SUSTAINABLE FLY ASH CONCRETE MIXTURES WITH SYNTHETIC FIBERS

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Abstract

This study explores the feasibility of replacing large quantities of Portland cement in concrete with Class C fly ash. The influence of structural synthetic fibers on the concrete performance was also explored. A total of 11 fibrous and plain concrete mixtures were designed and evaluated. The results showed that the concrete mixtures with 30% fly ash replacements experience compressive and flexural strengths comparable with companion control mixtures. The compressive and flexural strengths of the mixtures with 60% fly ash replacements were impressive despite the fact that these values are lower than their comparable values in companion control mixtures. The results revealed that replacing up to 60% of the cement in concrete with Class C fly ash is still feasible. The added fibers resulted in significant post-cracking residual strength and reduction in the drying shrinkage. Adding 5 lb/yd3 (3 kg/m3) of the structural synthetic fibers to the mix resulted in about 150 psi (1.0 MPa) residual strength compared with about 80 psi (0.55 MPa) for 3 lb/yd3 (1.8 kg/m3) of synthetic fibers. It was interestingly found that for the used water to cementitious materials (W/CM) ratio of 0.40, the mixtures with total CM of 650 lb/yd3 (390 kg/m3) experienced comparable performance as the mixtures with 750 lb/yd3 (450 kg/m3).

Keywords: Sustainability, Fly ash, Synthetic fibers, Shrinkage, Toughness

Introduction:

Fly ash is a byproduct of coal consumption and typically used in concrete to replace portion of the cement. Production of cement contributes about 4% to the total CO_2 released to the environment. Replacing substantial portion of the cement in concrete with fly ash is considered a sustainable and economical application since it: 1) reduces the impact of coal production and

CO_2 emission on the environment when manufacturing cement; 2) cuts on the amount of fly ash that goes to landfills; and also 3) lowers the concrete cost by reducing the amount of cement needed. On the other hand, incorporating structural synthetic fibers into concrete enhances its structural performance and increases its durability through minimizing the potential for shrinkage cracking and providing crack-arresting mechanism (Alhassan and Ashur, 2012 and 2011, Alhassan 2010, and Issa et al., 208). The enhanced performance combined with the cost reduction and minimized environmental impact are highly desirable for the infrastructure facilities such as highway pavements and bridge decks. These facilities often experience immature cracking and deterioration due to their large surface area that is exposed to the environment and to the effects of cyclic traffic loading conditions.

The use of large quantities of fly ash in concrete has some concerns, especially in terms of the early age strength gain. There is a general notion that fly ash reduces the strength gain at early age. Nevertheless, previous experience with concrete mixtures having 25% fly ash of the total cementitious materials (CM) content showed no such concern about the early age strength (Alhassan and Ashur, 2012 and 2011). Additional research is needed to investigate the effect of using high quantities of fly ash in concrete. On the other hand, incorporating synthetic fibers in fly ash concrete is pioneering since fly ash concrete is typically used in highway structures that experience aggressive environmental exposures, high drying shrinkage, and heavy live loading and impact. Synthetic fibers are noncorrosive, alkali resistant, and typically added in small quantities due to their low density, therefore, a substantial number of uniformly distributed fibers are added.

This study is conducted to obtain reliable experimental results about key-aspects of the performance of fibrous fly ash concrete in terms of strength, shrinkage, toughness, and constructability. It is expected that the availability of such data be of significant interest to many U.S. transportation agencies and researchers. This area of research is fundamental in terms of using special types of fibers and high percentages of fly ash to produce durable sustainable concrete with high resistant to cracking. Such high performance concrete mixtures are in need in many applications. For example, there are major cracking and deterioration problems in the highway pavements and infrastructure systems way before they reach their service lives due to the use of inadequate mix designs and inappropriate construction practices (Soroushian and Ravanbakhsh, 1998 and Ozyildirim et al., 1997). Extending the durability of such systems provides huge life cycle cost savings due to the huge cost of repair. Infrastructure systems with enhanced performance are safer and provide better riding quality.

Mix Designs and Parameters of Investigation:

A total of 11 concrete mixtures were designed to investigate the influence of major parameters on their performance mainly in terms of strength, shrinkage, and toughness. The mixtures were designed to allow for studying the effects of three major parameters as outlined in Table 1. The studied parameters are: 1) the fly ash content: 0, 30%, and 60% of the total CM content, 2) the fiber content: 0, 3 lb/yd^3 (1.8 kg/m^3), and 5 lb/yd^3 (3 kg/m^3), and 3) the total CM content: 650 lb/yd^3 (390 kg/m^3) and 750 lb/yd^3 (450 kg/m^3). The W/CM ratio was fixed at 0.40 for all mixtures. The coarse and fine aggregate contents were comparable for all mixtures. The mixing, finishing, curing, and testing practices were consistent for all mixtures and conducted according to the American Society of Testing and Materials (ASTM) standards. Similar dosages of superplasticizer and air-entraining admixtures were added for all mixtures to achieve comparable workability and air content values. The slump values ranged from 6 – 8 in. (150 – 200 mm), the air content values ranged around 6 ± 1%, and the unit weight was around 146 lb/ft^3 (2370 kg/m^3) for all mixtures. The specimens were covered with wet burlap and plastic sheets for 24 hours before being demolded and moist-cured in a standard moisture room for seven days.

The synthetic fiber type and dosage were selected so that notable performance enhancement is achieved while maintaining adequate constructability. The used fiber type is a 1.55 in. (40 mm) long polyolefin fiber with monofilament configuration and has aspect ration of 90, specific gravity of 0.92, elastic modulus of 1,378 ksi (9.5 GPa), tensile strength of 90 ksi (620 MPa), and high alkali, acid, and salt resistant. The constructability aspects of the fibrous mixtures were monitored during the fresh concrete state to evaluate whether the fibers jeopardize the mixing or the finishing practices. Within the used fiber types and dosages, the fibrous mixtures had a reduction in the slump of about 1-2 in. (25-50 mm) compared with the companion plain mixtures. The mixtures with 3 lb/yd3 (1.8 kg/m3) of fibers were easily constructable while the mixtures with 5 lb/yd3 (3 kg/m3) required some precaution to avoid complications during mixing, compacting, and finishing such as fiber remains in the mixer, clumps, and balling.

Table 1 Mix Designs and Parameters of Investigation

Ingredient	Quantity, lb/yd^3										
	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5	Mix 6	Mix 7	Mix 8	Mix 9	Mix 10	Mix 11
Total CM	650	750	650	650	650	650	650	650	750	750	750
Type I cement	650	750	455	455	455	260	260	260	300	300	300
Class C fly ash	0	0	195	195	195	390	390	390	450	450	450
% Fly ash	0	0	30%	30%	30%	60%	60%	60%	60%	60%	60%

Course	1,620	1,520	1,600	1,600	1,600	1,590	1,590	1,590	1,490	1,490	1,490
Fine aggregate	1,620	1,520	1,600	1,600	1,600	1,590	1,590	1,590	1,490	1,490	1,490
W/CM	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40
Synthetic fiber	0	0	0	3	5	0	3	5	0	3	5

* 1.0 lb/yd^3 = 0.601 kg/m^3

Compression tests were conducted for all mixtures at 7 and 28 days according to ASTM C39. Flexural performance tests were conducted at 90 days according to ASTM C 1609. A digitally controlled universal testing machine was used to test the compressive strength and the flexural performance. Unrestrained drying shrinkage tests were conducted for each mixture according to ASTM C157. The shrinkage measurements were taken over a 90 period. The average results are presented in the following sections. The results were then analyzed to evaluate the effects of the three major parameters of investigation of this study.

The plain mixtures Mix 3 and Mix 6 have 30% and 60% fly ash, respectively with a total CM content equivalent to the plain mixture Mix 1 that does not include fly ash. The plain mixture Mix 9 has 60% fly ash with a total CM content equivalent to the plain mixture Mix 2 that does not include any fly ash. Therefore, the effect of the fly ash content can be evaluated through comparing the results of Mix 3 and Mix 6 with Mix 1 as well as Mix 9 with Mix 2. The effect of the fiber content can be evaluated through comparing the results of the fibrous mixtures Mix 4 and Mix 5 with the plain mixture Mix 3, the fibrous mixtures Mix 7 and Mix 8 with the plain mixture Mix 6, and the fibrous mixtures Mix 10 and Mix 11 with the plain mixture Mix 9. The effect of the total CM content can be evaluated through comparing the results of Mix 1 with Mix 2 and Mix 6 with Mix 9.

Compressive Strength:

Figure 1 shows the average compression test results at 7 and 28 days. The compressive strengths of Mix 3 and Mix 6 were lower than Mix 1 by 13.7% and 31.4% at 7 days and 6.9% and 17.1% at 28 days, respectively. The compressive strength of Mix 9 was 34.1% and 13.5% lower than Mix 2 at 7 and 28 days, respectively. In spite of the reduction in the compressive strength when replacing the cement with 30% and 60% fly ash, Mix 3 that includes 30% fly ash achieved a compressive strength greater than 4000 psi (28 MPa) at 7 days and greater than 6000 (41 MPa) at 28 days. Mix 6 and Mix 9 that include 60% fly ash both achieved about 3500 psi (24 MPa) at 7 days, and about 5500 (38 MPa) and 6000 psi (41 MPa) at 28 days, respectively. The compressive strength development was better for the mixtures with the fly ash compared with the mixtures without fly ash.

Comparing the results of the fibrous mixtures that have 3 lb/yd^3 (1.8 kg/m^3) fibers with their control plain mixtures shows that the compressive strength of Mix 4 is 23.4% and 21.8% higher than Mix 3 at 7 and 28 days, respectively. The compressive strength of Mix 7 is 12.7% lower than Mix 6 at 7 days and 3.6% higher at 28 days. The compressive strength of Mix 10 is 3.1% higher than Mix 9 at 7 days and 2.3% lower at 28 days. Comparing the results of the fibrous mixtures that have 5 lb/yd^3 (3.0 kg/m^3) fibers with their control plain mixtures shows that the compressive strength of Mix 5 is 3.1% higher than Mix 3 both at 7 and 28 days. The compressive strength of Mix 8 is 7.2% lower than Mix 6 at 7 days and 2.2% higher at 28 days. The compressive strength of Mix 11 is 11.1% and 17.9% lower than Mix 9 at 7 and 28 days, respectively. The fibrous mixtures with 3 lb/yd^3 (1.8 kg/m^3) experienced higher strength than the companion fibrous mixtures with 5 lb/yd^3 (3.0 kg/m^3). The results do not show a general trend on whether the fibers increase or decrease the compressive strength; however, addition of fibers to concrete was never intended to increase its compressive strength. The failure modes of the compression test specimens revealed significant advantage for the fibrous additives. The fibrous specimens remained intact after failure due to the internal confinement provided by the fibers, while the plain specimens crushed at ultimate.

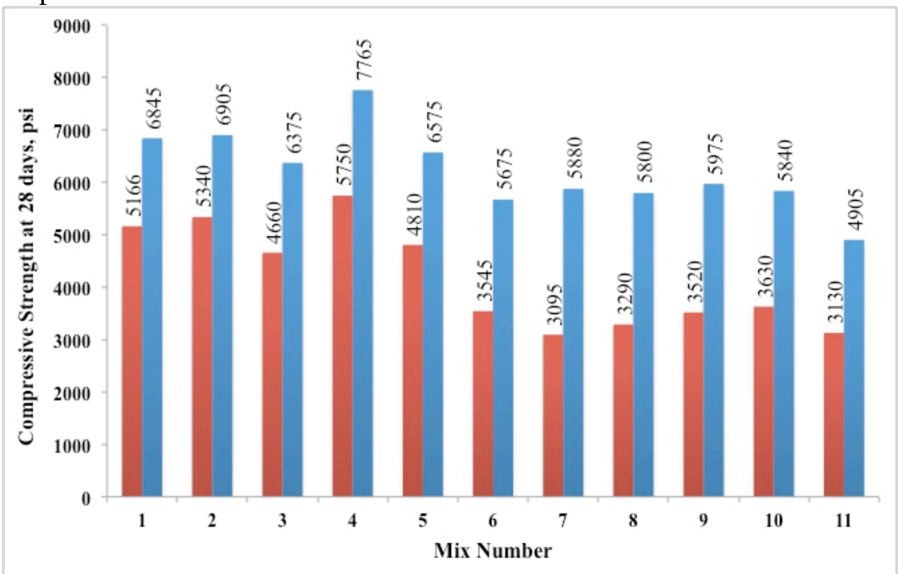

Figure 1 Compressive strengths at 7 and 28 days (1000 psi = 6.895 MPa).

Comparing the compressive strength of Mix 1 with Mix 2 shows that Mix 1 experienced approximately similar compressive strengths at 7 and 28 days as Mix 2 although Mix 1 has 13% less cement. Mix 6 also has 13% lower cement than Mix 9, and experienced almost similar compressive strength as Mix 9 at 7 days and just 5% less at 28 days. These results are very interesting and reveal that for a W/CM of 0.40, the use of 650 lb/yd^3 (390 kg/m^3) of CM in concrete results in almost similar compressive strength as the use of 750 lb/yd^3 (450 kg/m^3) of CM. One of the reasons might be that the course aggregate content in the mixtures with 650 lb/yd^3 (390 kg/m^3) of CM is around 6% higher than the mixtures with 750 lb/yd^3 (450 kg/m^3).

Shrinkage:

The drying shrinkage measurements were taken for each mixture over a 90-day period following 7-days of moist curing. The shrinkage-time responses were plotted for the companion mixtures as shown in Figure 2 to allow for clear analysis of the results. It is important to recall that all mixtures have the same W/CM ratio. Comparing Mix 1 with Mix 2 shrinkage results shows that Mix 2 experienced slightly higher shrinkage, which can be attributed to its higher CM content. Comparison between Mix 1, Mix 3, and Mix 6 shows that Mix 6 that has 60% fly ash experienced almost similar shrinkage as Mix 1, while Mix 3 that has 30% fly ash experienced noticeably higher shrinkage that Mix 1 and Mix 6. Comparing Mix 9 that has 60% fly ash with Mix 2 shows that Mix 9 experienced slightly lower shrinkage.

The effect of the fibers on the shrinkage is evaluated through comparing Mix 4 and Mix 5 with Mix 3, Mix 7 and Mix 8 with Mix 6 and Mix 10 and 11 with Mix 9. Inspection of the plots shown in Figure 2 shows that the fibrous mixtures experienced lower shrinkage than the companion plain mixtures. The fibrous mixtures with 3 lb/yd3 (1.8 kg/m3) experienced almost similar shrinkage as the companion fibrous mixtures with 5 lb/yd3 (3.0 kg/m3). At 28 days, the average shrinkage of Mix 4 and Mix 5 was about 18% lower than Mix 1, the average shrinkage of Mix 7 and Mix 8 was about 15% lower than Mix 6, and the average shrinkage of Mix 10 and Mix 11 was about 13% lower than Mix 9. These results show that the used dosages of the structural synthetic fibers resulted in significant reduction in the drying shrinkage of concrete. This is considered a desirable enhancement in the concrete performance increases resistant to cracking.

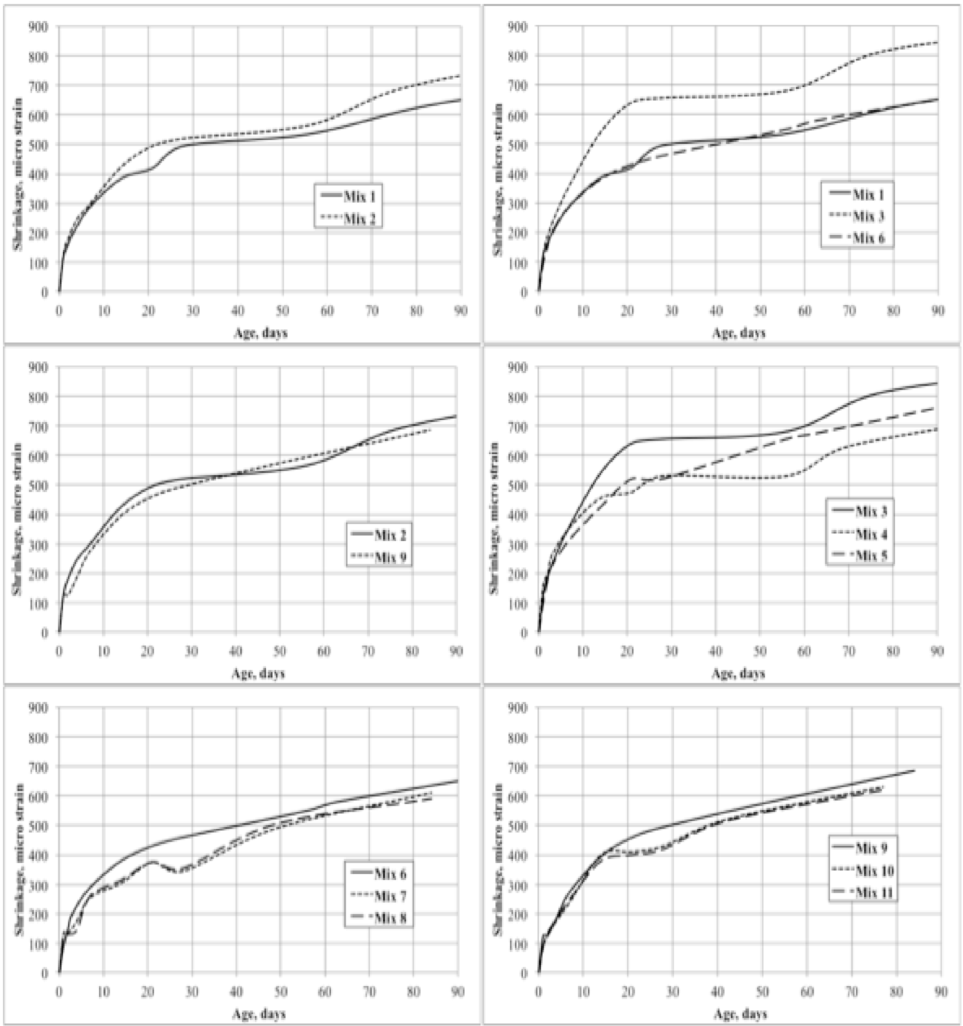

Figure 2 Shrinkage-time responses.

Flexural Performance:

Toughness and post-cracking residual strength evaluation were conducted for the fibrous mixtures according to ASTM C1609 using a servo-controlled testing machine. All specimens were tested at age of 90 days. Figure 3 shows the ultimate flexural strengths and the post-cracking and residual strengths (f D150) for each mixture as obtained from the flexural performance tests. The obtained results are the average of two to three specimens. As expected, all the plain mixtures failed suddenly without any residual strength after reaching the ultimate flexural strength. This is the major reason for adding fibers to concrete that is to arrest cracks at any location where the ultimate tensile strength is reached.

The residual strengths of Mix 4, Mix 7, and Mix 10 that include 3 lb/yd3 (1.8 kg/m3) of fibers were respectively 80 psi (0.55 MPa), 75 psi (0.52 MPa), and 80 ksi (0.55 MPa) with an average of 78 psi (0.54 MPa), which is about 11% of the average flexural strength of the previous three fibrous mixtures that is 727 psi. The residual strengths of Mix 5, Mix 8, and Mix 11 that include 5 lb/yd3 (3 kg/m3) of fibers were respectively 160 psi (1.1 MPa), 120 psi (0.83 MPa), and 190 ksi (1.3 MPa) with an average of 157 psi (1.1 MPa), which is about 21% of the average flexural strength of the previous three fibrous mixtures that is 735 psi (5.1 MPa). The results also show that the fibrous additives do not affect the flexural strength for the two used dosages of the synthetic fibers. Some fibrous mixtures experienced slightly higher flexural strengths than the companion plain mixtures, while others experienced slightly lower flexural strengths.

In terms of the influence of the total CM on the flexural strength, Mix 1 and Mix 2 almost experienced similar flexural strengths. Also Mix 6 and Mix 7 experienced almost similar flexural strengths. These interesting results were consistent with the compressive strength results for the same mixtures indicating that for W/CM = 0.40, the use of 650 lb/yd3 (390 kg/m3) of CM in concrete results in almost similar flexural and compressive strengths as the use of 750 lb/yd3 (450 kg/m3) of CM. In terms of the influence of the fly ash content on the flexural strength, Mix 3 that has 30% fly ash experienced higher flexural strength than Mix 1 by 8%, which is impressive. Mix 6 that has 60% fly ash experienced lower flexural strength than Mix 1 by 14.6%, and also Mix 9 that has 60% fly ash experienced 13.8% lower flexural strength than Mix 2. In spite of the reduction in the flexural strength when replacing the cement with 60% fly ash, Mix 6 and Mix 9 both achieved flexural strength above 650 psi (4.5 MPa).

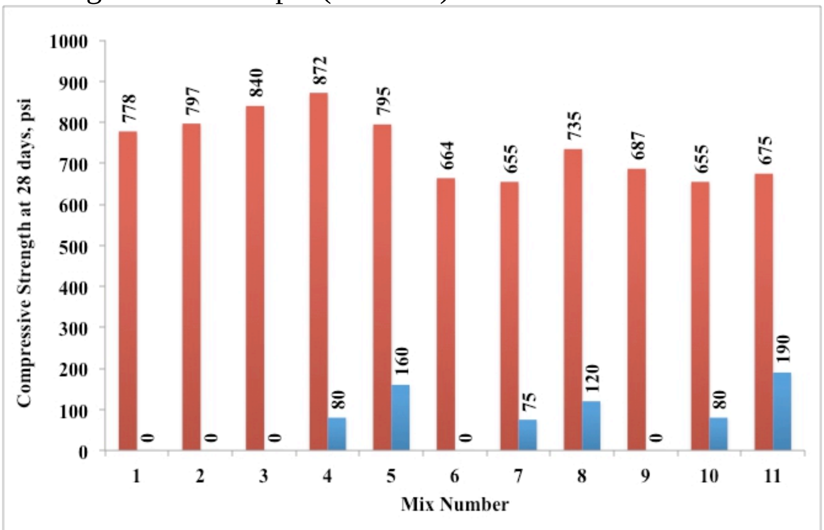

Figure 3 Flexural and residual strengths (1000 psi = 6.895 MPa).

Conclusion:

Based on the results, it can be concluded that replacement of 60% of cement in concrete with Class C fly ash is a feasible-sustainable measure resulting in large savings in the cost of concrete, lowering CO2 emission, and recycling effectively coal-consumption byproduct. The compressive and flexural strengths of the mixtures with 60% fly ash replacements were impressive, but lower than the companion mixtures. Replacement of 30% of the cement with Class C fly ash results in nearly comparable performance characteristics. Addition of 5 lb/yd3 (3 kg/m3) of the structural synthetic fibers to concrete results in about 150 psi (1.0 MPa) residual strength; while addition of 3 lb/yd3 (1.8 kg/m3) results in about 80 psi (1.0 MPa) residual strength. For similar W/CM of 0.40, the mixtures with total CM of 650 lb/yd3 (390 kg/m3) experienced comparable performance as the mixtures with 750 lb/yd3 (450 kg/m3).

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