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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 ofconcrete.

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 consumeshugeenergyandcausesabout7%oftotalgreenhousegasemissionintheworld(Malhotra2002).

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 ashisaby-productofthecombustionofpulverisedcoalandisapozzolanicmaterial.Whenitismixedwith Portland cement and water, it generates a product similar to that formed by cement hydration but having a densermicrostructurethatislesspermeable.Theflyashreplacementlevelas15-25%isrecommendedfor highstrengthconcrete(ACICommittee2112008),whileitcanbeusedasmorethan50%oftotalb inderfor normal strength concrete (Carette et al.1993).

Canada Center for Mineral and Energy Technology (CANMET) is the pioneer in the research on high-volumeofFlyashconcrete.NumerousreportsshowedtheconcretehavinghighvolumeofClass Ffly 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 differentfineness.Thoughthedryingshrinkageisinfluencedbymanyfactors,theresultsindicat edthatthe 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 inmortar.

Naik et al. (1994) tested concretes with up to 70% Class C fly ash and obtained reduced air and water permeabilityofflyashconcretesat91days.Tasdemir(2003)foundhighersorptivitycoefficient forflyash incorporatedconcreteascomparedtonormalconcreteatearlyageaddingflyclassCashas10%o fcement andusingawatertobinder(w/b)ratioof0.60.However,Camoesetal.(2003)obtainedreducedso rptivity coefficientbyusingw/bratiointherangeof0.25-0.40andClassFflyashcontentofashighas60%ofthe totalbinder.

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 containingClassFflyashsourcedfromWesternAustralia.Concretecontaining30%and40%fl yashhave been investigated and compared with those of ordinary Portland cement (OPC)concrete.

2. ExperimentalDetails

Materials

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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 flyash* (%)	-	-	-	70.00 min	10.00 max	- 0	5.0 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. Theaggregateswerenaturalsandandcrushedgranite.Anaphthalene-basedsuperplasticiserwasusedin addition to normal tap water to enhanceworkability.

Mixtureproportions

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+flyash).ThemixtureseriesAwasdesignedtoachievesimilar28-daycompressivestrengthwith varyingtotalbindercontentandvaryingwater-binder(w/b)ratio.Themixtureseries(B)wasdesignedwith 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 Table2.

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

Series	Mix ID	Fly ash (%)	Binder		Aggregate		Water (kg/m^3)	Superplasticiser (kg/m^3)	w/b	Slump (mm)
			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

Casting and preparation of testspecimens

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 shrinkagetest,prismsof75×75×280mmsizewerecastwithstudsplacedattwoendsexactlyat250mm. Thesamplesweredemouldedat24hoursaftercastingandthencuredunderwaterat23^{o}Cforupto 28days ofage.Specificspecimenswerepreparedfromthesecylindersduringanactualtestinaccordancewiththe specification for the particulartest.

3. TestMethods

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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.

Compressive strength and dryingshrinkage

Thecompressivestrengthwasevaluatedbytestsperformedoncylindricalspecimens(100y200mm)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 curedunder

water until the 7^{th} 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.

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 waterfor28daysandtestedat28daysand180daysofage.Twospecimenswerepreparedbycuttingatthe 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 oftime.

Rapid chloridepermeability

ChloridepermeabilitywasmeasuredinaccordancewiththeASTMC1202-07Standardattheageof28 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 thespecimenswasexpressedasthetotalchargepassedincoulombduringthetestperiod.Thisisusedasan indicative parameter of the chloride permeability ofconcrete.

4. Results andDiscussion

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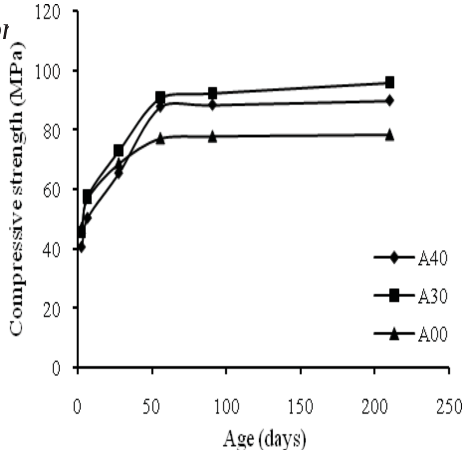

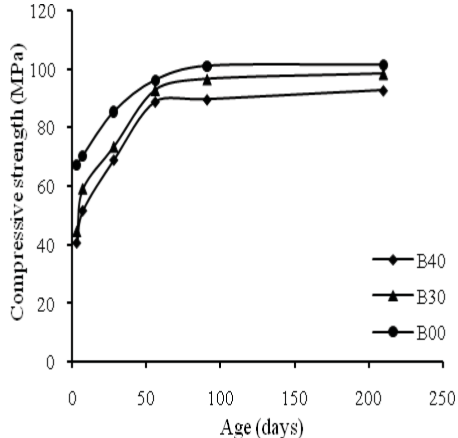

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Fig. 1 Compressive strength development in Series A (left) and Series B (right).

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 thanthosewith40%flyash.Thestrengthofflyashconcretesinbothseriesdevelopedatahigherra tethan that of control concrete until 56 days. The strength increase after 56 days of age is very small in all the mixtures.

InSeriesA,theflyashconcretegainedsimilarstrengthofcontrolconcreteat28days.At56day s,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 28days.

StrengthsoftheflyashconcretesinSeriesBwerelessthanthatofthecontrolconcretebecauset hew/b ratioandtotalbindercontentweresameinallthemixtures.However,flyashconcretesachieved over80% 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 (Siddique2004).

Dryingshrinkage

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). ShrinkagewassimilarfortheflyashconcretesandthecontrolconcreteofSeriesAupto21days.A fterthis 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).

InSeriesB,shrinkagevaluesoftheflyashconcretes(B30andB40)werehigherthanthatofthec ontrol 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 w

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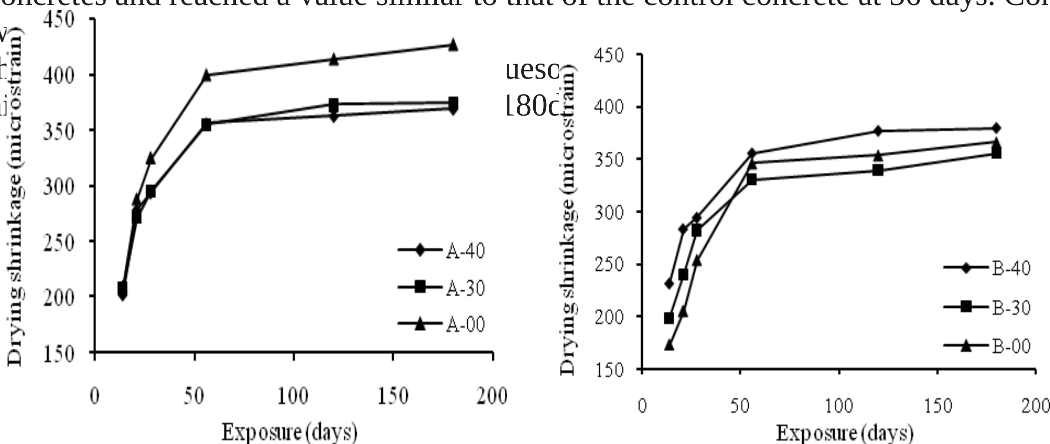

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Fig. 2 Effect of fly ash on drying shrinkage in series A (left) and series B (right).

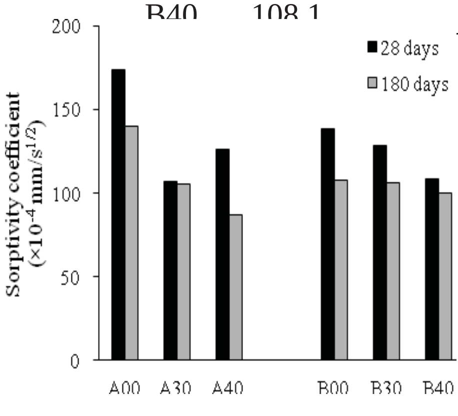
Sorptivity

ThesorptivitytestresultsareshowninTable3andFig.3.Itcanbeseenthat,incorporationoffly ash resultedinlesssorptionthanthatofthecontrolconcreteinbothseries.Similarresultswerereport edbyCamoes et al. (2003). The sorptivity coefficients of fly ash concretes are less than 129.1 mm/s$^{1/2}$,whichisconsidered as ‘very good’ performance of concrete (Papworth and Grace 1985). At 28 days of age,flyashconcretesshowedlesssorptivitythanthecontrolconcrete.After180days,therewasf urtherdecreasein sorptivityofboththecontrolandtheflyashconcretes.Sorptivityvaluesoftheflyashconcretesw erelessthanthatofthecontrolconcreteat180days.Thesorptivitydecreasedwiththeincreaseoff lyashcontent. ConcretesinSeriesA,thatachievedsimilarstrengthat28days,haveshownsignificantreductio nof capillarysuctionduetoinclusionofflyash.At28days,concretewith40%flyashshowedhighers orptionascomparedtoconcretewith30%flyash.However,after180days,sorptivitydroppedb y25%and37%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



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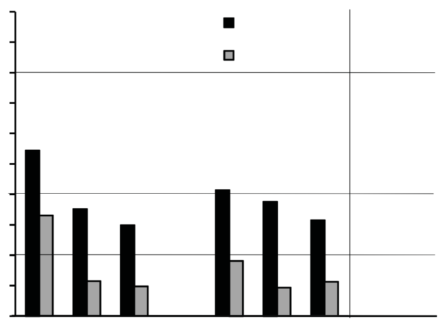

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Fig. 3 Comparison ofsorptivitycoefficients. Fig. 4 Chloride permeabilityresults.

Chloridepermeability

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 daysofage,flyashconcretesachieved‘Low’levelofCl^- penetrationincontrasttothe‘Moderate’levelof thecorrespondingcontrolconcretes.At180days,theCl^- penetrationleveldecreasedto'VeryLow'forthe flyashconcretes.TheCl^- penetrationvaluesoftheflyashconcretesarelessthanthoseofthecorresponding control concretes at thisage.

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 flyashcontentonsomedurabilitypropertiesofconcretesuntil180daysofage.Thefollowingconclusions are drawn from the testresults:

- The 28-day strength dropped when cement was partially replaced with fly ash without adjustment in thew/bratio.However,highstrengthconcretewith28-daycompressivestrengthof60MPacouldbe 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 controlconcrete.
- 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,itispossibletodesignhighstrengthconcreteofreducedpermeabilitybyincludingupto 40% Class F fly ash in the total binder.

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