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Effect of Fly Ash on the Durability Properties of High Strength Concrete

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Abstract

Utilization of fly ash as a supplementary cementitious material adds sustainability to concrete by reducing the CO_2 emission of cement production. The positive effects of fly ash as a partial replacement of cement on the durability of concrete are recognized through numerous researches; however, the extent of improvement depends on the properties of fly ash. In this study, durability properties of high strength concrete utilizing high volume Class F fly ash sourced from Western Australia have been investigated. Concrete mixtures with fly ash as 30% and 40% of total binder were used to cast the test specimens. The compressive strength, drying shrinkage, sorptivity and rapid chloride permeability of the fly ash and control concrete specimens were determined. The 28-day compressive strength of the concrete mixtures varied from 65 to 85 MPa. The fly ash concrete samples showed less drying shrinkage than the control concrete samples when designed for the same 28-day compressive strength of the control concrete. Inclusion of fly ash reduced sorptivity and chloride ion permeation significantly at 28 days and reduced further at 6 months. In general, incorporation of fly ash as partial replacement of cement improved the durability properties of concrete.

Keywords: Chloride permeability, drying shrinkage, durability, fly ash, sorptivity

1. Introduction

Concrete is the most widely used construction material in the modern world. The durability of concrete is a major consideration in its application in aggressive environments for a long service life. Concrete incorporates large amount of natural resources as aggregates and cement with water. Cement production consumes huge energy and causes about 7% of total green house gas emission in the world (Malhotra 2002).

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Hence, utilization of supplementary cementitious materials such as fly ash, slag and silica fume is being researched extensively over the last few decades to enhance durability and sustainability of concrete. Fly ash is a by-product of the combustion of pulverised coal and is a pozzolanic material. When it is mixed with Portland cement and water, it generates a product similar to that formed by cement hydration but having a denser microstructure that is less permeable. The fly ash replacement level as 15 - 25% is recommended for high strength concrete (ACI Committee 211 2008), while it can be used as more than 50% of total binder for normal strength concrete (Carette et al. 1993).

Canada Center for Mineral and Energy Technology (CANMET) is the pioneer in the research on high-volume of Fly ash concrete. Numerous reports showed the concrete having high volume of Class F fly ash exhibited excellent mechanical and durability properties such as low permeability to chloride ions and other aggressive agents (Langley et al. 1989; Mathotra 1990). Cao et al. (1996) reported fly ash concretes yielding better result in chloride diffusion and sulphate attack than OPC concrete. Fly ash in concrete reduces drying shrinkage (Atis 2003), thus generates fewer cracks which ensure greater resistance to deterioration. Chindaprasirt et al. (2004) found reduced drying shrinkage of mortars using fly ashes of different fineness. Though the drying shrinkage is influenced by many factors, the results indicated that the water to cement ratio was the prime factor. By replacing up to 45% class F fly ash, reduced pore diameter and porosity of concrete were observed at 28 days, whereas fly ash-cement paste revealed increased porosity (Poon et al. 2000). Papadakis (1999) observed increased porosity when Class F fly ash replaced cement and decreased porosity when fly ash replaced aggregate in mortar.

Naik et al. (1994) tested concretes with up to 70% Class C fly ash and obtained reduced air and water permeability of fly ash concretes at 91 days. Tasdemir (2003) found higher sorptivity coefficient for fly ash incorporated concrete as compared to normal concrete at early age adding fly class C ash as 10% of cement and using a water to binder (w/b) ratio of 0.60. However, Camoes et al. (2003) obtained reduced sorptivity coefficient by using w/b ratio in the range of 0.25-0.40 and Class F fly ash content of as high as 60% of the total binder.

Thus it is established that application of fly ash in concrete can enhance durability features, but the extent of improvement is dependent on the mix proportioning and the properties of fly ash. This study has focused on the drying shrinkage, water sorptivity and chloride ion penetration of high strength concrete containing Class F fly ash sourced from Western Australia. Concrete containing 30% and 40% fly ash have been investigated and compared with those of ordinary Portland cement (OPC) concrete.

2. Experimental Details

2.1. Materials

Table 1: Composition of cement and fly ash

Parameter	SiO_2	Al_2O_3	Fe_2O_3	$SiO_2+Al_2O_3+Fe_2O_3$	CaO	MgO	SO_3	K_2O	Na_2O	P_2O_5	Chloride	Loss on ignition
Cement (%)	21.10	4.70	2.70	28.50	63.60	2.60	2.50	-	0.50	-	0.01	2.00
Fly ash (%)	50.50	26.57	13.77	90.84	2.13	1.54	0.41	0.77	0.45	1.00	-	0.60
Class F fly ash* (%)	-	-	-	70.00 min	10.00 max	-	5.00 max	-	-	-	-	6.00 max

*ASTM C 618 specification.

The materials used in this study were those commercially available in Western Australia. A General Purpose (GP) Portland cement conforming to Standards Australia (AS 3972) and Class F (ASTM C 618) fly ash sourced from Western Australia were used. The compositions of these materials are shown in Table 1. The aggregates were natural sand and crushed granite. A naphthalene-based superplasticiser was used in addition to normal tap water to enhance workability.

2.2. Mixture proportions

Two series of concrete mixtures were designed in accordance with the ACI 211.4R-08 Guide, each series comprising of a control mixture and two mixtures with fly ash as 30% and 40% of the total binder (cement + fly ash). The mixture series A was designed to achieve similar 28-day compressive strength with varying total binder content and varying water-binder (w/b) ratio. The mixture series (B) was designed with a constant w/b ratio and total binder content. The mixture proportions and the measured slumps of the different batches of concrete are shown in Table 2.

Table 2: Concrete mixture proportions (kg/m^3)

Series	Mix ID	Binder			Aggregate		Water (kg/m^3)	Superplasticiser (kg/m^3)	w/b	Slump (mm)
		Fly ash (%)	Cement (kg/m^3)	Fly ash (kg/m^3)	Granite (kg/m^3)	Sand (kg/m^3)				
A	A-00	0	355	0	1185	740	145.5	5.11	0.41	140
	A-30	30	308	132	1185	661	141.0	4.77	0.32	170
	A-40	40	264	176	1185	665	136.5	4.75	0.31	185
B	B-00	0	517	0	1185	594	150	6.77	0.29	150
	B-30	30	362	155	1185	570	150	4.80	0.29	175
	B-40	40	311	207	1185	561	150	4.24	0.29	160

2.3. Casting and preparation of test specimens

The concrete was mixed in a laboratory pan mixer. Concrete cylinders of 100 mm diameter and 200 mm height were cast for compressive strength, sorptivity and rapid chloride permeability tests. For dying shrinkage test, prisms of 75 × 75 × 280 mm size were cast with studs placed at two ends exactly at 250 mm. The samples were demoulded at 24 hours after casting and then cured under water at 23^{o}C for up to 28 days of age. Specific specimens were prepared from these cylinders during an actual test in accordance with the specification for the particular test.

3. Test Methods

Durability of concrete depends on its resistance to ingress of aggressive agents through the pores. The effect of fly ash on the durability of concrete was investigated by using the drying shrinkage, water sorptivity and chloride ion permeability properties.

3.1. Compressive strength and drying shrinkage

The compressive strength was evaluated by tests performed on cylindrical specimens (100 X 200 mm) at the ages of 3, 7, 28, 56, 91 and 210 days. Drying shrinkage of each mixture was measured as per the AS 1012.13 Standard. The specimens were removed from moulds 24 hours after casting and then cured under water until the 7th day when the initial length was recorded. The samples were left for drying in the laboratory air (23^{o}C) and length change was recorded up to six months of age.

3.2. Sorptivity

The sorptivity test measures capillary suction of concrete when it comes in contact with water. The sorptivity test was performed in accordance with the ASTM C 1585 Standard. Samples were cured under water for 28 days and tested at 28 days and 180 days of age. Two specimens were prepared by cutting at the depth of 50 mm from the top of two separate cylinders. The specimens were oven dried until constant weight and then put in contact with water in one surface and sealing the other surfaces. Mass gain due to sorption was measured at definite intervals for the first six hours. The rate of sorption is the slope of the best-fit line to the plot of absorption against square root of time.

3.3. Rapid chloride permeability

Chloride permeability was measured in accordance with the ASTM C1202-07 Standard at the age of 28 days and 180 days. The 50-mm thick specimens were sliced from the top of the cylinders. The water saturated specimens were subjected to 60 volt electric potential for 6 hours. The chloride penetration of the specimens was expressed as the total charge passed in coulomb during the test period. This is used as an indicative parameter of the chloride permeability of concrete.

4. Results and Discussion

4.1. Compressive strength

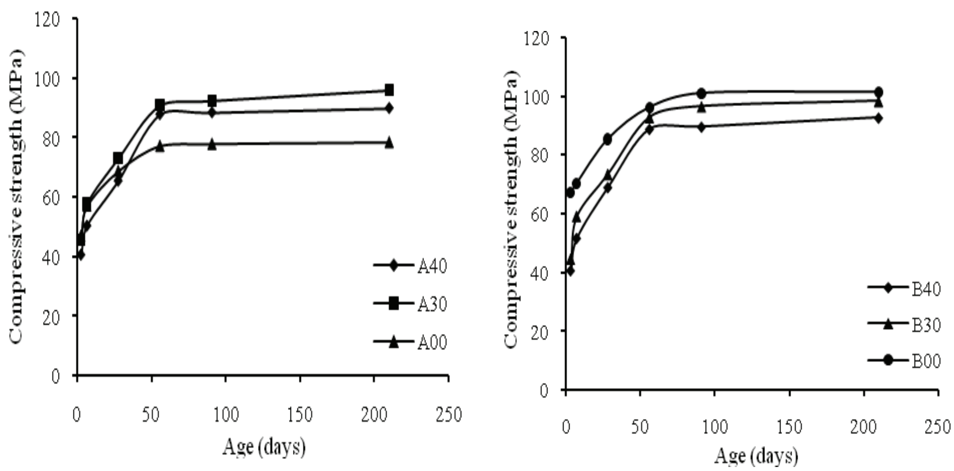

Fig. 1 Compressive strength development in Series A (left) and Series B (right).

The compressive strength developments of the concrete mixtures are shown in Fig. 1. The results indicate that incorporation of fly ash in concrete decreased strength at the earlier age as compared to the control concrete. However, they either gained more strength (series A) or reached very close to control concrete's strength (series B) at a later age. Concretes with 30% fly ash have shown higher strength gain than those with 40% fly ash. The strength of fly ash concretes in both series developed at a higher rate than that of control concrete until 56 days. The strength increase after 56 days of age is very small in all the mixtures.

In Series A, the fly ash concrete gained similar strength of control concrete at 28 days. At 56 days, both the fly ash concretes gained more than 110% strength of control concrete. It implies the notable strength development capability of fly ash concrete due to pozzolanic reaction after 28 days.

Strengths of the fly ash concretes in Series B were less than that of the control concrete because the w/b ratio and total binder content were same in all the mixtures. However, fly ash concretes achieved over 80% of control concrete's strength at 28 days. They reached 92% and 96% of control concrete's strength at 56 days, for 40% and 30% fly ash content respectively. The trends of the strength development of the fly ash concretes are similar to those reported in literature (Siddique 2004).

4.2. Drying shrinkage

The effect of incorporation of fly ash on drying shrinkage of concrete is shown in Fig. 2. It can be seen from this figure that most of the shrinkage took place within 56 days after casting the specimens. Fly ash concretes have shown less drying shrinkage than control concrete when they were designed with variable w/b ratio and variable total binder content to achieve similar 28 days compressive strength (Series A). Shrinkage was similar for the fly ash concretes and the control concrete of Series A up to 21 days. After this age, the rate of shrinkage decreased for fly ash concretes to reach a value 10% lower than that of control concrete at 56 days. At 180 days, the concrete containing 40% fly ash (A40) achieved slightly lower shrinkage than the concrete containing 30% fly ash (A30).

In Series B, shrinkage values of the fly ash concretes (B30 and B40) were higher than that of the control concrete (B00) until 28 days. After that, the rate of shrinkage decreased for fly ash concretes and reached a value similar to that of the control concrete at 56 days. Concrete with 30% fly ash showed less shrinkage than that with 40% fly ash. The shrinkage values of both of the fly ash concretes were very close (within 4%) to that of control concrete up to 180 days.

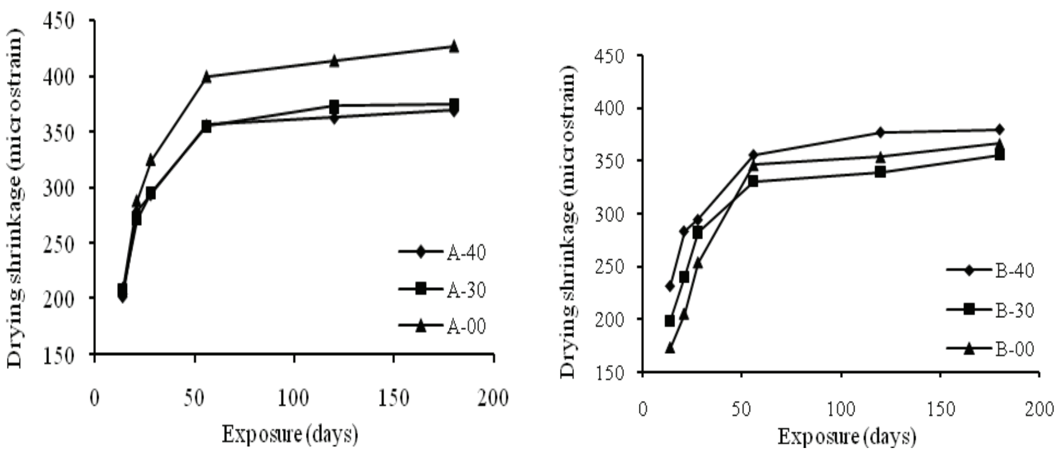

Fig. 2 Effect of fly ash on drying shrinkage in series A (left) and series B (right).

4.3. Sorptivity

The sorptivity test results are shown in Table 3 and Fig. 3. It can be seen that, incorporation of fly ash resulted in less sorption than that of the control concrete in both series. Similar results were reported by Camoes et al. (2003). The sorptivity coefficients of fly ash concretes are less than 129.1 mm/s$^{1/2}$, which is considered as 'very good' performance of concrete (Papworth and Grace 1985). At 28 days of age, fly ash concretes showed less sorptivity than the control concrete. After 180 days, there was further decrease in sorptivity of both the control and the fly ash concretes. Sorptivity values of the fly ash concretes were less than that of the control concrete at 180 days. The sorptivity decreased with the increase of fly ash content.

Concretes in Series A, that achieved similar strength at 28 days, have shown significant reduction of capillary suction due to inclusion of fly ash. At 28 days, concrete with 40% fly ash showed higher sorption as compared to concrete with 30% fly ash. However, after 180 days, sorptivity dropped by 25% and 37% of the control concrete's value for 30% and 40% fly ash concrete respectively.

On the other hand, in Series B, inclusion of fly ash with constant w/b ratio and total binder content has decreased absorption slightly. For 30% and 40% fly ash replacement, sorptivity at 28 days reduced by 6% and 20% of that of control concrete respectively. The rate of sorptivity of fly ash concrete tends to be similar to that of control concrete over the age up to 180 days.

Table 3: Sorptivity and rapid chloride permeability test results.

Mix ID	Sorptivity coefficient (X 10^{-4} mm/s$^{1/2}$)		Chloride permeability (Coulomb)	
	28 days	180 days	28 days	180 days
A00	174.0	140.0	2722.0	1652.5
A30	107.0	105.3	1757.5	573.0
A40	125.8	87.1	1493.0	489.0
B00	138.3	107.5	2070.5	910.0
B30	128.8	106.2	1881.0	466.0
B40	108.1	100.3	1574.0	566.5

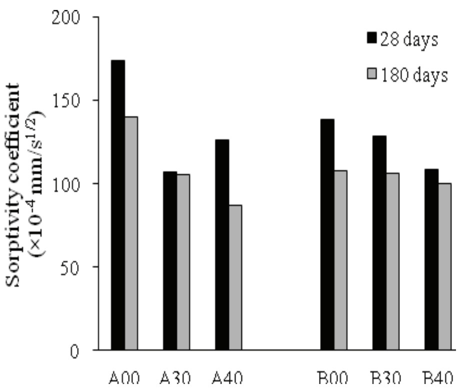

Fig. 3 Comparison of sorptivity coefficients.

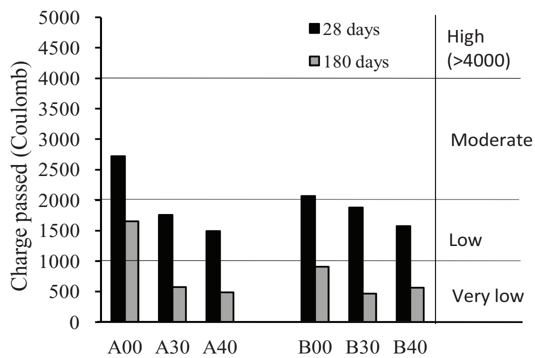

Fig. 4 Chloride permeability results.

4.4. Chloride permeability

The total charge passed in the rapid chloride permeability test (RCPT) indicates the chloride ion (Cl^-) penetration through the concrete. The total charge passed through the specimens of different mixtures of concrete at 28 days and 180 days of age are shown in Fig. 4. The fly ash concretes have shown better resistance at both the ages. Penetrability of Cl^- reduced with the increase of fly ash in the mixtures. At 28 days of age, fly ash concretes achieved 'Low' level of Cl^- penetration in contrast to the 'Moderate' level of the corresponding control concretes. At 180 days, the Cl^- penetration level decreased to 'Very Low' for the fly ash concretes. The Cl^- penetration values of the fly ash concretes are less than those of the corresponding control concretes at this age.

The fly ash concretes in Series A resulted in 35% to 45% reduced Cl^- permeability to that of control concrete at 28 days which further reduced as 65% to 70% in 180 days. Resistance to chloride penetration increased with the increase in fly ash content from 30% to 40% of total binder.

On the other hand, for concretes of Series B, inclusion of fly ash reduced Cl^- permeability up to 24% at 28 days which further reduced up to 48% at 180 days. The concrete with 40% fly ash has shown slightly higher Cl^- penetrability than that with 30% fly ash at 180 days. However, they both were in the range of 'very low' value of charge passed.

5. Conclusions

Six mixtures of high strength concrete were investigated to evaluate the effect of 30% and 40% Class F fly ash content on some durability properties of concretes until 180 days of age. The following conclusions are drawn from the test results:

- The 28-day strength dropped when cement was partially replaced with fly ash without adjustment in the w/b ratio. However, high strength concrete with 28-day compressive strength of 60 MPa could be obtained with w/b ratio of 0.31 and with 40% fly ash. The compressive strength reached more than 80 MPa at 56 days. Strength development of the fly ash concretes continued noticeably up to 56 days.
- Fly ash in concrete decreased drying shrinkage when the w/b ratio and the binder content were adjusted to achieve the same 28-day strength of the control concrete.
- Incorporation of fly ash reduced the sorptivity of concrete in early age and it decreased further at six months.
- The fly ash concretes yielded better resistance to chloride ion penetration both at 28 and 180 days. Thus, it is possible to design high strength concrete of reduced permeability by including up to 40% Class F fly ash in the total binder.

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