inches) long, 160-mm (6.3 inches) wide, and 300-mm (11.8 inches) deep. Reinforcement of all four beams was identical except for the spacing of the hoop stirrups. All bars met ASTM A615/A615M-90 [7] and were grade 60 with parallel (bamboo) deformation pattern. Details of the beams are shown in Figure 2. The concrete mix was designed to provide a nominal compressive strength of 24 MPa (3.5 ksi).

Testing was done after 28 days. Load was gradually applied at midspan of the beam in 10-kN (2.25 kips) increments. At each load stage, deflection readings were taken and flexural cracks were marked. In the shear beams, yielding occurred followed shortly by a sudden drop in the load associated with the formation of a larger shear crack extending from near the support and propagating diagonally along the beam web into the compression zone near the location of the concentrated load. In the flexure beams, yielding occurred followed by more random formation of flexural cracks and the extension of already formed cracks toward the compression zone. Load was halted when flexural cracks near the location of the concentrated load widened and propagated into the compression zone.

Load-deflection curves of companion beams, shown in Figure 3, are almost identical regardless of the mode of failure considered. The small difference in stiffness or maximum load reached is due to the difference in the ultimate concrete compressive strength. The white cement beam developed greater ultimate concrete compressive strength than the companion gray cement beam for reasons discussed before. If the load-deflection curves of companion beams are normalized at a common concrete strength, then the curves will be almost identical.

It could be concluded that there was no difference in the behavior, crack pattern, stiffness, or load-deflection history of companion beams, identical except for the type of cement (gray or white), that could be attributed to the type of cement used.

Conclusion

It could be concluded that no adverse effects on the characteristics of cement paste, cement mortar, portland cement concrete, or reinforced concrete members could be attributed to the chemical composition of the white cement used. The general impression, reported in the literature, that white cement is not quite as strong as ordinary portland cement was not supported by results of this study. On the contrary, results of the various strength tests conducted on the white cement and the gray cement used in the study proved that the ultimate compression strength was greater when white cement was used due to its greater C_2S and total silicate (C_3S + C_2S) percentages. The relatively higher percentage of C_3A in the white cement led to higher early rate of hydration and early strength gain of white cement concrete members. White cement concrete should be protected by proper curing procedures in the first few days after casting to avoid excessive drying shrinkage cracks. Finally, it is important to note that the test results reported in this paper are specific to the white cement used.

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