

DEVELOPMENT OF HIGH PERFORMANCE CONCRETE COMPOSITES USING CLASS F FLY ASH AND BOTTOM ASH

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ABSTRACT. With the rapid industrialization and globalization, the journey from ordinary concrete to high performance concrete (HPC) has been swift and remarkable. The aim of this study was to develop high performance concrete composites having different percentages of Class “F” fly ash and bottom ash by replacing the appropriate proportions of Type 1 portland cement and fine aggregate, respectively. The target was to develop high performance concrete composites that have compressive strength of 8,000 psi (55 MPa) after 28 days of curing in water and air content between 4 and 6 percent. The engineering parameters of the high performance concrete composites and an equivalent control mix were evaluated by conducting a detailed laboratory study which included several tests, e.g., slump, fresh air content, compressive strength, splitting-tensile strength, flexural strength, and resistance to rapid freezing and thawing. Based on the results of this study, it was concluded that the concrete composites have potential to be used on real world projects and thus help the environment by substantially reducing the amount of fly ash and bottom ash going to ash ponds or landfills.

Keywords: High Performance Concrete, Sustainability, Coal Combustion By-products

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INTRODUCTION

In the world of concrete composites, efforts are underway to make concrete more economical and environmentally friendly by using the waste products, such as fly ash and bottom ash obtained from burning of coal. It is estimated that the annual demand of cement in the world will exceed 2.4 billion tons in 2020 [1]. As per the report of American Coal Ash Association ACAA [2], over 130 million tons of coal combustion by-products were produced out of which only 56.6 million tons were used in various applications, which is just 43.46% of the production. So, there is still a huge scope for further exploration in this field.

In the past, the basic constituents of cement concrete: portland cement, coarse aggregate and fine aggregate remained unchanged with the exception that various concrete composites have been developed using different ingredients to meet the project specific requirements and to save the environment for the future generations. Portland cement was patented by Joseph Aspdin in 1824 and was named after the limestone cliffs on the isle of Portland in England [3]. Portland cement concrete is a simple material in appearance with a very complex internal nature. Despite its internal complexity, concrete's versatility, durability and economy have made it world's most used construction material. Portland cement concrete is basically a mixture of aggregates and cement paste, in which cement paste constitutes 25 to 40% and aggregates constitute 60 to 75% of the total volume of the concrete [3].

Cement based construction materials are used on almost all projects, small or large. Advanced technological aspects of cement based materials have recently focused on developing high-performance cementitious composites, which exhibit high compressive strength. Coal Combustion By-Products (CCBs) are the side effects of burning of coal used for the production of electricity. Due to its easy availability, coal has been the primary source for production of electricity in the United States, India and many other countries in the world. The United States holds the world's largest estimated recoverable reserves of coal and is a net exporter of coal. In 2014, the amount of coal produced at U.S. coal mines was 996.6 million tons [4]. More than 90% of the coal produced in the U.S. is being used by coal burning power plants to generate electricity. In 2013, total amount of coal combustible products were 114.69 million tons, out of which 51.38 million tons were used for various categories, which is just 44.49% of the total CCB produced [5]. Coal Combustion By-Products have posed a serious challenge to the planners and environmentalists for its safe disposal. For decades, these by-products were considered as waste material but slowly and slowly, they have created their own space in the construction industry. Stringent environment laws deserve credit for this transformation. Initially, these CCBs were used on less important engineering applications but lately these by-products are being used extensively on the load bearing engineering structures.

During the last decade, the use of coal combustion by-products in the normal strength concrete has definitely attained momentum throughout the globe. Proportions, properties, methods and procedures of producing normal strength concrete have been evaluated by a number of researchers. However, development of High performance Concrete Composites (HPCC) with fly ash and bottom ash has not been adequately studied.

During 2005, Italy, Denmark and Netherland have achieved 100% utilization of the fly ash whereas U.S.A and Germany have reached 65 and 85%, respectively. China and India has used between 38 and 45% [6]. American Coal Ash Association (ACAA), along with American Society of Civil Engineers (ASCE) and American Concrete Institute (ACI), have

taken up the challenge of converting coal combustible by-products from liability to an asset. They are quite successful in enhancing the utilization of these by-products not only in the conventional concrete but also in the development of the High Performance Concrete Composites (HPCC). American Concrete Institute (ACI) also defines high performance concrete (HPC) as concrete meeting special combinations of performance and uniformity requirements that cannot always be achieved routinely when using conventional constituents and normal mixing, placing and curing practices. According to American Concrete Institute (ACI), concrete having 28 days compressive strength of 6,000 psi (41 MPa) or higher is considered high strength or high performance concrete [7].

Several investigations have been carried out to develop normal strength concrete utilizing only bottom ash or only fly ash; however studies analyzing the combined effect of using bottom ash and fly ash are still very limited, especially for the development of high performance concrete composites. The goal of this research was to develop high performance concrete composite using Illinois Class F fly ash, PCC bottom ash, air-entraining agent, and high-range water reducer.

DESCRIPTION OF MATERIALS

In this study, the bottom ash and fly ash were brought from the City Water Light and Power (CWLP) in Springfield, Illinois. Type 1 portland cement was used in this study. An air-entraining agent, DARAVAIR 1400, was used to entrain air. The water-cement (w/c) ratio of 0.3 was maintained throughout the research. Regular municipal water was used for preparing the mixes. Since the water-cement ratio was too low at 0.3, high range water reducer, ADVA 140M, was used to obtain sufficient workability.

Fly Ash

The fly ash was used to replace Type 1 portland cement in the proportions varying from 0 to 30%. The fineness modulus and specific gravity of the fly ash was found to be 2.6 and 2.47 and absorption was 5%. The physical properties of the fly ash and sand used in this study are presented in Table 1.

Bottom Ash

The sieve analysis of the bottom ash specimen showed that the bottom ash contained large portions (more than 30%) of particles greater than 4.75mm. It was then decided to sieve the bottom ash through Sieve No. 4. After sieving, the fineness modulus of this bottom ash was calculated to be 3.71 against 4.47 before sieving. Figure 1 shows the grain distribution of the bottom ash before sieving (BS) and after sieving (AS), along with the particle distribution of natural sand.

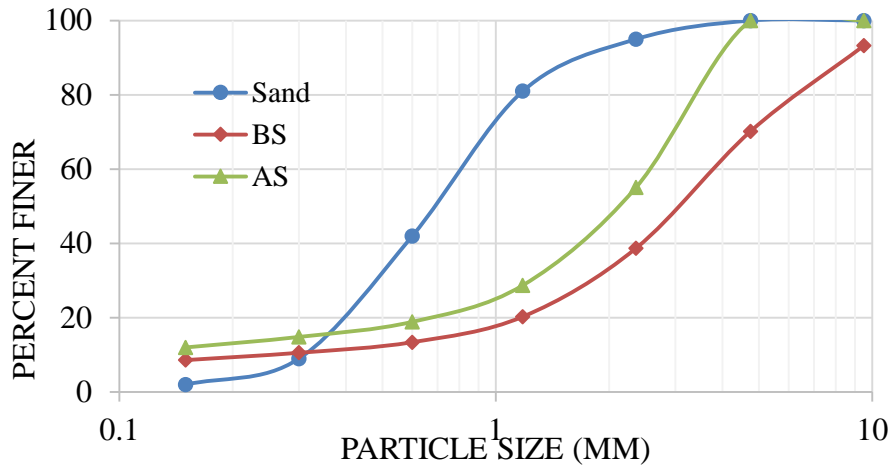


Figure 1 Grain size distribution of bottom ash and natural sand

After the drying process and sieving, the bottom ash was stored in drums. Moisture content of the bottom ash was checked from time to time and it was taken into account for calculation of the amount of water required for the mix. The physical properties of the bottom ash is also presented in Table 1.

Table 1 Physical properties of bottom ash, fly ash and sand

Name of Property	Values		
	Bottom Ash	Fly Ash	Sand
Specific Gravity (Oven Dry)	2.40	2.47	2.66
Absorption (%)	7.0	5.0	0.5
Fineness Modulus	3.7	2.6	2.7
Water Content (%)	0	0	0

Coarse Aggregate

Two characteristics of coarse aggregates; grading and shape of particles, have an important influence on proportioning concrete mixtures, because they affect the workability of fresh concrete. Also, the strength/quality of concrete depends on the aggregate source, particle shape and grading. The maximum size of crushed limestone coarse aggregate used in this research was $\frac{3}{4}$ inches (19 mm) and was brought from Illini Ready Mix Plant in Carbondale, IL. The physical properties of the coarse aggregate used in this research are presented in Table 2.

Table 2 Physical properties of coarse aggregate

Property	Result
Maximum Size (mm)	19.05
Specific Gravity	2.7
Absorption (%)	2.0
Dry Rodded Unit Weight (kg/m^3)	1508.94
Water Content (%)	0

CONCRETE MIX DESIGN

All tests were performed in general accordance with the procedures outlined in relevant ASTM standards. Seven mixes, including a control mix, were prepared and tested in this study. The mixes were prepared after fixing the quantities of all ingredients needed to obtain the targeted slump of $4\pm\frac{1}{2}$ " (102 ± 13 mm) and air content of 4 to 6 percent through preliminary testing.

After the preliminary testing, final mixes containing varying proportions of fly ash and bottom ash were prepared and tested. Mixes are designated with alphabet followed by percentage of bottom ash and fly ash in lieu of sand and cement, respectively. For example, B25F30 represents 25% of the natural sand replaced with bottom ash and 30% of Type 1 portland cement replaced with Class F fly ash. The word CM represents the control mix. The proportions of materials used for each mix are presented in Table 3. Table 4 shows the quantities of materials for a batch of 0.6 ft^3 (0.01699 m^3).

Table 3 Proportions of material and the mix designations

Name of Material		Mix Designation						
		B25F00	B25F10	B25F20	B25F30	B50F10	B50F20	CM
Fine Aggregate	Bottom Ash (%)	25	25	25	25	50	50	0
	Sand (%)	75	75	75	75	50	50	100
	Fly Ash (%)	0	10	20	30	10	20	0
Binder	Cement (%)	100	90	80	70	90	80	100

Curing of Specimens

It is a proven fact that concrete strength increases with age as long as moisture and favorable temperature are available for hydration of cement. After de-molding of specimens, each specimen was marked with date of mix, specimen number and designation of mix. Finally, the specimen were put in curing tanks with a water heater mounted to maintain the water temperature of $23\pm 3^\circ\text{C}$ ($73\pm 3^\circ\text{F}$) as per ASTM C 31 [8].

CONCRETE TESTING

Slump Test

Slump test is used as a measure of the consistency and workability of fresh concrete. Water-cement ratio of the concrete influences the slump of the concrete. Low water-cement ratio gives low slump unless water reducers are added to increase the slump. The test was carried out in general accordance with ASTM C143/C143M-08 [9].

Air Content Test

Air content test was performed as per the provisions of the ASTM C 231-05 [10]. This test determines the air content of freshly mixed concrete exclusive of any air that may exist inside the voids within the aggregate particles. Air content in concrete gives breathing space to concrete and helps in withstanding the cycles of freezing and thawing. Generally 4 to 6% air

content is considered appropriate for concrete without significantly affecting its compressive strength.

Unconfined Compressive Strength Test

This test method is used to determine compressive strength of cylindrical specimens prepared and cured in accordance with the provisions of ASTM C 31/C 31 M, C192/C 192M, C617 and C 1231/C 1231 M and Test methods C 42/C 42M and C 873. Compressive strength of concrete can be calculated directly by dividing the failure load by the cross-sectional area of the sample. The test was performed as per the provisions of ASTM C 39/39M 04a [11].

Splitting-Tensile Strength Test

It is a common knowledge that concrete is strong in compression and weak in tension but with the placement of reinforcement at appropriate place and spacing, it becomes very useful engineering material. The testing machine for this test shall conform to the requirements of Test Method C 39/C 39M, the same as described for the compressive strength test, however, the method of loading was different. This test was performed as per the provisions of ASTM C 496/C 496M [12].

Flexural Strength Test

The flexural strength of concrete is important for the design of road and airport concrete pavements. The flexural strength test was performed in general accordance with ASTM C 78-02 [13] Standard. The specimens were tested for flexural strength at 3, 7, 28 and 180 days of curing.

Freezing and Thawing Test

This test method involves determination of the resistance of concrete specimens to repeated cycles of freezing and thawing which gives an indication of the durability of the concrete. The test was performed as per the provisions of ASTM C 666/C 666M-03 [14]. The freezing and thawing cycle for this test method consists of alternatively lowering the temperature from 40 to 0° F (4 to -18°C) and raising it from 0 to 40°F (-18 to 4°C) in not less than 2 hours and not more than 5 hours.

RESULTS AND DISCUSSION

The detailed experimental testing for this study included performing tests on fresh and hardened concrete specimens. Results obtained from various tests conducted during this study are presented in the following sections. Tests on fresh concrete were carried out to evaluate the effects of bottom ash and Class F fly ash on the workability of the concrete composites and their ability to entrain air. Slump test and air content test were conducted on the fresh concrete before preparing specimens for testing on hardened concrete. Slump is an indicator of workability of the concrete whereas right amount of air-content enhances durability of the concrete. Therefore, targeted slump of 4±½" (102 ±13 mm) and air-content in the range of 4 to 6% were selected for this study.

Several tests were performed on hardened concrete samples to understand strength and durability characteristics of the concrete composites. Results were compared with those obtained from similar tests on an equivalent conventional concrete. Strengths were measured in terms of compression, splitting-tensile, and flexure strength. Durability of the composites was measured in terms of freeze-thaw.

Slump and Air Content Test Results

It is a well-known fact that the value of slump is inversely proportional to the compressive strength of concrete and directly proportional to the water-cement ratio, i.e., as the water-cement ratio increases the slump increases but the compressive strength of hardened concrete decreases. Table 4 shows the measured slump and the amount of water needed to obtain the targeted slump. Table 4 also shows the results of the air content tests on the fresh concrete composites along with the quantity of air entraining agent used.

Table 4 Slump and air content test results

Name of Mix	Slump	Water	Air Content	Air Entrainer Qty.
	mm	kg/m ³	%	kg/m ³
Control Mix (CM)	102	128.28	5.3	0.04
B25F00	102	153.52	4.5	0.05
B25F10	102	152.41	4.2	0.05
B25F20	109	152.23	4.5	0.04
B25F30	115	152.07	4.6	0.04
B50F10	109	166.48	4.0	0.05
B50F20	115	166.18	4.0	0.04

From the slump test results, it was concluded that the amount of water needed to obtain the targeted slump has been affected by the usage of coal combustion by-products (CCBs). The water requirement for concrete composites is more than that of the control mix. This may be due to irregular structure and high value of water absorption of bottom ash. The concrete composites with 50% bottom ash required more water than those with 25% bottom ash, whereas addition of fly ash reduced the amount of water needed, although the reduction was observed to be insignificant.

Air entraining agent produce tiny bubbles in the hardened concrete to provide space for water to expand upon freezing [15]. The air-entraining agent enhances the incorporation of bubbles of various sizes by lowering the surface tension of the mixing water. The resistance of hardened concrete to freezing and thawing is significantly improved by the use of entrained air [3]. In this research, an air entraining agent DARAVAIR1400 was used to achieve the targeted air content between 4 to 6 percent. The amount of air entraining agent required to achieve the targeted air content was fixed after conducting preliminary tests and also keeping in view the relevant literature. Table 4 shows the results of the air content tests on the fresh concrete composites along with the quantity of air entraining agent used. From the results presented above, it was concluded that the amount of air entraining agent required was slightly higher in concrete composites as compared to that required for the equivalent control mix. The results also show that the dose of the air entraining agent required decreased with

the increase in the fly ash content. The amount of bottom ash in the composites appears to have an insignificant effect on the dose of air-entraining agent required.

Unconfined Compressive Strength

Compressive strength is one of the most important properties of the concrete. Compressive strength in general is also considered an indicator of the quality, such as durability and resistance to weathering, of the concrete. The compressive strength tests were performed on cylindrical samples of size 4×8 in (102×203 mm) at 3, 7, 28, 60, and 180 days of curing in water under controlled laboratory conditions. For consistent results, at least two samples were tested at each curing age. Compressive strength test results are presented in Figure 2. From Figure 2, it was concluded that the compressive strength of all concrete composites and control mix has followed the standard trend of concrete gaining strength with time. However, the pattern of increase in strength was different for different concrete composites. For early curing periods, i.e., up to 28 days, the concrete composites had lower compressive strength than that of the control mix. However, compressive strength of all concrete composites after 28 days of curing was above the targeted compressive strength of 8,000 psi. The lower compressive strength of the concrete composites at early curing stage can be attributed to the lower cement content, lower calcium oxide content in Class F fly ash, and lower strength of the PCC bottom ash particles. However, at higher curing ages, pozzolanic reactions provided by the fly ash and PCC bottom ash contributed substantially to the strength gain of the concrete composites.

The concrete composites with 25% of bottom ash attained higher compressive strength as compared to concrete composites with 50% bottom ash after 28 days of curing age. It was also observed that the concrete composites had attained the compressive strength at par, and sometimes higher than that of the control concrete mix, at later stages of curing, i.e., at 180 days of curing, probably due to the pozzolanic reactions provided by the fly ash and the bottom ash. In conventional concrete, natural fine aggregate (sand) is an inert material which does not participate in the chemical reaction. However, chemical composition of the PCC bottom ash helps with the pozzolanic reactions, thus contributing towards concrete's strength.

Splitting-Tensile Strength

Splitting-tensile strength test is an indirect method of measuring the tensile strength of concrete as the samples are subjected to compressive load. Although, concrete is strong in compression and weak in tension, this property is still used in various engineering calculations, e.g., design of highways and airfield pavements. The tensile strength is generally about 10% of its compressive strength [15]. The tests were conducted on the cylindrical samples of size 4×8 in (102 × 203 mm) after 7, 28, 60, and 180 days of curing. The splitting-tensile strength results are presented in Figure 3.

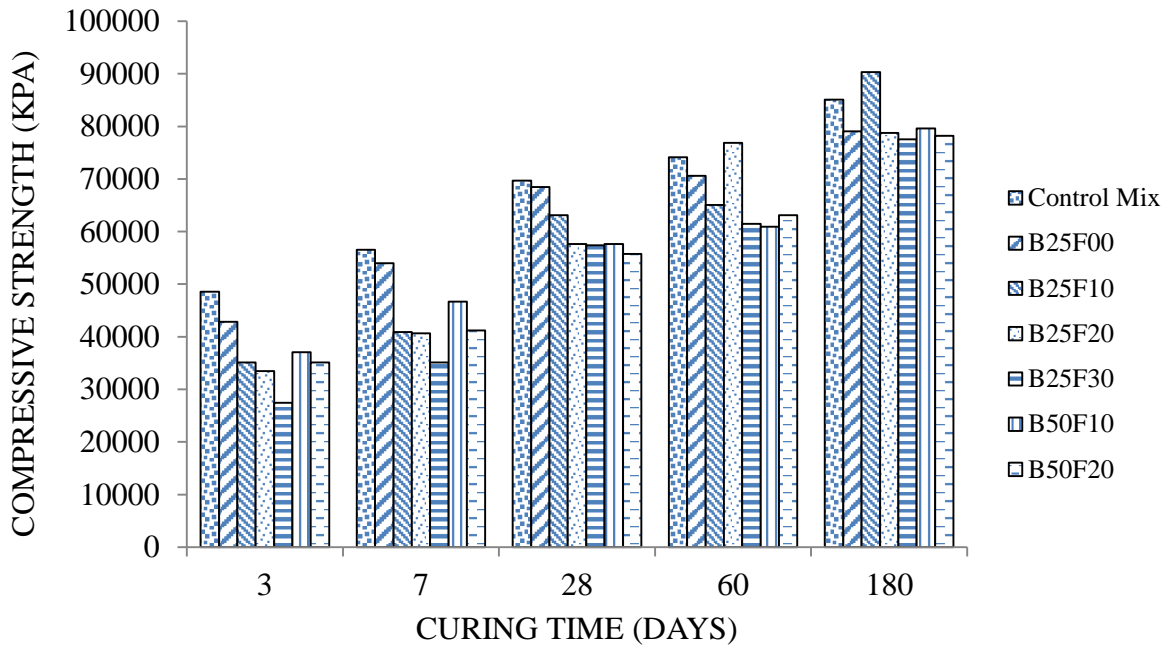


Figure 2 Unconfined compressive strength vs curing time

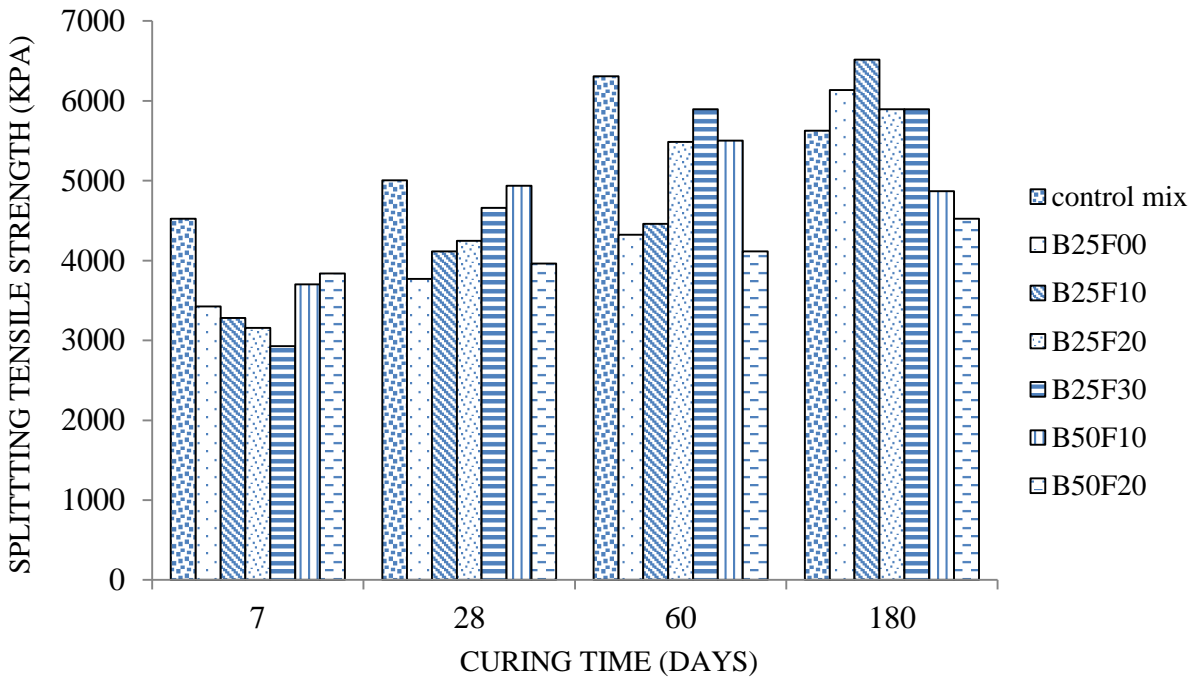


Figure 3 Splitting-tensile strength vs curing time

The data presented in Figure 3 show that that tensile strength of the composites in general has also followed the similar engineering pattern as the case of unconfined compressive strength, i.e., increase in the strength with the curing age. However, the strength gain trends are not as clear as in the case of unconfined compression strength. This is primarily due to heterogeneous composition of concrete and inherent difficulty with placing the specimen in

this test. It was also observed that the splitting-tensile strength of concrete composites in the initial curing age was less than that of the equivalent control mix but as the curing progresses beyond 60 days, the splitting-tensile strength of concrete composites with 25% bottom ash was almost equal to or greater than the splitting-tensile strength of the control mix. However, splitting strength of concrete composites with 50% bottom ash was lower than that of the control mix.

Estimating Splitting-Tensile Strength from Observed Compressive Strength

It is well understood that concrete is strong in compression and weak in tension. Therefore, in the design and construction of concrete structures, reinforcement is commonly used wherever tensile stresses are expected. It is not a common practice to test concrete for obtaining tensile strength. Therefore, indirect methods and mathematical co-relations are commonly used to estimate tensile strength of concretes. As per Mamlouk and Zaniewski [15], the tensile strength of concrete is about 10% of its compressive strength. ACI 318 suggests that if compressive strength of the concrete is known, the splitting-tensile strength can be calculated using Eqn. 1.

$$f_t = 6.7\sqrt{f'_c} \dots\dots\dots(1)$$

Where,

- f_t = Splitting-tensile strength of concrete
- f'_c = Compressive strength of concrete

The splitting-tensile strengths observed from the laboratory tests and calculated from Eqn. 1 using the measured compressive strengths are presented in Figure 4.

Comparison of the observed and calculated values presented in Figure 4 show that in approximately 61% of the cases, the observed values are higher than the values calculated using the ACI equation. However, in order to better understand the relationship between the observed values and ACI equation the data was plotted in Figure 4 which shows a relationship between the splitting-tensile strengths of the composites calculated from the ACI equation as well as measured from the test specimens. A 45 degree line was drawn to evaluate the effectiveness of the ACI equation in predicting the splitting-tensile strength of the concrete composites. Figure 4 shows that some data points, including all data points for the control mix, are above the 45 degree line indicating that the ACI equation under predicted the splitting-tensile strength whereas, some data points are below the 45 degree line indicating that the ACI equation over predicted the splitting tensile strength. However, in general most of the data points fall close to the 45 degree line indicating that the ACI equation provides a reasonable estimate of the splitting-tensile strength.

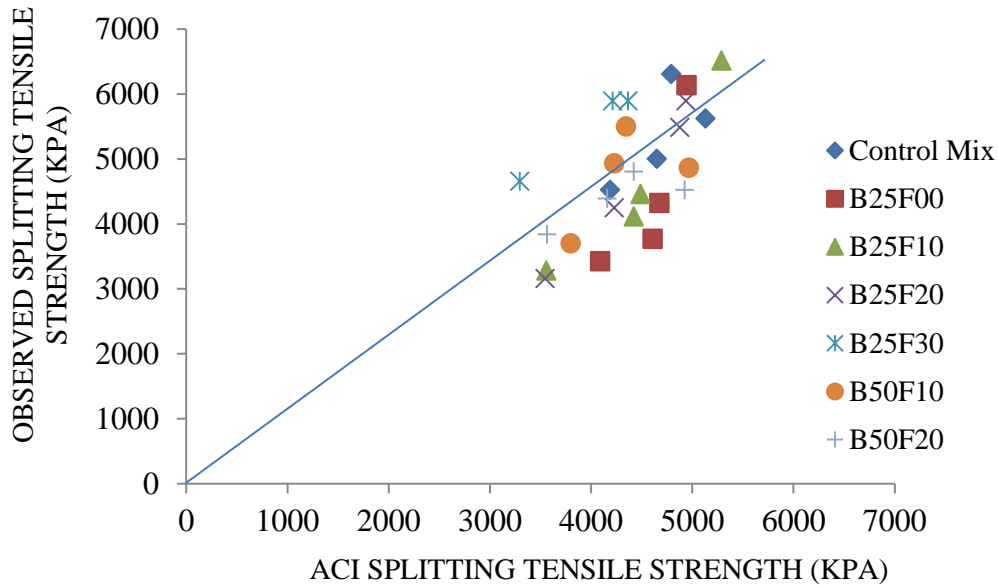


Figure 4 Observed Vs ACI splitting-tensile strength

From the data presented in Figure 4, it was also noted that all observed/measured values for conventional concrete are higher than the values calculated using the ACI equation. However, in case of concrete composites, generally the observed values are lower than the values calculated using the ACI equation at early curing periods, but are generally higher at higher curing periods.

Anoglu et al. [16] have evaluated the ratio between splitting-tensile strength and compressive strength of concretes upto 17,400 psi (120 MPa) and they concluded that this ratio is generally between 0.08 and 0.06 for very high strength concrete and between 0.15 and 0.10 for normal strength concrete. They also concluded that the relation between splitting-tensile strength and the square root of the compressive strength is not proportional.

In order to compare the results obtained from this study with those presented by Anoglu et al. [16] ratio of the splitting-tensile strength and the compressive strength for each concrete composite and the conventional concrete was calculated and is presented in Table 5.

Table 5 Ratio of observed splitting-tensile and compressive strengths

MIX/DAYS	7	28	60	180
Control	0.08	0.07	0.08	0.07
B25F0	0.06	0.06	0.06	0.08
B25F10	0.08	0.07	0.07	0.07
B25F20	0.08	0.07	0.07	0.08
B25F30	0.08	0.08	0.09	0.08
B50F10	0.08	0.09	0.09	0.06
B50F20	0.09	0.08	0.07	0.06

From Table 5, it is clear that all the values for the control mix and concrete composites with 25% bottom ash, except B25F30, fall within the range observed by Anoglu et al. [16], i.e., 0.06 to 0.08. The values of the concrete composites with 50% bottom ash varies between 0.06

and 0.09. There does not seem to be any regular trend between the ratios and the in curing age.

Flexural Strength

Compressive strength is used as an index of flexural strength, tensile strength and shear strength of concrete. The flexure strength or modulus of rupture of normal strength concrete is approximately 7.5 to 10 times the square root of the compressive strength [3]. In addition to compression and splitting-tensile strengths, flexural strength is another important property of the concrete which plays very crucial role in the design of the engineering structures, especially for the design and construction of road and airport concrete pavements. The flexure strength results are presented in Figure 5.

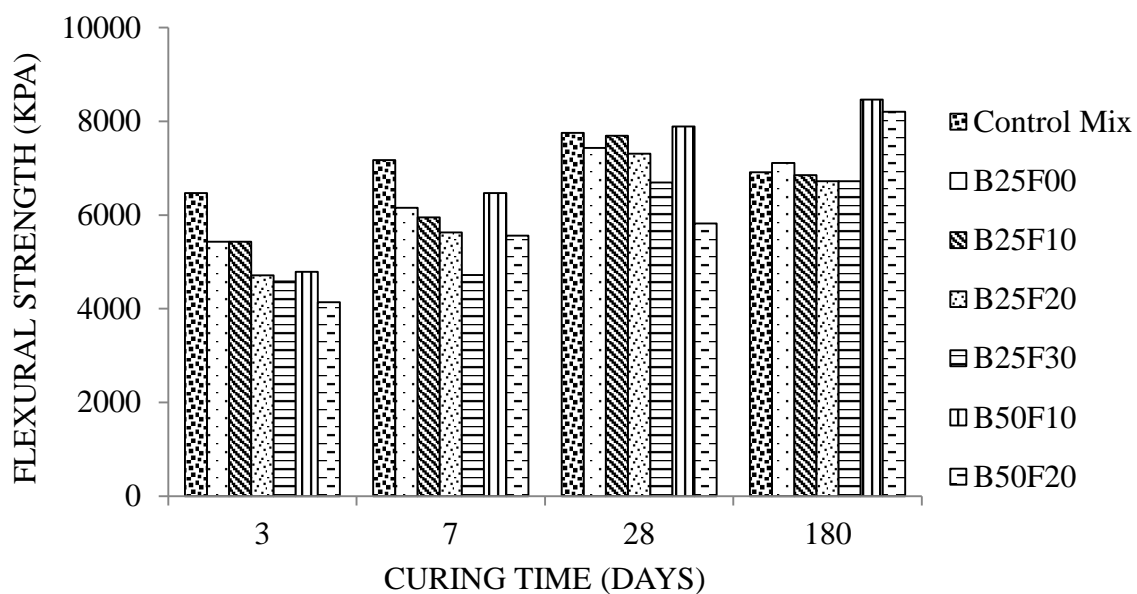


Figure 5 Flexure strength vs curing time

From the results presented in Figure 5, it is clear that the flexural strength of concrete composites and conventional concrete increased with the increase in the curing period up to 28 days. However, results show decrease in the flexural strength of 4 to 11% of several composites, including the control mix, beyond 28 days of curing. The reduction in the flexural strength of concrete with curing does not appear to be related to the quality of concrete; it is probably due to the heterogeneous nature of concrete and inherent difficulties in performing flexural strength test.

At initial days of curing, i.e., at 3 days, all the concrete composites have less flexural strength than the control mix. However, as the curing progressed to 28 days and beyond, the concrete composites started catching up with the flexural strength of control mix and in some cases exceeded the strength of control mix.

For concrete composites with 25% bottom ash with 0, 10, 20, and 30% fly ash, at 3 days of curing, the decrease in flexure strength as compared to that of the conventional concrete was observed to be 16, 16, 27 and 29%, respectively, whereas at 28 days of curing, the decrease in strength, as compared to that of the control mix, was observed to be between 1 to 14%. The

trend shows that with the increase in the fly ash quantity, the flexure strength decreases. Similar trend was observed in the compressive strength.

Figure 5 also shows the behavior of flexural strength of the concrete composites with 50% bottom ash (B50). At 3 days of curing, the flexural strength of concrete composites containing 50% bottom ash and 10 and 20% fly ash was measured to be 26 and 36% lower than that of the equivalent control mix. However, at 28 days of curing, concrete composite with 10% fly ash has flexural strength which is almost equal to that of the conventional concrete and the composite with 20% fly ash has flexural strength 25% lower than that of the conventional concrete. At 180 days of curing, flexural strength of concrete composites with 10 and 20% fly ash was observed to be 22 and 19% higher than that of the control mix. The principle behind late gain of strength is the same as explained under compressive strength i.e. the strength gain due to the pozzolonic reactions provided by the bottom ash and fly ash.

Resistance to Rapid Freezing and Thawing

Durability of concrete is another important property of concrete as it refers to the ability of the concrete to resist deterioration from the severity of environment. Although, rapid freezing and thawing test does not have any direct correlation with the ability of the concrete to resist freezing and thawing temperatures, yet it is considered an acceptable tool to evaluate durability against freezing and thawing in relative terms. In this research, the specimens were first subjected to cycles of rapid freezing and thawing after curing them in water for 14 days. However, all these specimens, including the specimens of the control mix, deteriorated after a few cycles of rapid freezing and thawing. Therefore, the specimens were re-casted and tested after curing them in water for 28 days. The specimens were subjected to 30 to 36 cycles of rapid freezing and thawing every week and the readings for the change in weight, change in length and transverse frequency were recorded. The test was continued until the specimens could not be tested for transverse frequency.

In order to measure the relative dynamic modulus (RDM) of the concrete, transverse frequency of the specimens before starting the test and after every 30 to 36 cycles of freezing and thawing were recorded and then the RDM was calculated. Figure 6 shows the RDM for all the concrete composites and the control mix.

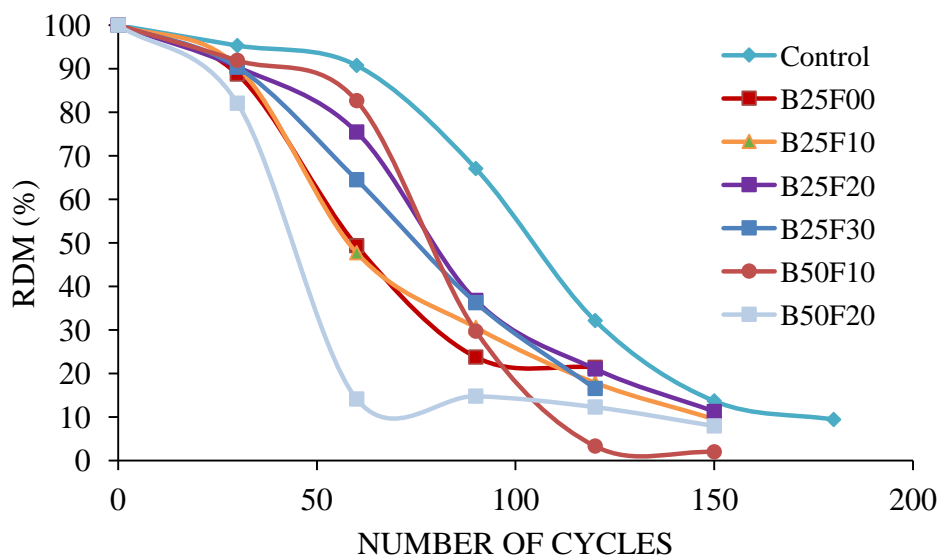


Figure 6 Relative dynamic modulus vs number of cycles

From Figure 6, it is clear that the relative dynamic modulus of the concrete composites and the control mix decreased with the increase in the number of cycles of rapid freezing and thawing. As evident from the results, RDM of concrete composites and the control mix decreased rapidly after approximately 30 cycles of freezing and thawing. Moreover, the RDM of all concrete composites prepared using fly ash and bottom ash was less than that of the control mix. After 30 cycles of rapid freezing and thawing, the RDM of concrete composites ranged between 82 and 91% compared to RDM of 95% for the control mix. After 120 cycles, the RDM of concrete composites ranged between 3 and 11% compared to RDM of 32% for the control mix. The RDM of concrete composites with 50% bottom ash at 120 cycles of rapid freezing and thawing was less than that of the composites containing 25% bottom ash. The literature suggests that if the aggregate is non-frost-resistant, with large void percentage, it will cause the concrete to deteriorate faster in freezing and thawing cycles. Therefore, higher reduction of RDM for concrete composites with 50% bottom ash is justified since the bottom ash is much more porous and weaker aggregate compared to the natural sand.

Mardani et al. [17] have studied the effect of high-volume fly ash on durability characteristics of roller compacted concrete (RCC). They reported that in the mixtures where cement was substituted with fly ash, increasing the fly ash content adversely affected the durability performance. However, fly ash substitution for a part of the aggregate improved the durability characteristics of the mixture with the increase in the amount of fly ash.

The reduction in the RDM with number of cycles presented in Figure 6 is not consistent with the results published by other researches for normal weight and normal strength concrete. The studies have shown that the concrete specimens, even those prepared by using fly ash and bottom ash, were able to withstand 300 cycles of rapid freezing and thawing with RDM of above 60% after 300 cycles. In this study, all specimens, including specimens of the control mix, failed before reaching 180 cycles. It is not clear whether the rapid reduction of the RDM in this study is due to the fact that it is high strength concrete, which may be more brittle and contains substantial amount of superplasticizer, or due to experimental errors.

Figure 7 shows the physical condition of specimens of concrete composite B25F00 after 4 weeks of rapid freezing and thawing whereas Figure 8 shows the physical condition of specimens of the control mix 6 weeks of rapid freezing and thawing. It is interesting to note that the concrete composite specimens do not show too much spalling or damage to the concrete surface. However, the specimens have developed substantial cracking. This is primarily the reason for substantial reduction in the transverse frequency and RDM. It is unclear whether the development of cracks was due to the presence of fly ash and bottom or possibly brittle nature of the high performance concrete. Therefore, further study on this topic for high strength concrete is needed to determine the reason for substantial decrease in the RDM.

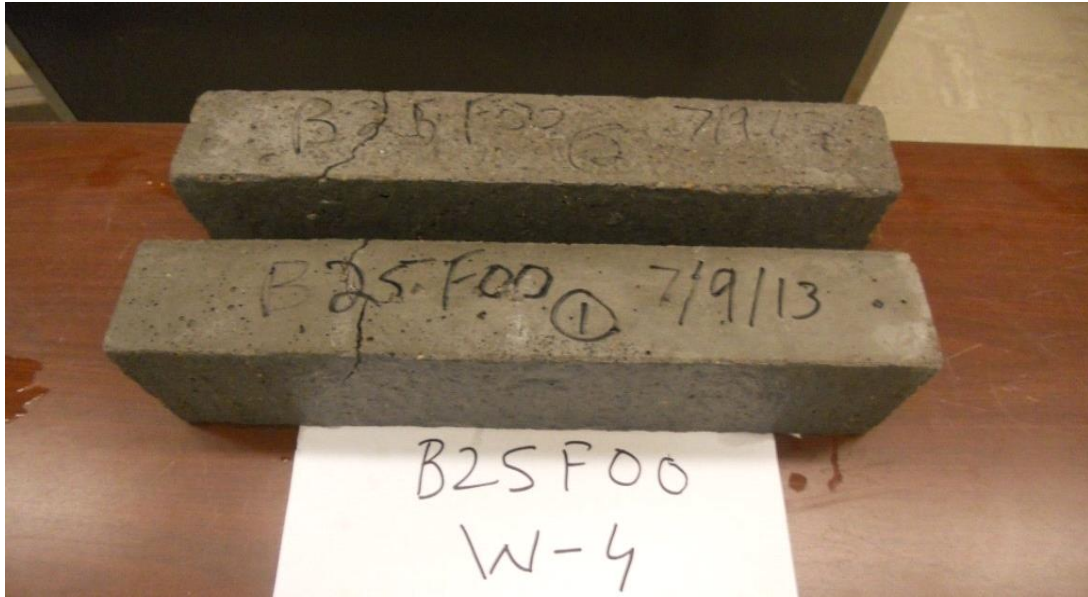


Figure 7 Condition of B25F00 specimen after 4 weeks (28 day curing)



Figure 8 Condition of Control Mix specimen after 6 week (28 day curing)

CONCLUDING REMARKS

Based on the comprehensive laboratory testing performed in this study, the following conclusions have been drawn.

1. Addition of Class F fly ash and PCC bottom ash require higher amount of water to achieve the targeted slump because of high absorption of bottom ash. The concrete composites with 50% bottom ash require more water than with 25% bottom ash, i.e., the quantity of water increased with the increase in the quantity of bottom ash.
2. The amount of air-entraining agent required for concrete composites was slightly higher than that was required for the equivalent control mix to achieve the same air-content level. The results also show that the dose of the air-entraining agent marginally decreased with the increase in fly ash content. Whereas, the increase in the amount of bottom ash from 25 to 50% appears to have an insignificant effect.
3. The compressive strength results show that all of the concrete composites prepared and tested in this study achieved the targeted compressive strength of 8,000 psi at 28 days of curing.
4. The compressive strength of the concrete composites was lower than that of an equivalent conventional concrete (control mix) for early periods of curing, i.e., up to 28 days, however, after that the compressive strength was almost at par or more than that of an equivalent conventional concrete.
5. The compressive strengths of the composites, at 28 days curing, were found to be 17-20 percent lower than that of the control mix. At higher curing periods, chemical composition of the fly ash and bottom ash played role in the strength gain of the composites. As a result, at 180 days of curing, the compressive strengths of concrete composites were within 7 percent of the compressive strength of an equivalent conventional concrete. Therefore, it was concluded that the long term compressive strength of concrete composites made with Class F fly ash and PCC bottom ash is likely to be similar to that of an equivalent conventional concrete.
6. For concrete composites containing 25% bottom ash, increased replacement of the portland cement with Class F fly ash resulted in decreased compressive strength. The total decrease in the compressive strength of concrete composites when the fly ash percentage increased from 0 to 30 at 3 day of curing was approximately 36% whereas at 28 days of curing the compressive strength decrease was approximately 16% when the fly ash percentage increased from 0 to 30%. At higher curing ages, i.e., 60 and 180 days, the trend is not as clear as at lower curing ages.
7. The splitting-tensile strength results show that at 180 days of curing, the strength of concrete composites made with 25% bottom ash was approximately 5 to 15% higher than that of an equivalent conventional concrete. Whereas, the splitting-tensile strength of the concrete composites made with 50% bottom ash at 180 days of curing was 13.5 to 19% lower than that of an equivalent concrete.
8. According to ACI, splitting-tensile strength of concrete can be estimated as 6.7 times the square root of the compressive strength. Based on the data developed in this study, it was concluded that a factor, 6.78 (instead of 6.7) is more appropriate for estimating the splitting-tensile strength of high strength concrete composites at 28 days of curing.
9. The flexural strength of concrete composites made with 25% bottom ash at 180 days of curing show flexural strength within 3% of the flexural strength of the control mix whereas, flexural strength of the concrete composites made with 50%t bottom ash was 18-22% more than that of the control mix. The overall trend of change in the flexural strength with the increase in the fly ash content was similar to that observed for the

compressive strength, i.e., with the increase in the quantity of fly ash from 0 to 30%, there was decrease in the flexural strength. The total decrease in the flexural strength, when the fly ash percentage increased from 0 to 30%, at 3 days of curing was 16%, at 7 days of curing was 23%, at 28 days of curing was 10% and at 180 days of curing was 5.5%. As the curing progressed, the percentage decrease of flexural strength also decreased except for 7 days of curing.

10. The behavior of the concrete composites under the rapid freeze-thaw tests observed in the study is not consistent with the results published by other researches for normal weight and normal strength concrete. In this study, all specimens, including specimens of the control mix, failed before reaching 180 cycles. It is not clear whether the rapid reduction of the RDM in this study is due to the fact that it is high strength concrete, which may be more brittle and contains substantial amount of superplasticizer, or due to experimental errors. Therefore, further study on this topic for high strength concrete is needed to determine the reason for substantial decrease in the RDM.

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