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PROPERTIES OF HIGH-STRENGTH CONCRETE USING A FINE FLY ASH

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ABSTRACT

A Class F fine fly ash (FFA) with a fineness of 99% passing a 45 μm sieve was used to produce workable high-strength concrete. Six mixtures were cast with total cementitious contents of 400 and 500 kg/m^3. The replacement of cement by FFA, on equal mass basis, was 0, 10, and 15%. The mixtures were tested for workability and strength. Drying shrinkage and water absorption characteristics were determined as indicative of durability. The slump varied between 45 to 110 mm and fluid/cementitious ratio varied between 0.25 to 0.38.

The optimum cement replacement for both 400 and 500 kg total cementitious material mixtures was 10%. The 28-day maximum strength for the two optimum mixtures was 94 and 111 MPa with a slump of 45 and 85 mm, respectively. The indirect tensile strength of the two concretes was only 5 and 6% of their compressive strength, respectively. The 2 h water penetration of the two concretes was comparatively low, 11 and 13mm, respectively. The drying shrinkage of all the six concretes were very similar with a maximum value of 470 microstrain after 56 days of standard exposure. The 28-day modulus of elasticity of all the concretes varied between 40–46 GPa. *© 1998 Elsevier Science Ltd*

Introduction

A judicious use of supplementary cementitious materials (SCMs) and superplasticisers (SPs) is responsible for the production of very-high-strength concrete (VHSC) and high-performance concrete (HPC) (1–5). It has been possible to produce concrete mixtures in laboratory conditions using both SCMs and SPs that exceed 180 MPa (1). The inplace strength in some tall buildings has attained a compressive strength of approximately 125 MPa (6). Amongst other stringent requirements for the production of HSC, the use of SCMs and SPs is mandatory.

The SCMs most often used in the production of HSC are: fly ash (FA), ground granulated blast furnace slag (GGBFS), and condensed silica fume (CSF). These SCMs are either pozzolanic or both pozzolanic and self-cementitious to a degree. Fortunately, most of these SCMs are industrial by-products, so their utilization not only produces technically very

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TABLE 1
Characteristics of FFA, FA, SF, and cement.

Chemical	Chemical analysis (%)			
	FFA	FA	CSF	GPC
SiO_2	70.3	51.8	93	21.4
Al_2O_3	24.8	24.4	0.6	4.5
Fe_2O_3	1.08	9.62	1.0	3.0
CaO	0.08	4.37	0.2	64.4
MgO	0.15	1.5	1.2	1.4
Na_2O	0.09	0.34	0.1	
K_2O	0.38	1.41	1.0	0.7
SO_3	0.01	0.26	0.3	2.4
LOI	0.2		0.5	0.9
Specific gravity	2.12	2.13	2.10	3.16
Bulk density (kg/m^3)	800–1200	1000–12000	180–250	1100–1600
Specific surface area (m^2/kg)	1720	1230		930

superior concrete but also both preserves and enhances the environment. Of the three main SCMs, CSF is the most effective and the costliest. The main reason of its effectiveness is due to the enormousness of its specific surface and the smallness of the mean particle size. Since FA is abundantly available and CSF is comparatively in short supply, it is surmised that the use of a finer grade fly ash may be more effective than a typical FA and less costly than CSF.

The main objective of this study was to explore the possibilities of producing VHSC and HPC using a Class F Fine Fly Ash (FFA) with a fineness of 99% passing a 45-μm sieve. Accordingly, six mixtures were cast with a total cementitious content of 400 and 500 kg/m^3. This study presents the characterization of these concretes.

Experimental Details

Materials

General purpose Portland cement similar to ASTM Type I, complying with Australian Standard and a Class F fine fly ash with 99%, passing through a 45-μm sieve were used in concrete making. The chemical composition and some of the physical characteristics of these materials along with CSF and a typical FA are given in Table 1.

The specific surface area of FFA, FA, and General purpose Portland Cement (GPC) was evaluated by Pozzolanic Industries, Ltd. using Malvern Mastersizer equipment. This method uses density and particle size distribution data to calculate the specific surface. Accordingly, these values seem to be more than twice those given by the Blaine Method. The values included in Table 1, however, do establish that the fine fly ash used in this investigation is much finer than those of the normal fly ashes often used in concrete making.

TABLE 2
Mix design of concrete (quantities/m^3, SSD basis).

Material	Mix designation					
	400–0	400–10	400–15	500–0	500–10	500–15
Cement (kg)	400	360	340	500	450	425
FFA (kg)	0	40	60	0	50	75
Water (l)	146.4	137.2	150.9	178.4	115.3	133.6
Superplasticizers (l)	6.0	6.0	6.0	7.5	7.5	7.5
Coarse Aggregate (kg)	1113.4	1084.1	1069.4	1011.8	976.1	957.7
Fine Aggregate (kg)	761.1	741.2	730.9	691.6	666.9	655.0

Mix Proportioning and Concrete Cast

To limit the number of mixes to six it was decided to use total cementitious material contents of 400 and 500 kg/m^3 of concrete and to replace cement by FFA on equal weight basis by 0, 10, and 15%. For all the concretes made, a proprietary superplasticizer was used at a dosage of 1.5 l per 100 kg of the total cementitious materials. The coarse aggregate used was 10 mm crushed granite with a sand/total aggregate ratio of 0.4. The mix quantities used, on SSD basis, are included in Table 2. The mixture designation used was CC-FFA, where CC is the total cementitious contents and FFA is the fine fly ash percent of the total cementitious contents.

The slump value, air content and density of all fresh mixtures were determined and are included in Table 3. In order to achieve a desired slump of about 100 mm and a good cohesive concrete mixture the following modified mixing procedure was adopted.

The solid concrete ingredients were added in the pan mixer with about one half of the mixing water and it was mixed for about 90 s. The superplasticizer was then added to the mix followed by the incremental addition of water until the desired slump was achieved. Thorough mixing of all ingredients was ensured.

The specimens cast from each mix consisted of sixteen 100-mm cubes, twelve 100 ×

TABLE 3
Characteristics of fresh concrete.

Mix designation	w/c	Air content (%)	Density (kg/m^3)	Slump (mm)
400-0	0.38	1.20	2390	130
400-10	0.35	1.00	2390	45
400-15	0.36	0.90	2385	collapse
500-0	0.37	0.80	2410	110
500-10	0.25	0.80	2420	85
500-15	0.28	1.10	2420	110

TABLE 4
Characteristics of the hardened concrete.

Mix designation	Compressive strength (MPa)				Modulus of elasticity (GPa)		28-Day indirect tensile strength (MPa)	2-h Water penetration (mm)
	7 Day	14 Day	28 Day	56 Day	28 Day	56 Day		
400-0	62.0	70.5	77.5		40.1	41.8	4.6	15
400-10	70.0	77.5	94.0	99.5	43.1	45.1	4.7	11
400-15	58.0	65.0	73.5		39.8	41.5	4.1	12
500-0	69.0	75.0	92.5	106.0	43.8	45.5	5.4	18
500-10	84.0	93.5	111.0	121.5	45.8	49.2	6.2	13
500-15	75.5	89.0	102.0	113.5	45.6	48.2	5.5	15

200-mm cylinders, four 150 × 300-mm cylinders, four 75 × 75 × 285-mm shrinkage prisms, and a 150 × 475 × 475-mm slab.

Specimen Conditioning and Testing

After casting, the specimens were stored for 24 h in the laboratory environment (20 ± 2°C and 80 ± 5% relative humidity (RH)) and then demoulded and stored in a fog room (at 21 ± 2° and 95 + 3% RH). The specimens cast for the shrinkage tests were transferred to the control room (23 + 2° and 40 ± 5% RH) after 7 days of initial fog curing.

The compressive strength of the cubes was determined after 7, 14, 28, and 56 days of fog curing. The strength results included in Table 4 are the average value of 4 specimens. The indirect tensile strength was evaluated using 100 × 200 mm cylinders after 28 days of fog curing. The modulus of elasticity was determined on 150 × 300-mm cylinders after 28 and 56 days of fog curing and the results included in Table 4 are the average of 2 specimens.

The sorptivity or water penetration test was conducted using 150 × 475 × 475-mm slabs that were cured in the fog room for 56 days. Prior to being placed in the water tank, each of the slabs was air dried. The test involved placing the slabs into a water tank with their bottom 10 mm soaking in water. The slabs were left there for 2 h and then removed. Measurements were taken over a cross section of the slab to determine the depth of water rise. This test measures the rate of absorption of water by capillary suction of unsaturated concrete placed in contact with water; no head of water exists. The results are, to a degree, indicative of durability of a concrete (7). The results are included in Table 4.

Drying shrinkage was monitored on initially 7 day fog cured prisms and subsequently stored in a control room. Readings were taken at 7, 14, 21, 28, and 56 days of drying on four samples per mixture. The average value of the shrinkage of the six concretes is plotted in Figure 1.

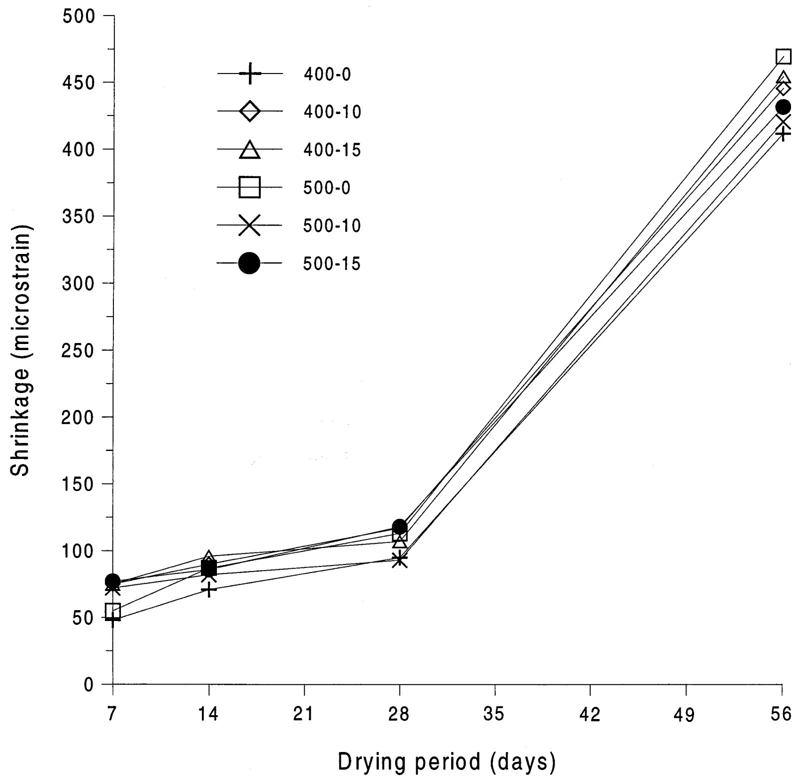

FIG. 1.
Drying shrinkage of the concretes tested.

Results and Discussions

Characteristics of the Fresh Concrete

The characteristics of the fresh concrete are included in Table 3. To produce workable and cohesive concretes of approximately 100 mm slump, mixtures containing no FFA (see 400–0 and 500–0, Table 3), achieved at a w/c ratio of about 0.38. Whilst in the 400 series concrete only a nominal reduction in w/c ratio resulted by the introduction of FFA, in the 500 series concrete a reduction of about 0.11 was obtained for a comparable workability (slump) (see Table 3). This can be attributed to the fineness and hence the reduction in interparticle friction due to the presence of FFA. The results also suggest that a 10% replacement of cement by the FFA was optimal in the two series of concrete tested. Beyond 10% replacement, the overall increase in the specific surface of the cementitious materials seems to more than offset the ball-bearing effect of the FFA. This effect is similar to that of a CSF (8).

Loss in slump due to ongoing hydration is a common feature in all types of concrete (9–10). However, 500–15 mixture lost its workability very rapidly. The 400–10 and 500–10 also lost their workability comparatively quickly. The results suggest that for field applications a rapid loss in slump should be allowed for and the FFA dosage should be limited to no more than 10%.

Most mixtures gave entrapped air content of about 1%, which is also indicative of ease of compactibility of these concretes. The variation in the wet density of the six mixtures cast is nominal, and the wet density can be approximated to 2400 kg/m^3. The air dry density of these concretes was also monitored; it was very similar to the corresponding wet density, and accordingly these values have not been reported here. The values included in Table 3 are an average of four measurements.

Characteristics of Hardened Concrete

Compressive Strength. All of the six concretes are high strength (HS), as even the 7-day compressive strength varies between about 60 to 84 MPa. The 28-day strength varies between 74 to 111 MPa. Again, consistent with water/cementitious ratio and the optimum addition of 10% FFA for workability (as discussed in the previous section), this optimum value holds for strength development as well. Accordingly, in both the 400 and 500 series of concrete 10% replacement of cement with FFA resulted in the highest 28-day strength of 94 and 111 MPa, respectively. At 56 days the two strengths were about 100 and 122 MPa respectively (see Table 4). At 28 days, with both the 400 and 500 series of concretes, 10% replacement of cement with FFA resulted in about 20% increase in strength. Accordingly, the use of FFA is not only technically superior in terms of producing HS and VHS concrete, but is environment enhancing as well.

Indirect Tensile Strength. The tensile/compressive strength ratio of concrete depends on the general level of the compressive strength; the higher the compressive strength, the lower the ratio (9–10). The ratio of the indirect tensile strength and the cube compressive strength for the two highest strength concretes (400–10 and 500–10) is 5 and 6%, respectively (see Table 4). The direct tensile/compressive strength ratio for medium strength concrete is reported to be between 8–9% (10). The expression given in Australian Concrete Structures (11) of

$$f'_{ct} = 0.4\sqrt{f'_c}$$

where f'_c is the cylinder strength of concrete and f'_{ct} is the indirect tensile strength, underestimates the indirect tensile strength of the two optimal strength concrete even when values of cube strength were used in the above expression. According to the above expression the calculated strengths are 3.85 and 4.20 MPa respectively.

A 10% replacement of cement by FFA in the 500–10 concrete increased the tensile strength by 15% although the corresponding increase in the 400–10 concrete was only 2%.

Modulus of Elasticity. The modulus of elasticity of the concretes determined both at 28 and 56 days are included in Table 4. The modulus of the two optimised concretes is also the highest; 43.1 and 45.8 GPA, respectively.

The modulus of elasticity of concrete is known to increase with an increase in the compressive strength, but there is no agreement on the precise form of relationship as the modulus of concrete is affected by the modulus of elasticity of the aggregate and the volumetric proportion of aggregate in the concrete (9). Of course, the increase in the modulus of elasticity of concrete is progressively lower than the increase in compressive strength. Using the expression of

$$E = \rho^{1.5}\left(0.043\sqrt{f'_c}\right)$$

where ρ is the density of concrete, as given in Australian concrete Structures (11), the 28-day calculated value of the modulus of the two optimised concrete is 48.7 and 54 GPa, respectively. These calculated values overestimate the values obtained by actual testing (see Table 4). Of course, f'_c in the above expression is the cylinder strength, whereas the values included in Table 4 and used in calculating the above numerical values are that of cube strength. Accordingly, the following expression recommended by the British standard for the structural use of concrete (12) was also used to calculate the modulus of elasticity of the concrete:

$$E_c = 1.7\rho^2 f_{cu}^{0.33} \times 10^{-6}\text{GPa}$$

The above formula gave the modulus values of 42.9 and 47.1 GPa for the 400–10 and 500–10 concretes, respectively. As can be seen in Table 4, these values are almost identical to the experimentally determined values. Likewise, the modulus values of 40.8 and 44 GPa of 400–0 and 500–0 concretes are almost equal to those determined in the laboratory.

On an average, where the use of 10% FFA has increased the compressive strength by 15 and 20% in 400 and 500 series of concretes, the increase in the modulus value is 7%. This corroborates that the rate of increase in the modulus is lower than that in the compressive strength of concrete (9–10).

Water Sorptivity. The 2-h water sorptivity of the two optimised concretes after 56 days of curing is very similar, 11 and 13 mm, respectively (see Table 4). The compressive strength of these two concretes at 56 days is about 100 and 122 MPa (Table 4). According to the compressive strength, the sorptivity of the 500–10 concrete should have been less than 11 mm. However, the stiffness of the higher strength concrete is also high, 49.2 GPa. Probably, while the slabs were air drying before being placed in the water tank, there could have been more microcracking in the higher strength-higher stiffness slab that resulted in a marginally higher value of the water sorptivity.

The water penetrability of the slabs containing FFA is lower than those slabs without FFA (Table 4). On the average, the water penetrability of the two optimised concretes is 28% less than the corresponding plain concrete. In this regard, the FFA seems to act like CSF. CSF reduces the permeability of the transition zone around the aggregate particles as well as the permeability of the bulk cement paste. The influence of CSF on permeability is much greater than on compressive strength (13).

Drying Shrinkage. The drying shrinkage of all the six concretes is very similar with a maximum value of 470 microstrain after 56 days of standard exposure (see Fig. 1). In the 400 series concrete, replacement of cement very marginally increased the drying shrinkage while in the 500 series, there was a nominal decrease. Most specifications allow drying shrinkage performance in the range of 600–800 microstrain at 56 days (14). Accordingly, the drying shrinkage characteristics of these HSCs is excellent. From this point of view, these concretes are considered within the high performance category.

Conclusions

1. At 10% replacement of cement by the FFA, it was possible to reduce the mixing water by 35% to produce a concrete of similar workability with a total cementitious contents of 500 kg/m^3. However, the corresponding reduction in a 400 series concrete was only 6%. The optimum level of cement replacement was found to be 10%. At 15% cement replacement there was a rapid reduction in the workability of the concrete.
2. The concretes with 10% FFA exhibited higher early strength followed by an excellent development of strength over time. The 28-day compressive strength of 400–10 and 500–10 concretes were 94 and 111 MPa, respectively. These values represent 20% increase in strength compared to the corresponding concrete without FFA. The addition of FFA also resulted in an increase in both the indirect tensile strength and the modulus of elasticity values.
3. The water penetrability of the two optimised concretes was about 28% less than the corresponding plain concretes. These results suggest that the proper use of the FFA can produce both high strength and high performance concrete.
4. The drying shrinkages of all the six concretes were very similar with a maximum value of 470 microstrain after 56 days of standard exposure. Again, the use of FFA in 500 series concrete resulted in a nominal reduction in shrinkage strain. As regards shrinkage performance, these concretes are high performance.

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