EARLY-AGE TENSILE STRENGTH OF CONCRETE CONTAINING LOW-CALCIUM FLY ASH AS PARTIAL REPLACEMENT OF CEMENT

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ABSTRACT

The benefits of using fly ash include improvements of the durability and sustainability features of concrete. However, the slow strength development of low-calcium fly ash concrete at the early ages is viewed as a drawback in applications such as tilt-up, precast and prestressed concrete structures, where specified early-age strength is required. This study investigated the development of the early-age tensile strength of concrete containing locally available low-calcium fly ash. Fifteen concrete mixtures containing fly ash from 0 to 40% of the binder were designed. The 3-day compressive strength varied from 22 to 51 MPa (3 to7.4 ksi). The splitting tensile strengths at 3 and 28 days were calculated from the compressive strengths using the AS3600, ACI 318 and the EC2 Codes. The test-prediction ratios of splitting tensile strengths show that the early-age tensile strength correlated well with the compressive strengths. No effect of the early age or inclusion of fly ash was observed on the test-prediction ratios. This suggests that the Code equations based on the compressive strength can be used for designs related to early-age tensile strength of concrete containing up to 40% of low-calcium fly ash.

Keywords: Early-age strength, Compressive strength, Low-calcium fly ash, Splitting tensile strength.

INTRODUCTION

Fly ash is a by-product material from the coal-fired thermal power plants. It has been used in concrete for many years. Using fly ash in concrete is beneficial both economically and environmentally. The use of fly ash in concrete has benefits to both fresh and hardened stages when correctly proportioned. In plastic state, it can reduce bleeding and segregation while enhancing workability. In the hardened state, it can increase ultimate strength and improve durability by reducing drying shrinkage, permeability, heat of hydration, and creep[1-3]. Production of cement is involved in emission of CO_2 which is the major green house gas. Thus, partial replacement of cement with fly ash has the benefit of reduction of green house gas emission of concrete[4]. Therefore, the use of fly ash helps improvement of the sustainability feature of concrete.

Typically, strength gain of low-calcium (Class F) fly ash concrete is slower than that of high-calcium fly ash (Class C). The early-age properties of concrete are important for applications such as tilt-up panels, precast and prestressed concrete members. Failure by sticking of tilt-up panels may occur at construction sites because of the low tensile strength of concrete at the lifting time. Compressive strength of concrete is usually used in the specifications while the tensile strength is considered as a simple function of the compressive strength of concrete. The design Codes and Standards recommend simple relationships between the compressive and tensile strength of concrete, where a correlation between tensile strength and compressive strength is used. Most of these relationships are based on the 28-day compressive strength of concrete. The development of tensile strength of concrete with time depends on various factors such as the type of cement, mixture proportions, and the curing and drying conditions[5, 6]. Also, the inclusion of fly ash in the binder may have considerable effect on the early-age tensile strength development[7]. Thus, the suitability of using a simple compressive strength-based relationship for calculating early-age tensile strength of concrete containing low-calcium fly ash needs to be evaluated.

The objective of this investigation is to evaluate the early-age tensile strength development of concrete containing low-calcium fly ash at the replacement rates of 10% to 40% of the binder. The compressive and tensile strengths were determined at 3 and 28 days of age. The concrete mixtures with different percentages of fly ash were designed to give a range of early-age compressive strengths applicable for structures such as tilt-up, precast and prestressed concrete structures. The relationship between tensile and compressive strengths contained in the Australian Standard (AS 3600)[8], ACI Code 318[9] and the Eurocode 2 (EC 2)[5] are used to calculate the splitting tensile strengths of 3 and 28 days of age. The calculated values were compared with the experimental splitting tensile strengths to find if the correlation between the tensile strength and compressive strength of concrete containing low-calcium fly ash at 3 days varies from that at 28 days of age.

EXPERIMENTAL WORK

Experimental work was carried out in the laboratory to determine the compressive and splitting tensile strengths of concrete containing fly ash as 0%, 10%, 20%, 30% and 40% of the total binder. Cement replacements at these percentages were used considering the very low calcium content of the fly ash and the requirement for relatively high early-age strengths.

MATERIALS AND MIXTURE PROPORTIONS

The concrete used to make the test specimens was mixed in the laboratory. The type of cement was general purpose Portland cement with a specific surface area of 412 m^2/kg. The fly ash used was a Class F (ASTM 618)[10] and fine grade fly ash commercially available in Western Australia. The percentage of the fly ash passing through a 45 μ sieve was 75%. The chemical compositions of the cement and fly ash are given in Table 1. The coarse aggregates were 7, 10 and 20 mm nominal size crushed stone. They were prepared to saturated surface dry (SSD) condition before mixing the concrete. The sand used was river sand. Tap water was used in mixing the concretes.

Three control mixes of concrete without fly ash, and 12 mixes containing fly ash at 10%, 20%, 30% and 40% of the total binder, were used to cast the test specimens. The mixture proportions of the three series of mixtures (A, B and C) are given in Table 2. The control mixtures are designated as OPCA, OPCB and OPCC. The mixtures of series A with 10, 20, 30 and 40% fly ash of the binder are designated as FA10A, FA20A, FA30A and FA40A respectively. The other mixtures of series B and C are designated in a similar way.

Table 1 Chemical Compositions of Cement and Fly Ash (mass %)

Compounds	SiO_2	Al_2O_3	Fe_2O_3	CaO	Na_2O	K_2O	TiO_2	MgO	P_2O_5	SO_3
Cement	20.4	4.8	2.9	64.2	0.29	-	-	2.0	-	2.4
Fly Ash	50.8	26.9	13.5	2.05	0.33	0.57	1.57	1.33	1.46	0.31

TEST SPECIMENS

Concrete was mixed using a pan type laboratory concrete mixer. Slump tests were carried out to determine the workability of the fresh concrete. The slump values of the mixes of series A and B were between 160 to 190 mm. Superplasticiser was used in the mixtures of series C. The slump values of the mixtures OPCC, FA10C and FAC20C were between 250 and 260 mm. Flow diameters of the mixtures FA30C and FA40C were 560 mm and 535 mm respectively. Standard 100 mm × 200 mm (3.9 in × 3.9 in) cylinders were cast for compressive strength tests and 150 mm × 300 mm (5.9 in × 11.8 in) cylinders were cast for splitting tensile tests. The cylinders were demoulded one day after casting and then cured by immersing in water at 23 ^{0}C. The specimens were tested for compressive and splitting tensile strengths in accordance with the Australian Standards.

Table 2 Mixture Proportions of Concrete (kg / m^3)*

Mixture	Cement	Fly ash	Water	Sand	Coarse aggregate				Superplasticiser
					7mm	10mm	14 mm	20mm	
OPCA	388	-	225	600		582		582	
FA10A	349	39	225	600		582		582	
FA20A	310	78	225	600		582		582	
FA30A	272	116	225	600		582		582	
FA40A	233	155	225	600		582		582	
OPCB	549	-	225	754		425		425	
FA10B	494	55	225	754		425		425	
FA20B	439	110	225	754		425		425	
FA30B	384	165	225	754		425		425	
FA40B	329	220	225	754		425		425	
OPCC	490	-	183	704	507		507		6
FA10C	441	49	183	704	507		507		6
FA20C	392	98	183	704	507		507		6
FA30C	343	147	183	704	507		507		6
FA40C	294	196	183	704	507		507		6

*1 lb / yd^3 = 0.593278 kg / m^3

TEST RESULTS AND DISCUSSION

STRENGTH OF CONCRETE

The average compressive and splitting tensile strengths of the concrete specimens at the ages of 3 and 28 days are given in Table 3. Generally, the differences between the strengths of the fly ash concrete and control concrete were higher at 3 days than at 28 days of age. The 28-day compressive strength of the concretes of series A, B and C were in the ranges of 41 – 49 MPa, 50 – 62 MPa and 52 – 63 MPa respectively. The ranges of the 3-day compressive strengths were 22 – 33 MPa, 31 – 42 MPa and 29 – 51 MPa for series A, B and C respectively. These early-age strengths are considered to be suitable for various applications such as tilt up, precast and prestressed concrete structures, where high early-age strength development is usually required. As expected, the strength gain with age varied depending on the mixture proportions and the percentage of fly ash.

RELATIONSHIP BETWEEN TENSILE AND COMPRESSIVE STRENGTHS

The tensile strength of concrete is usually calculated by using the simple relationships given in terms of the compressive strength. The concrete structures design Codes and Standards recommend such simple equations. The Australian Standard (AS 3600)[8] recommends Equation 1 at 28 days of age and for standard curing of the concrete.

$$f'_{ct} = 0.36\sqrt{f'_c} \qquad (1)$$

Where, f_{ct}' and f_c' are the characteristic uniaxial tensile and compressive strengths respectively. The mean uniaxial tensile strength (f_{ctm}) is obtained by multiplying the characteristic tensile strength by 1.4. The uniaxial tensile strength is taken as 0.9 times the splitting tensile strength ($f_{ct.sp}$) of concrete. The mean compressive strengths corresponding to the characteristic strengths for different grades of concrete are given in the Standard. For 25 to 65 MPa grade concretes, the relationship between the characteristic compressive strength and the mean compressive strength (f_{cm}) is given by Equation 2.

$$f_{cm} = f_c' + 3.0 \text{ (MPa)} \qquad (2)$$

The ACI 318 Code[9] recommends Equation 3 as the approximate relationship between the mean splitting tensile strength and the characteristic compressive strength of concrete. The relationship between the mean and characteristic compressive strengths is given by Equations 4 to 6.

$$f_{ct.sp} = 0.56\sqrt{f_c'} \qquad (3)$$

$$f_{cm} = f_c' + 7.0 \text{ (MPa)} \quad \text{for} \quad f_c' < 21\,MPa \qquad (4)$$

$$f_{cm} = f_c' + 8.3 \text{ (MPa)} \quad \text{for} \quad 21 < f_c' \leq 35\,MPa \qquad (5)$$

$$f_{cm} = 1.10\,f_c' + 5.0 \text{ (MPa)} \quad \text{for} \quad f_c' > 35\,MPa \qquad (6)$$

The Eurocode 2[5] recommends Equation 7 as the relationship between the mean uniaxial tensile strength (f_{ctm}) and the characteristic compressive strength for concrete up to grade 60 MPa. The relationship between the mean and characteristic compressive strengths is given by Equation 8. The uniaxial tensile strength is approximated as 0.9 times the splitting tensile strength of concrete.

$$f_{ctm} = 0.30\; f_c'^{(2/3)} \qquad (7)$$

$$f_{cm} = f_c' + 8.0 \text{ (MPa)} \qquad (8)$$

The calculation of the 3-day splitting tensile strength of the mixture FA20B by the above methods is presented below as an example. The mean compressive strength, f_{cm} = 40 MPa for this mixture.

Australian Standard (AS3600): By using Eq. 2, the characteristic compressive strength, f_c' = 37 MPa. Equation 1 gives characteristic uniaxial tensile strength, f_{ct}' = 2.2 MPa. The Mean uniaxial tensile strength, f_{ctm} = 2.2 × 1.4 = 3.1 MPa and the mean splitting tensile strength, $f_{ct.sp}$ = 3.1 / 0.9 = 3.4 MPa.

American concrete Institute (ACI 318): By using Eq. 5, f_c' = 31.7 MPa and then using Eq. 3, the mean splitting tensile strength, $f_{ct.sp}$ = 3.2 MPa.

Eurocode 2: By using Eq. 8, f_c' = 32 MPa. Use of Eq.7 gives f_{ctm} = 3.0 MPa and the mean splitting tensile strength, $f_{ct.sp}$ = 3.0 / 0.9 = 3.4 MPa.

Table 3 Test and Calculated Strengths

	Average test strengths			Calculated splitting tensile strength, MPa			Ratio of test to calculated splitting tensile strengths		
Mix	Age (days)	Compressive, f_{cm}, MPa*	Splitting tensile, $f_{ct.sp}$, MPa	AS 3600	ACI 318	EC 2	AS 3600	ACI 318	EC 2
OPCA	3	33	3.4	3.1	2.8	2.8	1.10	1.22	1.19
	28	49	4.1	3.8	3.6	4.0	1.07	1.15	1.03
FA10A	3	27	3.3	2.7	2.5	2.3	1.23	1.35	1.43
	28	40	4.4	3.4	3.2	3.4	1.29	1.40	1.31
FA20A	3	28	3.3	2.8	2.5	2.4	1.20	1.31	1.37
	28	46	4.3	3.7	3.4	3.8	1.18	1.27	1.15
FA30A	3	25	3.0	2.7	2.4	2.2	1.15	1.26	1.36
	28	48	4.1	3.8	3.5	3.9	1.09	1.16	1.05
FA40A	3	22	2.9	2.5	2.2	1.9	1.14	1.38	1.48
	28	41	3.9	3.4	3.2	3.4	1.13	1.22	1.14
OPCB	3	38	3.2	3.3	3.1	3.2	0.96	1.04	0.98
	28	60	4.5	4.2	4.0	4.6	1.06	1.13	0.97
FA10B	3	42	3.3	3.5	3.3	3.5	0.94	1.01	0.93
	28	59	4.5	4.2	3.9	4.6	1.06	1.14	0.97
FA20B	3	40	3.5	3.4	3.2	3.4	1.02	1.10	1.03
	28	62	3.8	4.3	4.0	4.8	0.89	0.95	0.81
FA30B	3	31	2.7	2.9	2.6	2.7	0.92	1.03	1.02
	28	53	4.1	3.9	3.7	4.2	1.04	1.11	0.98
FA40B	3	31	2.8	2.9	2.6	2.7	0.93	1.04	1.03
	28	50	3.8	3.8	3.6	4.0	1.00	1.07	0.95
OPCC	3	51	3.7	3.9	3.6	4.1	0.96	1.03	0.91
	28	63	3.6	4.3	4.1	4.8	0.83	0.89	0.75
FA10C	3	49	3.1	3.8	3.5	4.0	0.82	0.88	0.78
	28	61	4.2	4.3	4.0	4.7	0.98	1.05	0.89
FA20C	3	38	3.1	3.3	3.1	3.2	0.92	1.00	0.95
	28	57	3.6	4.1	3.9	4.5	0.88	0.94	0.81
FA30C	3	38	2.9	3.3	3.1	3.2	0.88	0.96	0.91
	28	54	3.8	4.0	3.7	4.3	0.96	1.03	0.90
FA40C	3	29	2.4	2.9	2.5	2.6	0.83	0.92	0.93
	28	52	3.6	3.9	3.7	4.2	0.92	0.98	0.86

*1 ksi = 6.89475 MPa

COMPARISON OF THE TEST AND CALCULATED TENSILE STRENGTHS

The 3-day and 28-day splitting tensile strengths of the concrete specimens of each batch were calculated from the compressive strengths at the corresponding ages by using the equations recommended in the AS 3600[8], ACI 318[9] and the EC 2[5]. The calculated values for each batch of concrete are given in Table 3. The ratios of the test to calculated splitting tensile strengths by these three methods are also given in this Table. The ratios of the test to calculated strengths for the same percentage of fly ash from the series A, B and C are combined to calculate an average test to calculated strengths ratio for each percentage of fly ash. These average values of the test to calculated splitting tensile strength ratios for 0, 10, 20, 30 and 40% fly ash are given in Table 4. The ratios obtained by the three methods at 3 and 28 days are then plotted against the percentage of fly ash in Figures 1 – 3.

Table 4 Ratio of Test to Calculated Tensile Strengths for Different Fly Ash Contents

Percentage of fly ash (%)	Average ratio of test to calculated splitting tensile strengths					
	AS 3600		ACI 318		EC 2	
	3 days	28 days	3 days	28 days	3 days	28 days
0	1.01	0.99	1.10	1.06	1.03	0.91
10	0.99	1.19	1.08	1.19	1.05	1.06
20	1.05	1.08	1.14	1.11	1.12	0.92
30	0.98	1.04	1.08	1.10	1.09	0.97
40	0.97	1.06	1.09	1.09	1.15	0.98

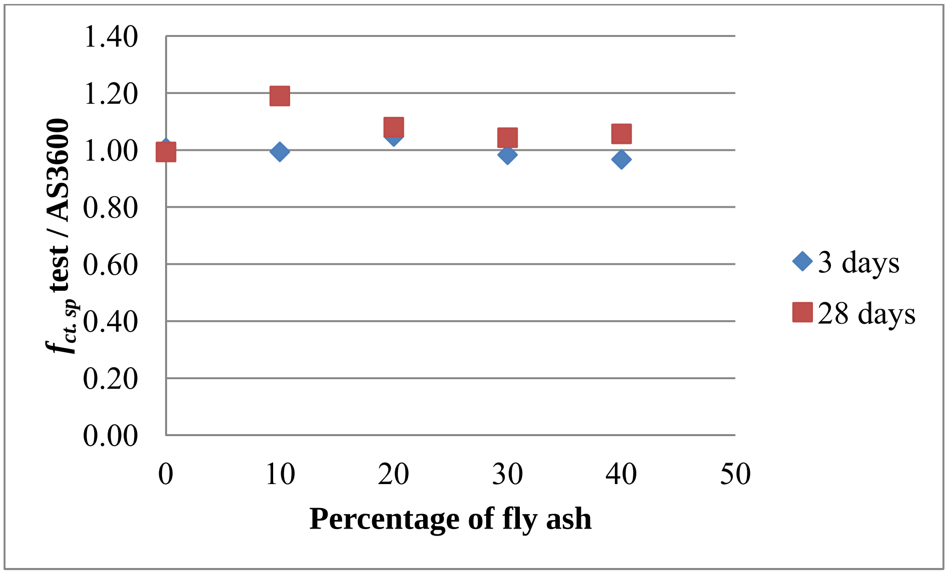

Fig. 1 Ratio of Test to Calculated Splitting Tensile Strengths by AS 3600

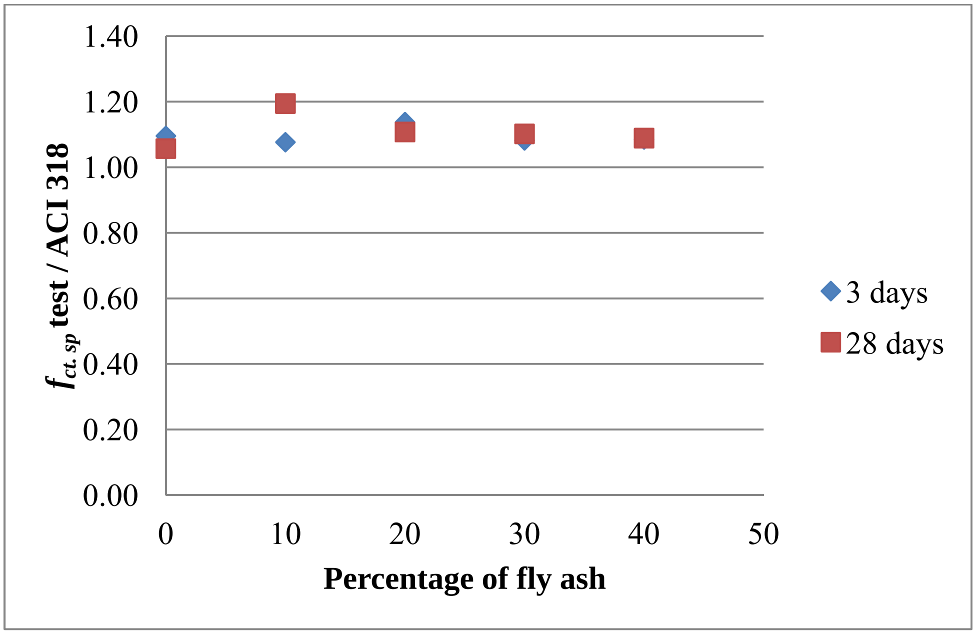

Fig. 2 Ratio of Test to Calculated Splitting Tensile Strengths by ACI 318

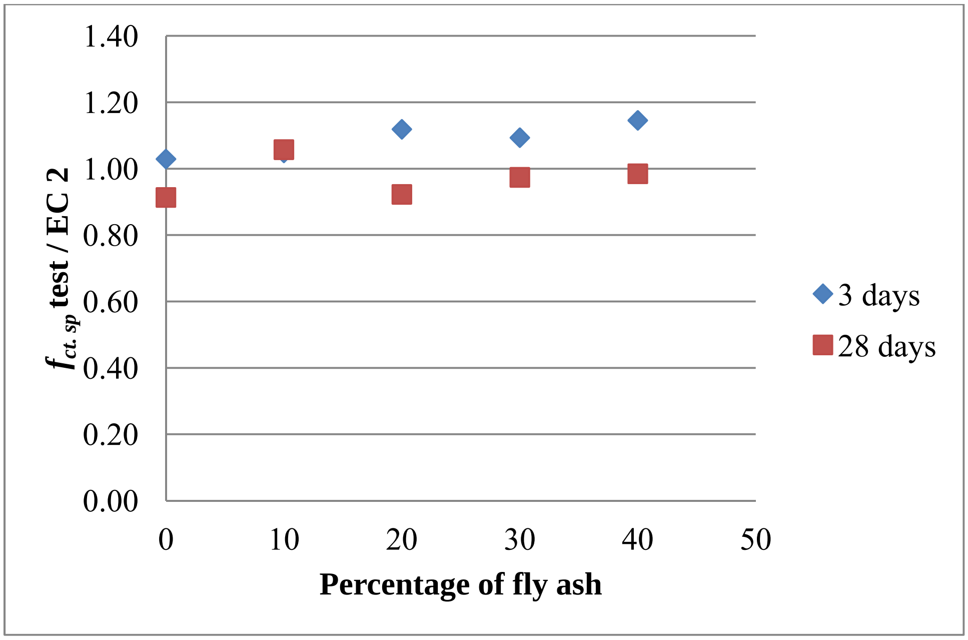

Fig. 3 Ratio of Test to Calculated Splitting Tensile Strengths by EC 2

It can be seen from these Figures that the predictions of the splitting tensile strengths by these three methods are generally good since the mean test to prediction ratios are close to 1.0. It is seen from Figures 1 and 2 that the predictions of splitting tensile strengths from the compressive strengths by AS 3600 and ACI 318 at 3 days of age are similar to those at 28 days of age. Some variations are observed between the 3-day and 28-day predictions by EC 2 for the mixtures with 20 to 40 % fly ash. The mean test-prediction ratios tend to remain approximately same with the variation of the percentage of fly ash. Thus, the inclusion of fly ash up to 40% of the binder did not affect the prediction of the splitting tensile strength from the compressive strength. Therefore, it is concluded that the splitting tensile strengths at early age are correlated well with the compressive strengths for the concretes at that age. This also suggests that design calculations for the required early-age, such as 3-day tensile strength of concrete containing up to 40% fly ash can be performed by the methods of the design Codes using the compressive strength at that age.

CONCLUSIONS

The early-age tensile strength of concrete containing low-calcium fly ash was evaluated. The percentage of fly ash varied from 0 to 40% of the binder. Since the 3-day compressive strength of the concrete samples varied from 22 to 51 MPa, the mixtures are considered to be suitable for a range of applications such as tilt-up, precast and prestressed concrete structures, where high early-age tensile strength is usually required. The 3 and 28-day splitting tensile strengths of the concrete samples were calculated by using the compressive strengths at these ages to evaluate if the Code equations yielded the same level of predictions at 3 days as in 28 days when low calcium fly ash is used. The following conclusions are drawn from the comparison of the test and calculated splitting tensile strengths:

1. The predictions of splitting tensile strengths by the AS3600, ACI 318 and EC 2 Codes were generally good for the mixtures both at 3 and 28 days of age.
2. Generally, there was no negative effect of the early age on the level of accuracy of the predictions when the test to prediction ratios at 3-day were compared with those at 28 days of age.
3. The percentage of fly ash in the binder did not affect the level of accuracy of the predictions when the test-prediction ratios for different percentages of fly ash up to 40% were compared.
4. The early-age tensile strengths correlated well with the compressive strengths and the compressive strength-based Code equations can be used for design calculations related to early-age tensile strength of concrete containing low–calcium fly ash.

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