IMPACT COMPACTED NON-CEMENT CONCRETES

N. Ghafoori and M. Najimi
Department of Civil and Environmental Engineering and Construction, University of Nevada Las Vegas, Las Vegas, Nevada, USA
Corresponding author: Nader Ghafoori, Professor, Department of Civil and Environmental Engineering and Construction, University of Nevada Las Vegas. 4505 Maryland Parkway, Box 454015, Las Vegas, Nevada 89154-4015, Phone: 702-895-2531, Fax:702-895-3936, nader.ghafoori@unlv.edu; Co-author email: najimim@unlv.nevada.edu

ABSTRACT

The study presented herein examines the medium and long-term characteristics of impact compacted non-cement composites made with fluidized bed combustion bottom ash, known as FBC spent bed, pulverized coal combustion (PCC) fly ash, and crushed limestone coarse aggregate. In the preliminary phase of this study, several mixtures were made, at their optimum moisture contents corresponding to Modified Proctor compaction method, using different proportions of raw materials. In the complementary phase, three optimum impact compacted non-cement concretes were subjected to an experimental program that included compressive, tensile, and flexural strengths; elastic modulus; resistance to internal sulfate attack; abrasion wear; and resistance to freezing and thawing. Laboratory results revealed higher compressive strength and resistance to internal sulfate attack with increasing coarse aggregate content. While strength, stiffness, and resistance to abrasion and freezing/thawing improved with decreases in FBC spent bed to PCC fly ash ratios, opposite performance was observed for sulfate-induced expansion.

Keywords: FBC spent bed; PCC fly ash; impact compacted; non-cement; FBC/PCC.

INTRODUCTION

The generation, transmission, and distribution of electricity is one of the nation's largest industries. With annual revenue in excess of $140 billion and assets of about $500 billion, the electric utility industry provides vital services to nearly every person in the United States (EPA, 1987). The demand of electricity in the U.S has increased considerably over the years and most likely will continue to grow in the years to come. Every major portion of the United States economy relies on electricity, both in the private and commercial sectors.

The coal utilized to generate electricity also produces a large amount of by-product residues which must be disposed of and/or utilized in an environmentally sound manner. The quantity and characteristics of these combustion by-products are mainly affected by the coal and boiler types, and by ash collecting devices employed by the power generating utilities across the country (EPRI, 1984). According to the degree of hardness, moisture and heat content, the coal is classified into four groups; namely, bituminous, sub-bituminous, lignite, and anthracite (Mora and Ghafoori, 1996). In the United States, bituminous coal is the most abundant of all and is used by both power generating utility and steel industry. To date, the power generating utility employs: (1) pulverized coal-fired, (2) cyclone, (3) stoker-fired, and (4) fluidized bed combustion boilers to transform coal chemical energy into electricity (EPRI, 1984). Undoubtedly, the differences in combustor operating conditions produce the type of end products with varying physico-chemical characteristics (Henke et al., 1987).

The research program presented herein was designed to investigate the engineering properties and long-term durability of impact compacted non-cement concretes. FBC spent bed, coarser particles obtained from bottom of FBC boilers and PCC fly ash, fine particles obtained from electrostatic precipitators of pulverized coal combustor, were combined with crushed limestone coarse aggregate at their optimum water contents and fabricated in accordance with the Modified Proctor compaction method. The concrete specimens were subjected to a series of laboratory tests in order to ascertain their suitability as paving materials.

MATERIALS

The matrix constituents used in this study included PCC fly ash as a binder, FBC spent bed as a primary fine aggregate and supplier of lime to activate pozzolan oxides of PCC fly ash, crushed limestone as a coarse aggregate, and tap water. The chemical and physical properties of PCC fly ash and FBC spent bed are presented in Tables 1 and 2, respectively.

Table 1. Chemical properties of FBC spent bed and PCC fly ash

Chemical composition, %	FBC spent bed	PCC fly ash	Fly ash specifications, ASTM C618
Silicon Oxide (SiO_2)	9.7	49.1	-
Aluminum Oxide (Al_2O_3)	3.69	25.5	-
Iron Oxide (Fe_2O_3)	2.16	16.6	-
Total (SiO_2+Al_2O_3+Fe_2O_3)	15.55	91.2	50.0 minimum,--> Class C 70.0 minimum, --> Class F
Sulfur Trioxide (SO_3)	24.42	0.5	5.0 maximum
Calcium Oxide (CaO)	53.10	1.56	Less than 10 percent, --> Class F More than 10 percent, --> Class C
Magnesium Oxide (MgO)	0.88	0.89	-
Loss of ignition	0.8	0.38	6.0 maximum
Free moisture	0	0.16	3.0 maximum
Total Na_2O	0.16	0.37	-
Available alkalis as Na_2O	-	0.08	1.5 maximum
Total K_2O	0.39	2.26	-
Others	2.04	2.6	-

Table 2. Physical properties of FBC spent bed, PCC fly ash, and coarse aggregate

Physical property	FBC spent bed	Fly ash		Coarse aggregate
		PCC fly ash	Specifications	
Fineness modulus	1.80	-	-	-
Specific gravity (OD)	1.92	2.40	-	2.64
Specific gravity (SSD)	2.19	-	-	2.67
Absorption, %	14.60	-	-	0.75
Organic impurities, %	-	-	-	-
Amount retained on No. 325 sieve, %	-	22.4	Max, 34	-
Autoclave expansion, %	-	0.03	Max, 0.8	-
Water requirement; % of control	-	96.30	Max, 105	-
7-day compressive strength; % of control	-	82.0	Min, 75	-

The summation of silica, alumina and iron oxides for the PCC fly ash was 91.2%, exceeding the 70% requirement of ASTM C618 (ASTM, 2012) for class F fly ash. The summation of pozzolanic oxides was low for the FBC spent bed (15.55%). On the other hand, FBC spent bed consisted of 53.1% calcium oxide which was an excellent source for activation of PCC fly ash. No organic impurities were found in the FBC spent bed when tested according to ASTM C40 (ASTM, 2011). The amount of sulfate ions of the FBC spent bed was high (24.4%), a source contributing to formation of ettringite compounds. Physical properties of the FBC spent bed were different from those of natural fine aggregates. It was finer and lighter than a regular natural fine aggregate, having fineness modulus of 1.8 and specific gravity of 2.19. Its absorption was significantly higher than the usual absorption of natural fine aggregate due to its porous micro-structure. The physical properties of coarse aggregate are also presented in Table 2.

MIXTURE PROPORTIONS

Prior to the actual experimentation, several trial non-cement concrete were prepared using Modified Proctor compaction method and tested to determine their optimum moisture contents. They were used to prepare 15 different impact compacted non-cement concretes as shown in Table 3. As can be seen, these mixtures were designed with different FBC spent bed to PCC fly ash ratios of 1:1, 1.5:1, 2:1, 3:1, and 4:1, and coarse aggregate contents of 50, 55, and 60%.

Table 3. Mixture proportions of impact compacted non-cement concretes

Mixture identification	FBC/PCC	Coarse aggregate content (%)*	PCC fly ash (%)*	FBC bottom ash (%)*	Optimum moisture content (%)	W/b ratio	Demolded density (kg/m^3)
IC4-50	4 to 1	50	10.00	40.00	10.15	1.015	2225.0
IC4-55		55	9.00	36.00	8.27	0.919	2261.3
IC4-60		60	8.00	32.00	8.11	1.014	2279.4
IC3-50	3 to 1	50	12.53	37.47	10.00	0.798	2241.8
IC3-55		55	11.27	33.73	7.87	0.698	2265.3
IC3-60		60	10.00	30.00	7.73	0.773	2292.4
IC2-50	2 to 1	50	16.67	33.33	9.50	0.570	2248.2
IC2-55		55	15.00	30.00	7.73	0.515	2273.8
IC2-60		60	13.33	26.67	7.60	0.570	2298.0
IC1.5-50	1.5 to 1	50	20.00	30.00	9.07	0.453	2251.1
IC1.5-55		55	18.00	27.00	7.67	0.426	2276.5
IC1.5-60		60	16.00	24.00	7.47	0.567	2300.3
IC1-50	1 to 1	50	25.00	25.00	8.87	0.355	2257.8
IC1-55		55	22.50	22.50	7.53	0.335	2284.9
IC1-60		60	20.00	20.00	7.40	0.370	2303.5

* Percentage by weight of total dry solids

PRELIMINARY STUDIES (PHASE I)

In this phase of study, the designed impact compacted FBC/PCC contained concretes of Table 3 were examined for their compressive strengths and sulfate-induced expansions. The findings are reported and discussed in the following subsections.

Compressive Strength

Compressive strength of impact compacted non-cement concretes was measured at the ages of 7, 28, 90 and 180 days and the results are shown in Table 4. Compressive strength enhanced by increasing FBC spent bed to PCC fly ash ratio and decreasing coarse aggregate content. For a given FBC/PCC, the highest compressive strength was observed for the mixtures containing 60% coarse aggregate. Moreover, the FBC spent bed to PCC fly ash ratio of 1/1 produced the highest compressive strength amongst mixtures of the same coarse aggregate content. It was also observed that the gap between the best and worst performed concretes was narrowed with increases in curing time.

Table 4. Compressive strength of impact compacted non-cement concretes

Mixture identification	FBC to PCC ratio	Coarse aggregate content (%)	Compressive strength (MPa)				Strength ratios		
			7 days	28 days	90 days	180 days	7/180	28/180	90/180
IC4-50	4 to 1	50	3.2	11.8	20.5	25.1	0.13	0.47	0.82
IC4-55		55	4.1	13.2	22.8	26.6	0.15	0.50	0.86
IC4-60		60	4.9	14.6	27.1	30.3	0.16	0.48	0.89
IC3-50	3 to 1	50	4.5	13.5	26.5	31.2	0.14	0.43	0.85
IC3-55		55	5.7	15.6	31.5	33.2	0.17	0.47	0.95
IC3-60		60	6.3	16.7	32.7	35.7	0.18	0.47	0.92
IC2-50	2 to 1	50	5.6	19.9	35.6	36.7	0.15	0.54	0.97
IC2-55		55	6.6	20.6	36.6	38.3	0.17	0.54	0.95
IC2-60		60	7.1	21.7	37.2	39.4	0.18	0.55	0.94
IC1.5-50	1.5 to 1	50	6.6	21.4	37.9	39.0	0.17	0.55	0.97
IC1.5-55		55	7.4	22.1	38.7	40.0	0.19	0.55	0.97
IC1.5-60		60	8.8	24.0	39.5	41.4	0.21	0.58	0.95
IC1-50	1 to 1	50	8.4	24.3	40.2	41.4	0.20	0.59	0.97
IC1-55		55	10.7	25.3	41.0	44.2	0.24	0.57	0.93
IC1-60		60	11.2	26.5	42.7	43.7	0.26	0.61	0.98

The 28-day compressive strength of impact compacted non-cement concretes with FBC/PCC of 4/1, 3/1, 2/1 and 1.5/1 were averagely 48, 40, 18 and 11% lower than those of mixtures with FBC/PCC of 1/1. These values decreased to 37, 23, 11 and 7%, respectively, at the curing age of 180 days. This observation suggested that a higher portion of 180-day compressive strength can be achieved at early ages through reduction in FBC spent bed to PCC fly ash ratio. While the 28- and 90-day compressive strengths of concretes having FBC/PCC of 1/1 were on the average 59 and 96% of the 180-day strength, respectively, these values decreased to 46 and 86% for the FBC/PCC of 4/1. The afore-mentioned behavior can be credited to the higher availability of fly ash for binding as FBC spent bed to PCC fly ash ratio reduced. The fly ash contents for the mixtures having FBC/PCC of 4/1 were 8 to 10% in comparison to more than 20% for the concretes made with FBC/PCC of 1/1.

The compressive strength of the selected concretes also increased when coarse aggregate content increased. This improvement mostly occurred at early ages. On the average, the 7-day compressive strength of the mixtures containing 50 and 55% coarse aggregate were 26 and 10%, respectively, lower than that of the concretes with 60% coarse aggregate by weight of total dry solid. Once curing age increased to 90 days and beyond, these values reduced to nearly 10 and 5%, respectively. This finding can be attributed to the amount of PCC fly ash and FBC spent bed. Concretes with a higher coarse aggregate content had a smaller amount of PCC fly ash to contribute to late strength.

Internal sulfate attack

Since FBC spent bed contained high concentration of sulfate ions, there was an undeniable potential of internal sulfate attack due to formation of ettringite compounds. As such, sulfate-induced expansion can be recognized as an important issue potentially limiting applications of the studied concretes. Linear expansions of impact-compacted concretes due to internal sulfate attack were measured and the results are presented in Figures 1 through 3 for different coarse aggregate contents. As can be seen, all concretes continued expansions for 7 weeks, after which they experienced slight shrinkage-like behavior due to depleted source of water. The sulfate-induced expansions reduced with increases in FBC spent bed to PCC fly ash ratio and coarse aggregate content.

While increasing FBC spend bed to PCC fly ash ratio reduced sulfate-induced expansions, the most reduction was seen for the impact compacted concretes containing 60% coarse aggregate by weight of total dry solid. The 78-week expansion of the mixtures containing 50% coarse aggregate improved by nearly 39, 5 and 7% when FBC/PCC increased from 1/1 to 2/1, 2/1 to 3/1 and 3/1 to 4/1, respectively. These improvements were 48, 40 and 24% for the mixtures having 55% coarse aggregate, and 68, 72, and 100% for concretes containing 60% coarse aggregate. On average, increasing coarse aggregate content from 50 to 55 and 55 to 60 led to 36 and 56% reductions in expansion, respectively. These improvements can be related to the lower availability of pozolanic oxides, as well as higher degree of restraint induced by the use of additional coarse aggregate.

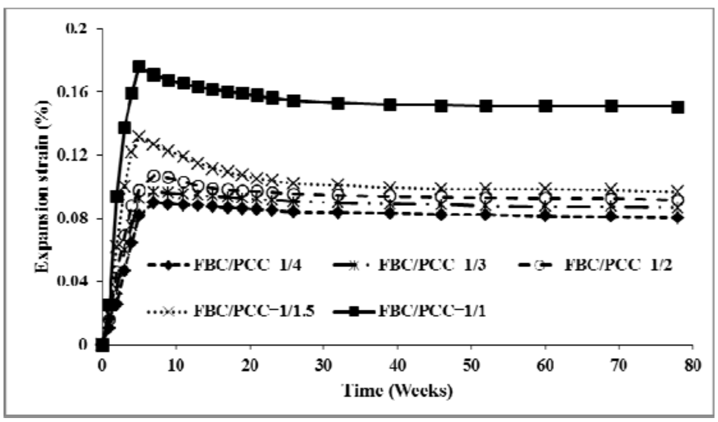

Figure 1. Expansion of impact compacted non-cement concretes with 50% coarse aggregate

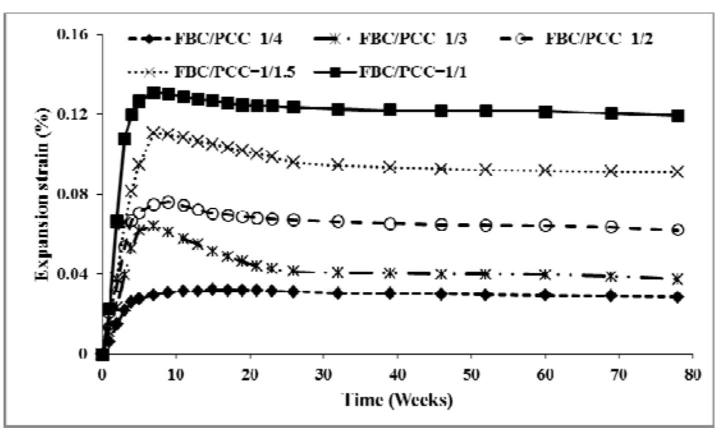

Figure 2. Expansion of impact compacted non-cement concretes with 55% coarse aggregate

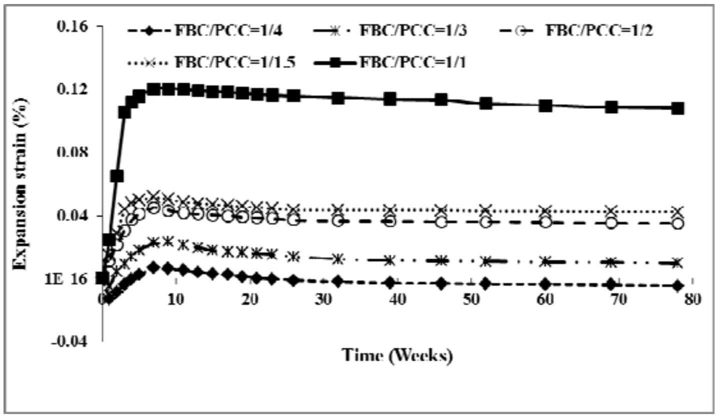

Figure 3. Expansion of impact compacted non-cement concretes with 60% coarse aggregate

COMPLEMENTARY STUDIES (PHASE II)

Three mixtures; namely, IC1-60, IC2-60 and IC4-60 were selected for the phase II of this investigation. These mixtures provided reasonable to best performance in generating maximum strengths and minimum sulfate-induced expansions.

Strength and stiffness properties

The strength and stiffness properties of the selected impact compacted non-cement concretes were measured at the ages of 28 and 90 days, and the results are reported in Table 5. The evaluated strength properties included compressive, splitting tensile, and flexural strengths; and static modulus of elasticity.

Table 5. Strength properties of impact compacted non-cement concretes

FBC to PCC ratio	Compressive strength (MPa)			Splitting tensile strength (MPa)			Flexural strength (MPa)			Modulus of elasticity (GPa)		
	Days			Days			Days			Days		
	28	90	28/90	28	90	28/90	28	90	28/90	28	90	28/90
4/1	14.6	27.1	0.54	2.2	3.4	0.65	2.6	3.9	0.67	15.5	18.5	0.84
2/1	21.7	37.2	0.58	2.7	3.5	0.76	3.1	4.4	0.71	19.4	24.4	0.80
1/1	26.5	42.7	0.62	3.0	3.8	0.79	3.5	4.9	0.71	22.2	26.1	0.85

Generally speaking, strength properties of the selected impact compacted concretes improved with reductions in FBC spent bed to PCC fly ash ratio. The 28-day compressive strength improved 48% when FBC/PCC decreased from 4/1 to 2/1, and an additional 22% when it reduced from 2/1 to 1/1. These improvements were 23 and 11% for 28-day splitting tensile resistance; 17 and 13% for 28-day flexural strength; and 25 and 14% for 28-day elastic modulus. A similar trend, but not to the same extent, was observed at the curing age of 90 days. The afore-mentioned improvements can be related to 1) increase in PCC fly ash content and 2) reduction of water-to-binder ratio.

While strength properties of impact compacted concretes elevated with increases in curing age, the most improvement was noticed for compressive strength than splitting tensile resistance and flexural strength. The 28-day compressive strength of selected concretes was 45 to 62% of their 90-day compressive strength. The 28 to 90-day ratios for splitting tensile resistance and flexural strength were 56 to 79% and 67 to 71%, respectively. The elastic modulus of the impact compacted concrete followed a similar trend, exhibiting 28 to-90 day stiffness ratio of 80 to 85%. This behavior is consistent with the hypothesis that inclusion of new aggregate (i.e. FBC spent bed) affects compressive strength differently than it does tensile strength and elastic modulus.

The ratios of tensile to compressive strengths were also examined. These ratios varied between 0.096 to 0.150 and 0.096 to 0.180 for splitting tensile resistance and flexural strength, respectively, well within the range known for conventional concrete.

Resistance to abrasion

Abrasion resistance was measured according to ASTM C779, Procedure C, ball bearings (ASTM, 2010). Depth of wear was recorded every 30 seconds for a total test duration of 20 minutes or when a terminal depth of 3 mm was reached. Abrasion depths of the selected impact compacted non-cement concretes are shown in Figures 4 and 5 for wet and dry testing conditions, respectively.

Under both wet and dry conditions, abrasion resistance improved by decreasing FBC spent bed to PCC fly ash ratios. The impact compacted concrete with FBC/PCC of 1/1 showed the lowest depth of wear capable of completing 20 minutes of test duration, without reaching a terminal depth of 3 mm, under both wet and dry testing conditions. Under dry conditions, reduction of FBC spent bed to PCC fly ash ratios from 4/1 to 2/1 and 2/1 to 1/1 improved abrasion resistance by nearly 22 % for each increment. This behavior can be attributed to the decrease in water-to-binder ratio, as well as the increase in compressive strength.

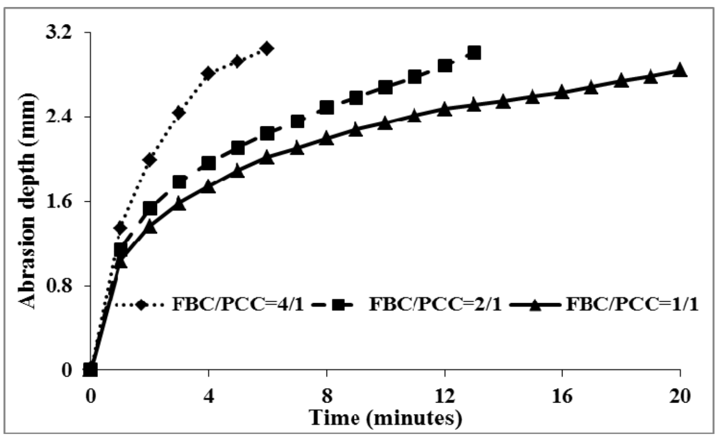

Figure 4. Abrasion wear of impact compacted non-cement concretes (wet at testing)

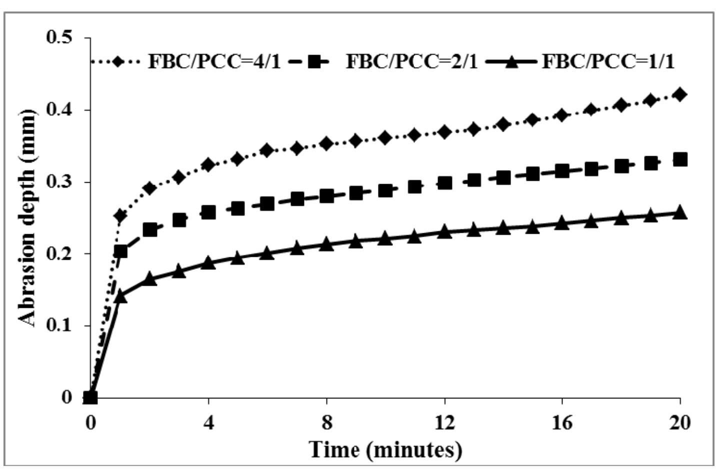

Figure 5. Abrasion wear of impact compacted non-cement concretes (dry at testing)

Resistance to freezing and thawing

The freezing and thawing resistance of the studied impact compacted non-cement concretes was evaluated for mass loss and volume expansion, and the results are presented in Table 6. As can be seen, mass loss and volume expansion of the trial matrices decreased with reductions in FBC spent bed to PCC fly ash ratios. After 10 freezing and thawing cycles, the mass loss reduced by nearly 62.5 and 83% when FBC/PCC decreased from 4/1 to 2/1 and 2/1 to 1/1, respectively. Similarly, the volume expansions reduced by 35 and 44 %. Improvement in frost resistance can be related to the decrease in water-to-binder ratio, increase in compressive strength, and decrease in water absorption of concretes through reduction in FBC spent bed to PCC fly ash ratios. Water absorption of impact-compacted non-cement concretes were 3.53, 3.17 and 2.63% for FBC spent bed to PCC fly ash ratios of 4/1, 2/1 and 1/1, respectively.

Table 6. Freezing/thawing resistance of impact compacted non-cement concretes

Freeze and thaw cycles	Cumulative mass loss (%)			Volume expansion (%)		
	FBC/PCC					
	4/1	2/1	1/1	4/1	2/1	1/1
1	0.12	0.08	0.04	0.27	0.19	0.10
2	0.26	0.16	0.08	0.29	0.21	0.11
3	0.38	0.28	0.12	0.31	0.22	0.12
4	0.55	0.41	0.15	0.33	0.25	0.13
5	0.74	0.54	0.18	0.36	0.26	0.14
6	0.94	0.65	0.22	0.40	0.27	0.15
7	1.47	0.84	0.25	0.43	0.30	0.17
8	2.10	1.05	0.28	0.48	0.33	0.18
9	3.27	1.49	0.30	0.55	0.36	0.20
10	5.16	1.94	0.33	0.60	0.39	0.22

CONCLUSIONS

From the results of this study, the following conclusions can be drawn:

1. Strength and stiffness properties of the studied impact compacted non-cement concretes improved with decreases in FBC spent bed to PCC fly ash ratio and with increases in coarse aggregate content. Concrete containing 60% coarse aggregate by weight of total dry solid and FBC/PCC of 1/1 produced highest strength and elastic modulus.
2. Increases in coarse aggregate content and FBC spent bed to PCC fly ash ratio reduced sulfate-induced expansion of the studied impact compacted non-cement concretes.
3. Improvement in compressive strength, with an increase in curing age, was more for compressive strength than it was for splitting-tensile resistance, flexural strength, and elastic modulus.
4. Depth of wear, mass loss and volume expansion due to freezing and thawing cycles, and water absorption of the studied concretes decreased when FBC spent bed to PCC fly ash ratio reduced.

ACKNOWLEDGMENTS

This research was funded by grants made possible by the Illinois Department of Energy and Natural Resources, and by the US. Department of Energy (Grant number DE-FB22-91PC91334). However, any opinions, findings, conclusions, or recommendations expressed herein are those of authors and do not necessarily reflect the views of the IDENR and DOE. Thanks are extended to a number of manufacturers who contributed materials used in the investigations. Their names are withheld to avoid any concern of commercialism or private interest.

REFERENCES

ASTM C40 (2011) *Standard test method for organic impurities in fine aggregates for concrete,* American Society for Testing and Materials.

ASTM C618 (2012) *Standard specification for coal fly ash and raw or calcined natural pozzolan for use in concrete*, American Society for Testing and Materials.

ASTM C779 (2010) *Standard test method for abrasion resistance of horizontal concrete surfaces,* American Society for Testing and Materials.

EPA reports to congress. (1987) Wastes from the combustion of coal by electric utility power plants, United States Environmental Protection Agency.

EPRI report. (1984) *Coal-combustion by-products utilization manual, V. 1: Evaluating the utilization option*, Report No. CS-3122, prepared by Baker M.

Henke, K. R., Zobeck, B. S., Moretti, C. J., Mann, M. D. (1987) "Leaching studies of solid wastes generated from fluidized bed combustion of low-rank western coals." Proceedings: 9th international conference on fluidized bed combustion, Boston, 954-959.

Mora, C. A. M., and Ghafoori, N. (1996) Laboratory-made non-cement roller compacted coal combustion utilizing fluidized bed and pulverized coal combustion by-products, MSc thesis, 274 pp.