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VIBRATORY-PLACED NON-CEMENT AND PARTIALLY-CEMENT CONCRETES CONTAINING FLUIDIZED BED AND PULVERIZED COAL COMBUSTIONS RESIDUES

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ABSTRACT

The research study presented herein evaluates fresh and hardened properties of laboratory-made vibratory-placed non-cement and partially-cement concretes containing various dosages of pulverized coal combustion fly ash and Portland cement as binders, fluidized bed combustion spent bed as a primary fine aggregate, river sand as a secondary fine aggregate, and crushed limestone as a coarse aggregate. While test results revealed that unit weight of fresh concrete increased by increasing cement content, plastic shrinkage and setting times displayed the contrary. Early strengths of non-cement and partially-cement concretes were lower than those of control concrete, whereas late strengths were similar to or higher than those of reference concrete. The selected non-cement and partially-cement concretes produced higher expansion and lower drying shrinkage than those of reference concrete. Abrasion resistance of non-cement and partially-cement mixtures under sealed conditions were better than that of reference concrete, whereas opposite results were obtained under wet conditions. Rapid chloride permeability test results of non-cement and partially-cement mixtures were twice of that of control concrete.

KEYWORDS: Non-cement concrete; partially-cement concrete; fluidized bed combustion ash (FBC spent bed); pulverized coal combustion ash (PCC fly ash); FBC to PCC ratio.

INTRODUCTION

In an attempt to reduce the potential hazard of acid rain, coal-fired plants burning high sulfur coal have adopted a new technology called fluidized bed combustion unit (FBC). This system is attractive because it increases generating capacity, extends life of coal-fired plants, and reduces air pollution at a cost lower than any other external sulfur reduction systems (EPRI, 1987; Ghafoori and Mora, 1998).

FBC by-product residues are generated by burning high sulfur coal in a limestone bed (EPRI, 1987) producing spent bed obtained from bottom of boiler, fly ash collected by fabric filters or electrostatic precipitators, and char which is a coarser flue gas residue. FBC residues contain lower amount of pozzolan oxides and considerably higher amount of calcium oxide (mostly in free form) and SO_3 ions (mainly anhydrate calcium sulfate) than coal by-products generated by conventional coal combustion units. Once water is added, FBC residues display a considerable amount of heat as it reacts with free lime to form hydrated lime. Moreover, the combination of anhydrate calcium sulfate ($CaSO_4$) and water generates hemi-hydrate calcium sulfate ($CaSO_4.1/2H_2O$) and subsequently calcium sulfate dihydrate ($CaSO_4.2H_2O$). Hydration of lime to calcium hydrate results in a nearly 100% molar volume change, whereas hydration of anhydrate calcium sulfate results in a minimal increase in molar volume (Ghafoori and Sami, 1992). When FBC by-product residues are combined with pozzolanic materials, such as fly ash (used as a cementitious material), a series of chemical reactions results in formation of ettringite compounds. The formation of ettringite compounds is temperature dependent which can be made possible by the temperature generated through hydration reaction of free lime.

In order to prevent heating and expansion during mixing and early age of the matrix, and to reduce formation of ettringite-related reactions, preconditioning of FBC by-products was required (Ghafoori and Sami, 1992). A simple and effective water preconditioning was developed to completely exhaust the heat of hydration of FBC residue and to convert its free lime to hydrated lime at an optimum hydration of nearly 12% by weight of water addition (Ghafoori and Sami, 1992). Preconditioned FBC residue was rich in calcium oxide and capable of activating pozzolan oxides of conventional fly ash. For this reason, a combination of preconditioned FBC spent bed as a granular material and supplier of lime, and class F pulverized coal combustion (PCC) fly ash with its abundant pozzolan oxides provided a unique opportunity to examine the suitability of these two by-products for construction materials. This study examines fresh and hardened properties of vibratory-placed non-cement and partially-cement concretes containing different amounts of PCC fly ash and FBC spent bed. The results are also compared with those of reference concrete.

EXPERIMENTAL PROGRAM

Materials

The matrix constituents used in this study included PCC fly ash and Portland cement as primary and secondary binders, respectively; FBC spent bed as a primary fine aggregate and supplier of lime to activate fly ash; siliceous natural sand as a secondary fine aggregate; crushed limestone as a coarse aggregate; and tap water. The chemical and physical properties of PCC fly ash, FBC spent bed, and Portland cement are presented in Tables 1 and 2, respectively.

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

Chemical composition, %	FBC spent bed	PCC fly ash	Portland cement
Silicon Oxide (SiO_2)	9.7	49.1	21.88
Aluminum Oxide (Al_2O_3)	3.69	25.5	4.37
Iron Oxide (Fe_2O_3)	2.16	16.6	2.84
Total (SiO_2+Al_2O_3+Fe_2O_3)	15.55	91.2	-
Sulfur Trioxide (SO_3)	24.42	0.5	2.76
Calcium Oxide (CaO)	53.10	1.56	62.62
Magnesium Oxide (MgO)	0.88	0.89	3.94
Loss of ignition	0.8	0.38	0.73
Water of hydration	2.65	0	-
Total Na_2O	0.16	0.37	0.55
Available alkalis as Na_2O	-	0.08	-
Total K_2O	0.39	2.26	-
Others (TiO_2+P_2O_5+SrO+BaO)	2.04	2.6	-

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

Physical property		PCC fly ash	Fine aggregate		Coarse aggregate
			FBC spent bed	Siliceous sand	
Fineness modulus		-	1.80	2.80	-
Specific gravity	OD	2.40	1.92	2.65	2.64
	SSD	-	2.19	2.66	2.67
Absorption, percent		-	14.60	0.50	0.75
Organic impurities		-	-	-	-
Clay lump friable particles, %		-	-	1.75	-
Amount retained on No. 325 sieve, %	actual	22.40	-	-	-
	limit, max	34.00	-	-	-
Autoclave expansion, %	actual	0.03	-	-	-
	limit, max	0.80	-	-	-
Water requirement, percent of control	actual	96.30	-	-	-
	limit, max	105.00	-	-	-
7-day compressive strength, percent of control	actual	82.00	-	-	-
	limit, min	75.00	-	-	-

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 total pozzolan oxides was really 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 aggregate. It was finer and lighter than natural fine aggregate, having fineness modulus of 1.8 and specific gravity of 2.19. Its absorption was significantly higher than natural fine aggregate due to its porous micro-structure. The physical properties of natural fine and coarse aggregates are presented in Table 2.

Mixture proportion

Based on the preliminary studies, the FBC spent bed to PCC fly ash ratio of 3 to 1 was selected for this research investigation (Ghafoori, 1994). Table 3 documents mixture proportions of the studied non-cement, partially-cement, and control concretes. In this table, non-cement concrete (NonCem-0) was designed based on FBC/PCC of 3 to 1, and without using natural fine aggregate and Portland cement. Other non-cement and partially-cement mixtures were designed based on mixture NonCem-0 by replacing 20% by volume of FBC spent bed with natural fine aggregate, and 1/3 and 2/3 by weight of PCC fly ash with Portland cement. The control concrete was a regular concrete without coal combustion by-products. All laboratory mixtures were prepared at a constant slump value of 102±6 mm (4±1/4 inches) and subjected to fresh and hardened properties tests including initial and final setting times, air content, plastic shrinkage, unit weight, compressive strength, internal sulfate attack, drying shrinkage, resistance to abrasion and rapid chloride permeability. The test specimens were seal-cured until testing time.

Table 3. Mixture proportions of non-cement and partially-cement concretes

Mixture identification	FBC spent bed (Kg/m^3)	PCC fly ash (Kg/m^3)	Portland cement (Kg/m^3)	Natural coarse aggregate (Kg/m^3)	Natural fine aggregate (Kg/m^3)	W/b ratio*
NonCem-0	772.8	282	0	851.2	0	0.69
NonCem-20	618.2	282	0	851.2	187	0.61
ParCem1/3-20	618.2	211.5	93.1	851.2	187	0.60
ParCem2/3-20	618.2	141	186.2	851.2	187	0.60
Control	0	0	297	851.2	998	0.62

* W/b ratio: Water to binder (PCC fly ash plus Portland cement)

TEST RESULTS AND DISCUSSION

Fresh properties

Table 4 documents fresh properties of the studied concretes. Due to the porous structure of FBC spent bed, FBC/PCC contained concretes demanded higher amounts of adding water than control concrete in attaining a uniform slump.

The unit weight of non-cement and partially-cement concretes were lower than those of control concrete. While these concretes produced lower unit weight, the results remained in a typical range of normal weight concrete. The lower unit weight of non-cement and partially-cement concretes can be related to the lower specific gravity of FBC spent bed and PCC fly ash in comparison with those of natural fine aggregate and Portland cement, respectively. Air contents of non-cement and partially-cement concretes were in a typical range of non-air entrained concretes.

Table 4. Fresh properties of non-cement and partially-cement concretes

Mixture identification	Two-day unit weight (Kg/m^3)	Setting time (hours)		24 hours Plastic Shrinkage (%)
		Initial	Final	
NonCem-0	2098	46.5	65.25	-0.508
NonCem-20	2147	50.5	70.5	-0.537
ParCem1/3-20	2199	12.0	21.5	-0.203
ParCem2/3-20	2217	5.0	11.0	-0.195
Control	2333	6.5	8.5	-0.252

Setting times of non-cement and partially-cement concretes were 7 to 8 and 1 to 3 times of those of control concrete, respectively. An increase in cement content drastically decreased the initial and final setting times. While initial and final setting times of non-cement concretes were about 2 to 3 days, replacing 1/3 and 2/3 of PCC fly ash with Portland cement led to considerable reductions of setting times. The higher setting times of non-cement and partially-cement concretes can be attributed to the higher demand for mixing water to achieve the desired slump, as well as slow reactivity of class F fly ash.

Plastic shrinkage of non-cement concretes were higher than that of control concrete, while partially-cement mixtures produced lower plastic shrinkage when compared with control concrete. On average, plastic shrinkage of control and partially-cement concretes was nearly 50 and 60% lower than that of non-cement concrete, respectively. These findings can be attributed to the internal curing ability of FBC spent bed. It means that FBC spent bed as a porous material absorbed a significant amount of water in fresh state of concrete and this water gradually migrated out during drying of hardened concrete. This phenomenon is welldocumented for concrete mixtures incorporating lightweight or porous aggregates (Weber and Reinhardt, 1997; Suzuki et al., 2012; Ghourchian et al., 2013; Najimi et al., 2012).

Compressive Strength

Compressive strength of concrete mixtures were measured at the ages of 28, 60, 90, 120 and 180 days under sealed and soaked testing conditions and the results are presented in Table 5. As can be seen, the non-cement and partially-cement concrete specimens produced lower compressive strengths than those of control concrete at early ages, i.e. 28 days. Once curing age was extended to 180 days, the compressive strengths of these mixtures were similar to or higher than those of control concrete. In the case of non-cement mixture (NonCem-0), its 28-day compressive strength was almost 50% lower than that of control concrete, whereas the gap between these two concretes were narrowed to just 5 to 16% at the age of 180 days. The non-cement concrete containing 20% natural fine aggregate (NonCem-20) had a lower strength than control concrete at 28 days by nearly 40%. Its late-age strength (90 days and beyond) were similar to those of control concrete. Partially-cement concrete with Portland cement replacing 1/3 of PCC fly ash by weight showed 10 to 25% lower 28-day compressive strength than that of control concrete. This trend was reversed at the ages of 60 days and beyond. The strength of partially-cement concrete containing 2/3 cement in its binder was similar to or higher than that of control concrete at all ages of curing. The above-mentioned observations can be related to the late reactions of PCC fly ash. While control concrete developed almost 30% of its strength between 28 and 180 days, non-cement and partially-cement concretes produced more than half of their strengths during this period. Compressive strengths of all non-cement, partially-cement and control concretes were higher under sealed testing conditions than under soaked testing conditions. The reduction in strength was more evident in non-cement mixtures than in partially-cement and control mixtures. The lower strength under soaked testing conditions can be attributed to the higher availability of moisture at the time of testing.

Table 5. Compressive strengths of non-cement and partially-cement concretes

Mixture identification	Sealed condition at testing					Soaked condition at testing				
	28 days	60 days	90 days	120 days	180 days	28 days	60 days	90 days	120 days	180 days
NonCem-0	12.7	22.0	26.3	27.8	30.1	9.5	15.9	18.6	20.8	21.9
NonCem-20	14.4	23.1	28.4	30.4	33.2	12.0	17.2	21.6	22.7	23.9
ParCem1/3-20	17.6	25.3	29.7	34.0	34.4	15.0	20.6	23.4	25.5	27.0
ParCem2/3-20	21.4	27.4	30.6	32.4	34.9	17.3	22.0	24.2	26.2	27.7
Control	23.5	25.6	28.6	30.2	31.9	17.7	20.5	22.8	24.1	25.0

Internal sulfate attack

Since FBC spent bed contained high amount of sulfate ions, there was an undeniable potential of internal sulfate attack due to the formation of ettringite compounds. The issues regarding sulfate attack provided an impetus to investigate sulfate-induced expansions of non-cement and partially-cement concretes. Accordingly, linear expansions of non-cement and partially-cement concretes at different ages were measured under soaked and sealed conditions. The results are presented in Figures 1 and 2. As can be seen, expansions under soaked condition was significantly higher than those experienced under sealed conditions. On average, sealed expansion of non-cement and partially-cement concretes was 92.6% lower than that obtained under soaked conditions. Higher availability of moisture under continuously wet condition facilitated the formation of ettringite compounds and the resulting expansions.

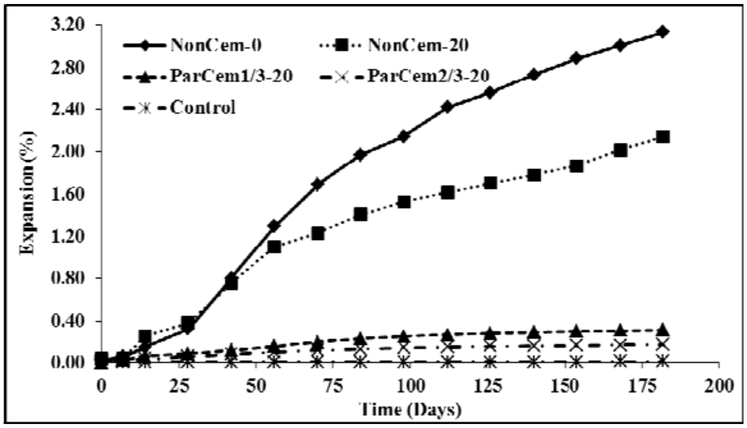

Figure 1. Internal sulfate attack expansions under soaked conditions

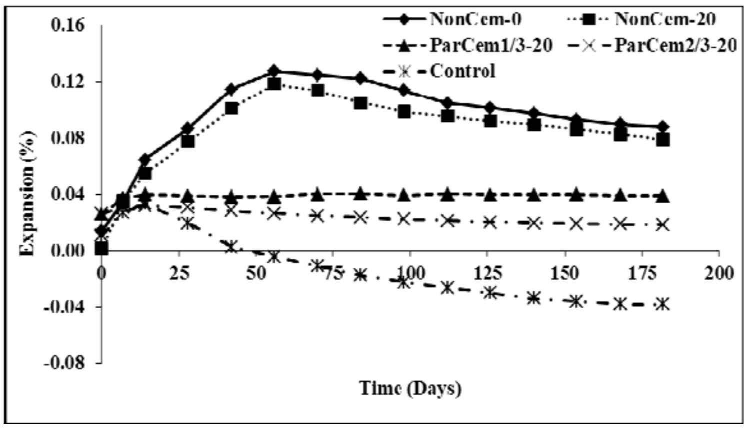

Figure 2. Internal sulfate attack expansions under sealed conditions

The sulfate-induced expansions of the trial mixtures decreased with increases in cement content. While expansion of non-cement concretes were really high under soaked condition, replacing 1/3 and 2/3 of PCC fly ash with Portland cement reduced expansions by nearly 85 and 92%, respectively. However, the expansion of the best performed partially-cement concrete was still higher than that of control concrete. The highest expansion under sealed conditions was observed for non-cement concretes. The sulfate-induced sealed expansions were only 3 to 4 % of those observed under soaked conditions. When Portland cement replaced 1/3 and 2/3 by weight of PCC fly ash, expansion of partially-cement concretes reduced by 51 and 77%, respectively. Replacing 20% of FBC spent bed with natural fine aggregate also decreased expansions of non-cement concretes. The reduction was 31.5 and 10% under soaked and sealed conditions, respectively. This behavior can be attributed to the reduction in availability of sulfate ions due to decreases in FBC spent bed contents.

Drying shrinkage

Drying shrinkage of non-cement, partially-cement, and control concretes were measured and the results are presented in Figure 3. While control concrete showed shrinkage strains of approximately 0.05% after a year, non-cement concretes exhibited 0.04 to 0.06% expansion during the same period. Partially-cement concretes showed the best performance with a minor expansion after a year of exposure to room temperature (23±1°C and RH 50±5%). The occurrence of expansion in drying shrinkage test is related to the sulfate-induced expansion of FBC/PCC contained concretes. Comparing the results shown in Figure 2 (internal sulfate attack in sealed condition) with those displayed in Figure 3 (drying shrinkage), a similar expansion can be seen at the age of 28 days for which it also became the peak expansion in drying shrinkage test. While drying shrinkage of the tested specimens occurred, combination of shrinkage with the earlier expansion didn't lead to any shrinkage measurements.

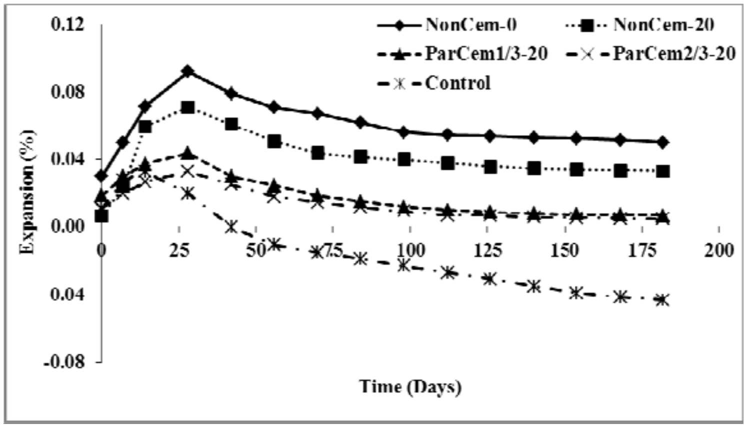

Figure 3. Drying shrinkage strains of non-cement and partially-cement concretes

Other properties

Since the studied non-cement and partially-cement concretes can be used for paving applications, their resistance to abrasion and chloride permeation were also evaluated.

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 non-cement, partially-cement and control concretes are shown in Figures 4 and 5 for wet and dry testing conditions, respectively. Abrasion test under wet conditions was harsh, as concrete abraded faster and deeper in a shorter duration. Under wet conditions, the selected non-cement and control concretes displayed the highest and lowest abrasion depths, respectively. While non-cement concretes gained 3 mm depth of wear just after 90 seconds, replacing 1/3 and 2/3 of PCC fly ash with Portland cement increased this time to 150 and 195 seconds. Time to reach a terminal depth of 3 mm was 315 seconds for control concrete. Under dry conditions, a reverse trend took place as the depth of wear of all non-cement and partially-cement mixtures were lower than that of control concrete. While control concrete reached a depth of 3 mm in 20 minutes under sealed conditions, the final abrasion depth of non-cement and partially-cement concretes were nearly 49 to 52% and 65 to 71% lower than that of control concrete, respectively.

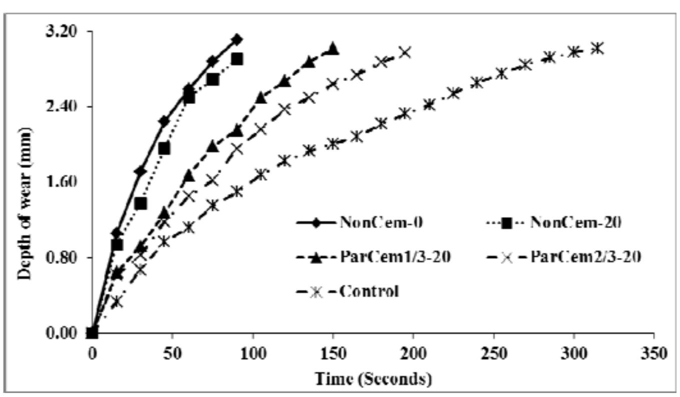

Figure 4. Abrasion wear of non-cement and partially-cement concretes (wet at testing)

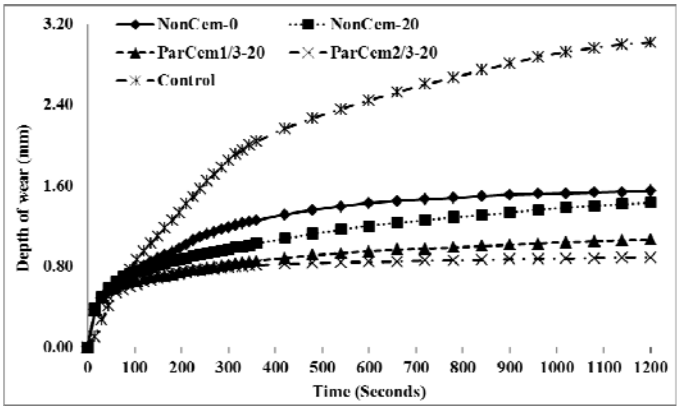

Figure 5. Abrasion wear of non-cement and partially-cement concretes (dry at testing)

Rapid chloride permeability of the studied concretes was measured at the ages of 28 days and in accordance with ASTM C1202 (ASTM, 2012). The results are presented in Table 6. While the designed control concrete could be categorized as a concrete with high chloride permeability, non-cement and partially-cement concretes allowed for twice as many of passing charges. The weak performance of FBC/PCC contained mixtures can be related to some extent to the slow reactivity of PCC class F fly ash at the tested age of 28 days.

Table 6. Rapid chloride permeability test results for non-cement and partially-cement concretes

Mixture identification	Charge passed (Coulomb)
NonCem-0	13060
NonCem-20	12885
ParCem1/3-20	12493
ParCem2/3-20	12240
Control	5732

CONCLUSIONS

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

1. Unit weight of the studied non-cement and partially-cement concretes were lower than that of control concrete. An increase in cement content increased the unit weight.
2. Setting times of non-cement and partially-cement concretes were higher than those of control concrete. Setting times of non-cement concretes were significantly high and impractical, whereas partially-cement concretes offered reasonable setting times.
3. While plastic shrinkage of non-cement concretes were higher than that of control concrete, partially-cement concretes exhibited similar or lower plastic shrinkage when compared to that of control concrete.
4. Compressive strengths of non-cement and partially-cement concretes were lower than those of control concrete at early ages, while their strengths were similar to or higher than the strengths of control concrete at late ages. Sealed strengths of FBC/PCC contained concretes were superior to those obtained under soaked conditions.
5. Non-cement and partially-cement concretes showed higher expansion strains than that of control concrete. Increases in cement content decreased the observed expansions. The selected FBC/PCC contained mixtures also expanded during drying shrinkage test.
6. Abrasion resistance of non-cement and partially-cement concretes was superior to that of control concrete under dry conditions. This trend was reversed under wet conditions.

7. Non-cement and partially-cement concretes allowed for twice as much chloride permeation than reference concrete did.

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