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Influence of Fly Ash on Behavior of Fibres Reinforced Concrete Structures

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Abstract: Steel fibre and fly ash are common cement additives that can improve concrete performance. The aim of this study was to measure compressive and tensile strengths of concrete with different steel fibre and fly ash percentages. Concrete specimens with fibre contents of 0.50, 1.0 and 1.50% by volume were tested. Fly ash contents in mixes ranged between 0 and 30% by weight. Sixteen concrete mixes were prepared. A hydraulic testing machine was used to measure the compressive and flexural strength of each block. The result of this study confirmed that the addition of steel fibre has a negligible effect on the compressive strength of concrete. However, it can dramatically improve flexural strength. This occurs when the volume of the fibres exceeds the minimum percentage required to prevent brittle failure of the concrete matrix.

Key words: Cracking, compressive strength, flexure strength, mix design, tensile strength

INTRODUCTION

Steel Fibre Reinforced Concrete (SFRC) can be defined as 'concrete made of hydraulic cements containing fine or coarse aggregate and discontinuous discrete steel fibres' (ACI, 2009). SFRC is a beneficial building material, particularly when deformed steel fibres with an aspect ratio under 100 are used (Edgington *et al*., 1974; Trottier and Bantha, 1994; Bentur and Mindess, 2009; Tsai *et al*., 2009). When properly mixed and placed, SFRC can be a very durable material, improving the long-term service ability of a structural member (ACI, 2009). SFRC has better flexural toughness and is impact resistant. Furthermore, it has the ability to withstand more flexural fatigue than ordinary concrete.

Fibre reinforced concrete, in general, has been used in a variety of applications including thin bridge deck overlays, marine structures and tunnel linings (ACI, 2010). SFRC can be a cost-effective building material because it can reduce the thickness of members and reduced thicknesses results in lighter structures, inevitably leading to decreased building costs (ACI, 2009). SFRC is thus extremely useful in construction in which permanent tensile reinforcement is not vital, such as in floor construction on grades, pavements, overlays, ground support and shotcrete linings.

Research shows that the addition of steel fibres does little to increase compressive strength. ACI reports strength increases from 0 to 15% and slightly higher in studies by Johnston (1974), Williamson (1974) and others. However, Bentur and Mindess (2009) state that compressive strength can increase perhaps up to 25% for normal fibre contents (<2%) (Atepegba and Regan, 1981; Mangat and Azari, 1985). Recent studies confirm the former findings, that steel fibres have little effect on compressive strength (Kayali *et al*., 2003; Lee and Barr, 2003; Song and Hwang, 2004). Trottier and Bantha (1994) note that increasing the amount of fibres does not improve compressive strength.

Whilst steel fibres do not significantly increase compressive strength, their ability to increase flexural strength has been well documented. Portland Cement Association (1993) reports that first-crack flexural strength for conventional SFRC can increase up to 150%. Furthermore, fibre additions can decrease permeability of cracked concrete (ACI, 2010). Fibres overlap across cracks and keep them from growing, significantly improving the strength of the concrete (Trottier and Bantha, 1994). Research by Padmarajaiah and Ramaswamy (2004) on high-strength concrete in fully/partially pre-stressed beam specimens shows that adding fibres enhanced their flexural strength.

Fly ash, a by-product of coal production, has been widely used as a cement additive because it can improve long-term strength performance and durability; it reduces heat of hydration and lessens the risk of alkali-silica reactions (Rukzon and Chindaprasirt, 2008). In addition, less water is required for cement workability when fly ash is used in a mix (Jones *et al*., 2003; Elsageer *et al*., 2009; Ahmaruzzaman, 2010). Furthermore, fly ash is regarded as

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an environmental pollutant. While the production of fly ash is increasing, its use is not (Ahmaruzzaman, 2010). Therefore, recycling it for use in concrete structures makes good environmental sense because it lessens the amount in landfills. Cement is also the most costly and energy consuming aspect of concrete production. Replacing Portland cement with fly ash is a cost-effective way of producing modern mixes (Barros *et al*., 2005; Rukzon and Chindarprasirt, 2008; Ahmaruzzaman, 2010).

In terms of fly ash's effects on compressive and flexural strengths of SFRC, Al-Amoudi *et al*. (1996) found that fly ash concrete may reduce compressive strength initially but after 180 days of curing, this trend reverses. High Volume Fly Ash (HVFA) concentrations of greater than 50% by mass of the total cementitious materials can also have higher long-term compressive strengths (Crouch *et al*., 2007). Siddique and Kukreja (1999) established that exchanging cement with 3% fly ash reduces compressive strength considerably. However, when steel fibres are added, there is a marginal improvement in strength. In their research, the maximum compressive strength increase was 18.6% when the fly ash content was 45% and the steel fibre content was 0.75%. In effect, fly ash and steel fibres seemed to balance compressive strength gains and losses. In a study by Topcu and Canbaz (2007) found similar trends. Compressive strength was decreased with fly ash replacement. Yet, compressive strength increased by 95% when steel fibres were added to the mix. On the other hand, Atis and Karahan (2009) observed that steel fibres in their study did not recover fly ash compressive strength loss. In terms of flexural strength, fly ash SFRC had increased flexural strength improvements from "0 to 15% at 1.0% fraction and grew to 30-66% increment at 1.5% fraction".

Variations in study results are due to the types of fly ash, age of concrete and types of steel fibres. In an empirical literature evaluation, Xu and Shi (2009) confirmed that many factors can affect the mechanical properties of SFRC. These include specimen geometry, curing time, water/binder ratio (w/b), types of cement and supplementary cementitious material, steel fibre geometry, aspect ratio and volume fraction. Hence, researching these variables is important for a better understanding of their interactions. The goal is to develop stronger and more durable concrete. In fact, Livingston and Bumrongjaroen (2005) stated that mix proportions are usually developed by trial and error. The key is understanding the effects of different additive volumes to mixes and how these volume percentages influence concrete properties in the harden state.

In this study, varying amounts of fly ash and steel reinforced hooked fibres were added to ordinary Portland cement. The study investigates the effects of these additions on the compressive and flexural strengths of the resulting concrete.

MATERIALS AND METHODS

Cement: Locally available ordinary Portland cement satisfying the requirements of ASTM C150/C150 was used in the present study. The cement had a specific gravity of 3.15 and an initial and final setting time of 68 and 260 min, respectively. The standard consistency of the cement was 29%.

Aggregates: Locally available dry aggregate satisfying the requirements of ASTM C33-08 was used in the concrete mixes. The maximum nominal size of the coarse aggregate (gravel) was 18 mm, its specific gravity was 2.70 and its unit weight was 16.8 kN m^{-3}. The fineness modulus of the gravel was measured and found to be 6.80. The specific gravity of the fine aggregate (sand) was 2.66 g cm^{-3}, its unit weight was 16.9 kN m^{-3} and its fineness modulus was 2.33.

Fly ash: Class F fly ash was used in this study, satisfying the requirements of ASTM C618-08a. Its specific gravity was 1.70 with non-plastic consistency. The chemical composition of fly ash was: SiO_2: 62.24%, Al_2O_3: 24.18%, Fe_2O_3: 2.65%, CaO: 5.47%, MgO: 3.02%, SO_3: 1.06%, K_2O: 1.51%, Na_2O: 0.78%, LOI: 2.27%.

Steel fibres: RC-80/60-BN steel fibres with both ends hooked were used in the mixes. The steel fibres had a length of 60 mm and a diameter of 0.75 mm (an aspect ratio of 80). The density of the fibres was 7.65 g cm^{-3} and the Young's Modulus was 210 GPa. This type of steel fibre meets the requirements of ASTM A820-06.

Water: Potable water that was clear and free of organic, chemical and physical impurities was used during the mixing and curing of the concrete specimens in accordance with the requirements of ASTM C1602-06.

Plasticizer: To improve the workability of the prepared SFRC mixes, super plasticizer of modified lignosulfonate, satisfying the requirements of ASTM Standard C494-10, was used in all mixes to maintain the workability of the fresh concrete and limit the slump to greater than 15 cm (as per ASTM C143). The dosage of the plasticizer was 1% of the cementitious weight of the concrete.

Table 1: Concrete mix composition per cubic metre

Mix	Cement (kg m^{-3})	Fly ash		Steel fiber		Sand (kg m^{-3})	Gravel (kg m^{-3})	Water (kg m^{-3})	Plasticizer (kg m^{-3})
		kg m^{-3}	%	kg m^{-3}	%				
A1	400	0	0	0	0.0	762	1142	160	4
A2	400	0	0	39	0.5	757	1134	160	4
A3	400	0	0	78	1.0	751	1127	160	4
A4	400	0	0	117	1.5	743	1115	160	4
B1	360	40	10	0	0.0	756	1133	160	4
B2	360	40	10	39	0.5	751	1125	160	4
B3	360	40	10	78	1.0	746	1118	160	4
B4	360	40	10	117	1.5	739	1110	160	4
C1	320	80	20	0	0.0	752	1128	160	4
C2	320	80	20	39	0.5	745	1118	160	4
C3	320	80	20	78	1.0	738	1107	160	4
C4	320	80	20	117	1.5	732	1095	160	4
D1	280	120	30	0	0.0	741	1111	160	4
D2	280	120	30	39	0.5	736	1104	160	4
D3	280	120	30	78	1.0	730	1095	160	4
D4	280	120	30	117	1.5	725	1085	160	4

Test specimens: Sixteen concrete mixes were prepared for this study. The composition of each of these mixes is given in Table 1. The fine to coarse aggregate ratio per weight was maintained at 1:1.5 for all mixes. The combined mass of cement and fly ash of 400 kg m^{-3} and a water to cement ratio (w/c) of 0.40 was kept constant for all the mixes. Given that the specific gravity of the fly ash was about 0.63 of that of cement, the maximum change in volume was calculated for the mix with fly ash content of 30% and found to be only 6%. A small value of this magnitude was not expected to affect the comparison between the various mixes based on the volume of the cementitious paste.

Four percentages of 0, 0.5, 1.0 and 1.5% per volume were used for steel fibres, each with a fly ash content of 0, 10, 20 and 30% by weight, replacing a similar amount of Portland cement (Table 1). The maximum volume of 1.5% for the steel fibres was deliberately selected to ensure that the volume exceeded what was required to carry the load after flexural yield, as will be discussed later.

Test procedure: The cement and fly ash were first added and mixed thoroughly in the dry state until homogeneity was achieved. The dry aggregates were added to the mixture and again mixed thoroughly, after which the steel fibres were spread evenly during the dry mixing. Water was slowly added and mixed thoroughly for 3 min followed by the plasticizer. After mixing all the ingredients, concrete specimens were cast using steel moulds and compacted with a table vibrator in three layers. For each mix, at least three 150 mm cubes and three 100×100×500 mm beams were produced for measurement of the compressive and flexural strengths, respectively. After 24 h, each specimen was removed from the mould and cured under water at 32±2°C until testing at age of 7, 28 and 90 days. All specimens were cured in the same water tank to ensure uniform curing conditions.

The tests for measuring the compressive and flexural strength of the concrete specimens were carried out using a hydraulic testing machine with a load (without shock) at a constant rate within the range of 0.140 to 0.350 MPa per sec. A frame was used to hold the concrete beams for measuring the flexural strength with third-point loading.

RESULTS AND DISCUSSION

Compressive strength: The compressive strengths of the concrete mixes measured at 7, 28 and 90 days are presented in Table 2. It was observed that, under compressive loading for specimens without fibres, extensive cracks were produced in the concrete during the pre-peak stage and then suddenly failed at peak load (brittle failure). When steel fibres were added to the concrete, the propagation of the cracks was restrained due to the bonding of fibres into the concrete (ductile failure). These results support the conclusions of Trottier and Bantha (1994).

Table 2 shows the variations in mix compressive strengths. The fly ash mix without steel fibres had a reduced compressive strength at 7 days. This was particularly true for the 30% fly ash mix. Its early strength was reduced by about 27%. However, significant recovery of the compressive strength occurred after 28 days and the recovery was more pronounced after 90 days, at which time a loss of only 3.6% took place (Table 1). These results are similar to those of Al-Amoudi *et al.* (1996) and Crouch *et al.* (2007). This observation reveals the benefit of using fly ash in concrete as long as the delayed strength during the early age of the concrete can be tolerated (assuming that the cementitious content does not change).

In the absence of fly ash, the steel fibre had only a small net effect on the compressive strength (-1.3 to 6.1% change compared with control mix values). The results for compressive strength tests are in accordance with earlier research studies which show that compressive strength is not increased with steel fibre additions (Kayali *et al.*, 2003; Lee and Barr, 2003; Song and Hwang, 2004).

The average compressive strengths obtained after 7, 28 and 90 days for all mixes were 33, 37 and 46 MPa, respectively. Atis and Karahan (2009) carried out similar tests on steel fibre concrete with fly ash. The average compressive strengths in their study after 7, 28 and 90 days for all mixes were 58, 71 and 82 MPa, respectively. There numbers were much greater than in this study. The difference can be due to the myriad factors that can alter concrete strengths that are discussed by Xu and Shi (2009). Some of the differences between this current study and Atis and Karahan (2009) study were steel fibres, mix design and aggregate type, to name a few. In terms of steel fibres, this study used ones with a length of 60 mm, a diameter of 0.75 mm and an aspect ratio of 80. The density of the fibres was 7.65 g cm^{-3}. The steel fibers employed in (Atis and Karahan, 2009) experimental study had a length of 35 mm, a diameter of 0.55 mm and an aspect ratio of 64. The density of the fibres was 7.85 g cm^{-3}.

However, a general trend of an increase of compressive strength with increased fibre was observed. Despite the negligible effect of the steel fibres on the concrete compressive strength, the mode of pre- and post-peak stages was very different between the control specimens and the ones reinforced with steel fibres. The control specimens exhibited extensive cracks during the pre-peak stage and then failed violently and suddenly at peak load (i.e., brittle failure). Yet, the steel fibre reinforced specimens showed a ductile response with the crack propagation being restrained by the fibres. This can be explained by the fact that some tensile stresses must have developed close to peak strength. The steel fibres arrested these cracks, thereby preventing a sudden spalling failure.

Finally, the age of the concrete specimens does not appear to have influenced the effect of the steel fibre on the compressive strength.

Table 2: Summary of compressive strength test results

Mix	Fly ash (%)	Steel fiber (%)	Compressive strength (Mpa) 7 days	28 days	90 days
A1	0	0.0	37.0	39.7	47.2
A2	0	0.5	38.2	40.7	46.4
A3	0	1.0	36.5	41.9	48.5
A4	0	1.5	38.7	42.3	49.1
B1	10	0.0	31.8	39.5	46.8
B2	10	0.5	32.2	35.5	43.8
B3	10	1.0	31.7	37.3	45.5
B4	10	1.5	34.0	37.7	47.1
C1	20	0.0	30.3	33.3	46.0
C2	20	0.5	31.8	35.9	44.5
C3	20	1.0	31.4	37.5	45.1
C4	20	1.5	31.1	38.7	45.9
D1	30	0.0	27.0	34.2	45.5
D2	30	0.5	30.1	34.9	47.3
D3	30	1.0	30.9	35.4	46.2
D4	30	1.5	31.2	33.2	45.5

Table 3: Summary of flexural tensile strength test results

Mix	Fly ash (%)	Steel fiber (%)	Flexural strength (Mpa) 7 days	28 days	90 days
A1	0	0.0	4.30	4.38	4.49
A2	0	0.5	4.42	4.13	4.42
A3	0	1.0	4.58	4.61	4.91
A4	0	1.5	5.52	5.68	6.42
B1	10	0.0	3.52	3.76	4.30
B2	10	0.5	3.72	3.90	4.20
B3	10	1.0	3.59	4.26	4.42
B4	10	1.5	4.57	5.08	5.65
C1	20	0.0	3.26	3.60	3.98
C2	20	0.5	3.16	3.75	3.89
C3	20	1.0	3.31	3.92	4.14
C4	20	1.5	4.02	4.98	5.50
D1	30	0.0	2.72	3.30	3.51
D2	30	0.5	3.01	3.66	3.68
D3	30	1.0	3.22	3.61	4.03
D4	30	1.5	3.66	4.87	5.31

Flexural tensile strength: Table 3 summarizes the results obtained from the flexural tensile strength tests. Table 3 also shows the influence of steel fibres on the flexural strength of the fly ash concrete. The adverse effect of the fly ash on the flexural strength is clearly apparent. This trend continued even for the steel fibre specimens. In the absence of steel fibres, a reduction of up to 20% in the flexural strength was obtained for specimen D1 with 30% fly ash after 90 days. This magnitude of reduction is much higher than the 3.6% reduction that was discussed above for the same mix's compressive strength test. This result can only be justifiable if the tensile strength of the fly ash is less dependent on the compressive strength than plain concrete is.

The results shown in Table 3 indicate that steel fibres at 0.5% had a slight effect on the flexural strength. A tangible increase of 14% in the flexural strength was obtained after 90 days at 1% steel fibres. However, the effect of the 1.5% steel fibre was remarkable, leading to an increase in the flexural strength for all mixes. Specifically, the increase in the flexural strength for the 1.5% steel fibres ranged between 36 and 51%, the latter being related to the mix with 0% fly ash (specimen A4).

The remarkable increase in the flexure strength due to addition of 1.5% steel fibres can be explained using Hannant (1978) simplified analysis (Eq. 1). It suggests that there is a critical 'minimum' volume ratio of steel fibres

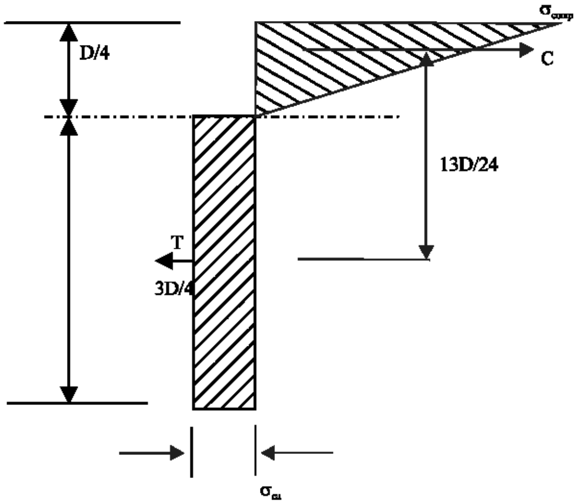

Fig. 1: Post-yield idealized distribution of stresses in a flexural test (Hannant, 1978). D: Initial depth of section, C: Compression force, T: Tension force

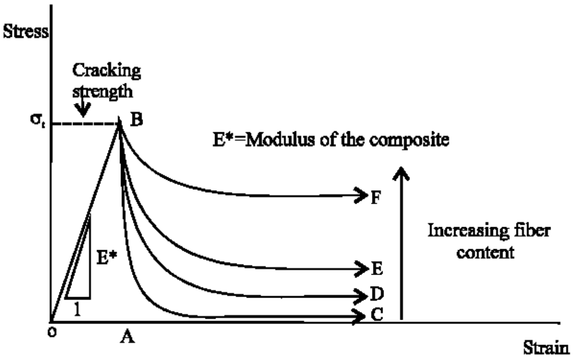

Fig. 2: Contribution of fibres to improvement of flexural strength and toughness

with which the fibres can carry all tensile loads after initial yield in a direct tensile strength test:

$$V_{fcrit} = \frac{2\sigma_t}{\sigma_f} \tag{1}$$

where, σ_t is the tensile strength of the concrete matrix and σ_f is the tensile strength of steel fibres that are randomly distributed in three dimension.

For the idealized section shown in Fig. 1, it can be readily shown that the stresses within the fibres after initial cracking is about half the value experienced by the same fibres in a direct tensile strength test. Therefore:

$$V_{fcrit(flexure)} = \frac{\sigma_t}{\sigma_f} \tag{2}$$

The steel fibre tensile strength is 500 MPa and the tensile strength of the composite section is 10% of the compressive strength (σ_t = 4 MPa). Thus, the critical volume of the fibres is about 0.8%. This amount is reasonably within the range that produced improved tensile strength in bending.

The mechanism associated with increased flexural strength (and consequently toughness) is illustrated schematically in Fig. 2. When the maximum tensile strength (i.e, resistance to cracking) of the matrix of the composite section (i.e, concrete and fibres) is reached at Point B, the fibres receive a portion of the tensile stress imposed on the concrete element, the magnitude of which depends on the relative volume between the fibres and concrete. According to the magnitude of the tension stress carried by the fibres, the post-peak stress-strain curve may follow one of the paths: BC to BF. As the volume of the fibres increases, the post-peak stress-strain curve moves closer to the peak strength and the brittle failure is suppressed, increasing the toughness of the element (that is, the area under the stress-strain curve). The final strain that the composite element can sustain would then be a function of the maximum strain that can be endured by the fibres. The mechanism of post-cracking resistance stems from the fact that the failure strain of the fibres is greater than that associated with cracking of the concrete matrix.

To illustrate the influence of fibres on increasing the energy that can be absorbed by a concrete element due to the fibre, it can be readily shown that the ratio of strain to failure between steel fibres (for example) and plain concrete ranges from about 500 to 1150.

Two essential points should be noted in relation to the schematic presented in Fig. 2. First, the volume of the fibres may influence the peak strength at Point B. The strength tends to increase when the fibre volume exceeds the minimum value that would be required to carry the load beyond point B. Second, the slope of the line OB (i.e. elastic modulus E^*) would also increase with both the volume of the fibres as well as the modulus of the fibre material.

The fact that fibre inclusion can improve both the flexural strength and toughness can have economic implications. SFRC can enable designs of sections with smaller thicknesses in many situations. This is true when the flexural strength of the unreinforced concrete governs design, such as in watertight structures.

CONCLUSIONS

This study investigated steel fibre influence on the compressive and flexural strengths of fly ash concrete containing 10, 20 and 30% of fly ash. The steel fibre contents investigated were 0.5, 1 and 1.5% by volume. These percentages were chosen, as they are sufficient to carry full stress after cracking of the concrete matrix. A number of conclusions can be drawn from this study. First, the addition of steel fibres into the concrete mixes did not significantly improve ultimate compressive strengths but it was very effective in resisting flexural tensile stresses. Second, the optimum parameters for compressive strength were obtained at 90 days, 1.5% steel fibre and 0% fly ash. Third, the most noticeable variables effecting compressive strength were time, fly ash percentage and steel fibre percentage. Fourth, steel fibres have no effect on flexural tensile strength at 0.5% of the mix. However, an improvement of 0-15% in the flexural strength was observed at 1.0% of steel fibre and increased to 30-66% at 1.5% fibres. Fifth, flexural strength is dependent on steel fibre and fly ash percentages as well as on curing time. In addition, an increase of compressive and flexural strengths with ages of the specimens was observed. The compressive strength increase is more pronounced between 28 and 90 days than between 7 and 28 days, whilst the opposite was true for flexural strength increases in the specimens. Finally, compressive and flexural strength ratios can enhance a lower steel fibre content coupled with the addition of more fly ash.

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