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Project Title: FIELD STUDIES OF ILLINOIS PCC BOTTOM ASH FOR STRUCTURAL GRADE CONCRETE PAVEMENTS

ICCI Project Number:	96-1/3.1A-26
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ABSTRACT

In the past four years, Southern Illinois University at Carbondale (SIUC), under the sponsorship of Materials Technology Center, has performed a series of laboratory research into engineering properties and long-term durability of vibratory-placed and roller compacted structural grade concretes containing bituminous pulverized coal combustion (PCC) bottom ash. These laboratory efforts have resulted in identification of a number of potentially viable commercial applications for PCC bottom ash by-product residues.

One potential and promising application of the Illinois PCC solid waste residues, which also accounts for the large utilization of coal-based by-product materials, is in pavement construction. The proposal presented herein is intended to embark on a new endeavor in order to bring the commercialization aspect of the initial laboratory project a step closer to reality by conducting a field demonstration of the optimized mixtures identified during the four-year laboratory investigation. Eight different pavement slabs (each 24 ft wide by 24 ft long) were constructed at an identified site located in the Illinois Coal Development Park, Carterville, by two construction contractors who were part of the industrial participants of the initial projects. All sections were subjected to an extensive engineering evaluation and monitored for approximately two years for short, medium, and long-term performance. The field results were compared to that of the equivalent laboratory-prepared mixes in order to ascertain the suitability of the proposed PCC bottom ash concretes for field paving applications. Field cores taken from paving slabs were also tested for leaching of solid waste to obtain an aqueous solution which are used to determine the materials that could leach into groundwater under the specific testing conditions. The results were then compared with the requirements of Class I and II of IEPA Groundwater Quality Standards.

EXECUTIVE SUMMARY

Most modern pulverized-coal boilers have dry bottom furnaces; that is, the ash is intended to be removed as a dry solid before complete melting occurs. The PCC units operating within the state of Illinois are all dry boilers. These furnaces generally have open grates at their bases. Below the open grates there is generally a water-filled ash pit designed to receive the ash from the furnace. Although a small amount of molten slag will form on the internal walls of the boiler and find its way into the ash pit, a large portion of the dry bottom ash is collected in a dry state. By collecting the ash in a dry state, the physical properties of dry bottom ash are quite different from wet bottom slag. The dry bottom ash has the appearance of natural sand and, when examined under magnification, the spherical nature of these particles appear to be internally porous rather than externally porous. In addition, the predominant material is light in color and has a sand paper-like surface texture. The dry bottom ash is also lighter in weight than the slag bottom ash and, thus, generates a lighter product.

The objective of this program is to examine the performance of Illinois PCC bottom ash structural grade concrete pavements by conducting a demonstration project at a designated site in Carterville, Illinois. The major tasks assigned to this field study fully examine the engineering characteristics, long-term performance, and environmental issues involved in large-scale utilization of Illinois PCC bottom ash surface course highway pavements.

An experimental two-lane road, consisting of eight different vibratory-placed concrete slab sections, was constructed. Each 24 x 24 ft slab was 8 inches deep. In addition to longitudinal joints, shrinkage/construction joints were provided at 24 ft intervals. Dowels were used to transfer loads between slabs. A portion of the experimental road consisted of six solid slab sections. Three of them were made with 100% PCC bottom ash as a fine aggregate component of concrete. The remaining three solid sections were the control concretes made with 100% natural siliceous fine aggregate. There were two sandwich sections made with 4 in. deep of a richer concrete encased between 2 in. leaner mixtures. Cement factors of 550, 650, and 750 lb/yd^3 were used. Concretes were prepared with a uniform consistency of 4± 1/4 inches and an air-entrainment of 6 ± 1%. All trial mixtures possessed an identical volume of solid particles and were prepared with a constant slump, water-cement ratio, and air content. However, to achieve these uniform characteristics, the amount of added water-reducing and air-entraining admixtures had to vary among mixes. The dry components and proportion of each field and laboratory mixture are shown in Tables 1 and 13, respectively, along with the actual water-cement ratio and the amount of admixtures utilized. Once consolidation and final finishing were completed, slab sections were sprayed with curing compound and covered with a plastic sheet for a period of 7 to 10 days prior to opening to vehicular traffic flow.

Short-Term Properties of Field Paving Slabs - Table 2 documents the fresh properties of paving slabs. For a practically similar water-to-cement ratio and workability, the amount of bleeding water for the PCC bottom ash concrete was nearly 90% lower than

that of the control mix. This is explained through the finer PCC bottom ash particles which attached themselves to the cement particles, reducing the channels for bleeding and leaving very little free water available in fresh concrete for bleeding. Table 2 also reveals that inclusion of PCC bottom ash improved initial and final setting times when compared to that of the control concretes. When the fine aggregate portion contained 100% bottom ash, the initial and final setting times of the field mixtures decreased, over those of equivalent control mixes, by 17 and 20%, respectively. Increases in cement factor reduced the initial and final setting times of both PCC bottom ash and natural fine aggregate concretes in an approximately linear fusion. The peak adiabatic temperature rise and the corresponding elapsed time for both PCC bottom ash and reference field mixes are shown in Table 2. Test results indicate that all mixtures under consideration produced peak temperature at a rate similar to each other. The number of hours elapsed to reach the maximum temperature was also similar for PCC bottom ash concretes and reference mixtures. And finally, Table 2 displays the measured air content of the field freshly-mixed concretes which remained within the intended range of 6±1%.

Medium-Term Properties of Field Paving Slabs – As shown in Table 3, the unit weight of the PCC bottom ash concrete were slightly below that of the reference paving slabs. However, they remained in the range typically seen for normal weight concrete. Table 3 also documents wet (soaked) and air-dry compressive strengths of both PCC bottom ash and natural fine aggregate (control) concretes. The PCC bottom concretes gained 75.6% of its 28-day compressive strength in the first seven days after casting, and the 28-day compressive strength was exceeded by an average of 19 and 28% for the pavement ages of 91 and 180 days, respectively. The strength development of the control slabs followed a similar pattern, averaging 80% of the 28-day compressive strength by the first week. At the end of 91 and 180 days, additional gains of 21 and 31% were recorded over that observed after 28 days of pavement age. Under air-dry conditions, the compressive strength of the PCC bottom ash and natural sand concretes was nearly 11% higher than that obtained under soaked conditions. When compared against the control field slab specimens, the PCC bottom ash concrete exhibited a 9.2%, 10.41%, and 16.93% strength gain for the mixtures containing cement content of 550, 650, and 750 lb/yd^3, respectively.

The splitting-tensile strengths of the PCC bottom ash and natural sand paving slabs are illustrated in Table 4 for both wet and air-dry conditions. The splitting-tensile strength improvements, over that of the reference concrete, were approximately 2.5%, 15.7%, 14.8%, 9.5% at pavement ages of 7, 28, 91, and 180 days, respectively. The splitting-tensile resistance under air-dry conditions was 9.5% and 12.6% higher than those tested in wet conditions for the PCC bottom ash and natural sand concretes, respectively. The splitting tensile-compressive strength ratios were in the range of 0.101 – 0.121 for the PCC bottom ash slabs, reproducing the results obtained for the control concretes (0.993 – 0.128).

The progression of flexural strength with respect to cement content and curing age is shown in Table 5. The flexural strength ratio of the PCC bottom ash to natural sand concretes was 1.08, 1.09, and 1.22 for the mixtures containing 550, 650, and 750 lb/yd^3

portland cement, respectively. The 91-day flexural strength exceeded the 28-day result by nearly 11 and 11.2% for the PCC bottom ash and reference mixes.

Table 6 documents the shrinkage strain of the test mixtures containing 550, 650, and 750 lb/yd^3 portland cement. The drying shrinkage of the paving slabs increased with time and stabilized after roughly 180 days from the time of initial casting. PCC bottom ash slabs displayed higher ultimate drying shrinkage strains (30.8, 17.6, and 17.7% at cement factors of 550, 650, and 750 lb/yd^3, respectively) than the equivalent paving sections made with control concretes.

Long-Term Properties of Field Paving Slabs – The results of accelerated chloride permeability tests are shown in Table 7. The control mixtures allowed, on average, 970% higher current flow than the PCC bottom ash concretes. All reference slabs are considered moderately permeable, whereas the PCC bottom ash paving sections can be classified as having very low permeability to chloride.

The resistance to abrasion of the PCC bottom ash and natural sand concretes (for the saw-cut surface of the cross section) is shown in Table 8 for the mixtures containing 550 through 750 lb/yd^3 portland cement. The abrasion resistance (via depth of wear) of the control mixtures improved by 9.7 and 23.8% when cement content increased from 550 to 650 to 750 lb/yd^3, respectively. The PCC bottom ash concretes also exhibited a similar trend, and resistance to abrasion improved by 12.2 and 23.4% when the same cement contents were utilized. The average depth of wear for the bottom ash mixes was nearly 18% higher than that of the natural sand (control) concretes.

The absorption, an indirect measure of moisture conductivity, of both PCC bottom ash and natural sand slabs is shown in Table 9. The higher amount of fines in PCC bottom ash, as compared to that of the natural sand, provided lower absorption for the bottom ash concrete slabs. The 7-day absorptions of the PCC bottom ash concrete was lower by nearly 30% than that of the equivalent control mixes.

The resistance to freezing and thawing with deicing salts expressed in mass loss and surface rating of the field paving slabs is shown in Table 10. Although the impermeability of the bottom ash concretes surpassed that of the control mixes, the porous nature of the less-densed PCC bottom ash aggregate and the higher water-cement ratio resulted in a greater resistance to freezing and thawing with deicing salts for the natural sand concrete slab sections.

As documented in Table 11, all field specimens completed 300 freezing and thawing cycles with the lowest durability factor recorded at 95.4%. The PCC bottom ash concretes exhibited a similar resistance to rapid freezing and thawing when compared to that of the control field samples. Although the failure criterion (relative dynamic modulus of elasticity of 60%) was never reached, a moderate amount of surface scaling was found (after 300 freezing and thawing cycles) in the bottom ash specimen containing a low cement content of 550 lb/yd^3. The mass loss and surface rating of all test specimens taken after 50 freezing and thawing cycles, up to 300 cycles, are shown in Table 11.

Leachate Studies – The results of ASTM shake tests for portland cement, PCC bottom ash, and field paving slabs are reported in Table 12. In general, all paving slabs under consideration, complied with the requirements of Class I and II of IEPA Groundwater. However, elements Tl and Sb recorded nois levels and they may be closely examined under (1) recalibration of ASTM shake test or (2) graphite furnace atomic absorption test.

Fresh and Hardened Properties of Laboratory–Made Specimens – the matrix components and proportions, and the resulting water-to-cement ratios are shown in Table 13. The results of the tests conducted for fresh and hardened properties are documented in Tables 14 and 15, respectively, for the PCC bottom ash and natural sand concretes.

Table:1 Mixture Proportions of Field Paving Slabs

Mixture No.	Cement Content (lb/yd^3)	Natural Fine Aggregate (lb/yd^3)	PCC Bottom (lb/yd^3)	Limestone Coarse Aggregate (lb/yd^3)	Actual Water (lb/yd^3)	Water-Cement Ratio	Water Reducer Admixture (oz/100# of cement)	Air Entraining Admixture (oz/100# of cement)	Air Content Designated %
100	550	0	1160	1878	258	0.47	10	2	6+/- 1
200	650	0	1039	1878	272.35	0.419	10	2	6+/- 1
300	750	0	906	1878	288.8	0.385	10	2	6+/- 1
400*	550	1157	0	1936	246.5	0.448	0	1	6+/- 1
500*	650	1040	0	1936	243.4	0.375	0	1	6+/- 1
600*	750	899	0	1936	280	0.373	0	1	6+/- 1
S200, T or B	650	0	1039	1878	267.42	0.411	10	2	6+/- 1
S100, M	550	0	1160	1878	260.7	0.474	10	2	6+/- 1
S300, T or B	750	0	906	1878	286.36	0.381	10	2	6+/- 1
S100, M	550	0	1160	1878	260.7	0.474	10	2	6+/- 1

* Control Pavements S=Sandwich sections T, B, & M=top, bottom and middle

Table 2: Fresh Properties of Field Paving Slabs

Mixture No.	Slump (in.)	Air Content Measured (%)	Bleeding (%)	Initial Time of Setting (hrs)	Final Time of Setting (hrs)	Peak Adiabatic Temperature (degree F)	Time to Reach Peak Adiabatic (hrs)
100	3.8	6.25	0.01	4.02	5.27	125	11
200	4.0	5.7	0.015	3.43	4.43	131	10
300	4.3	7	0.042	3.03	3.77	140	11
400	4.0	7	0.18	4.72	5.87	120	10
500	4.0	6.4	0.21	4.02	5.43	126	12
600	4.0	5.8	0.22	3.77	4.93	136	12
S200, T or B	4.0	7	0.023	3.53	4.64	132	10
S100, M	4.0	6	0.01	4.39	5.53	124	11
S300, T or B	4.3	6	0.05	3.22	4.00	143	11
S100, M	4.0	5.5	0.01	4.39	5.53	122	11

Table: 3 Unit Wieght and Compressive Strength of Field Paving Slabs

Mixture No.	Unit Wieght (lb/yd^3)	Soaked Comprssive Strength (psi)				Air-Dry Compressive Strength (psi)			
		Pavement Age (Days)				Pavement Age (Days)			
		7	28	91	180	7	28	91	180
100	136.8	2779	3730	4443	4783	3087	4143	4944	5322
200	140.2	3247	4291	5071	5493	3517	4648	5417	5868
300	145.4	3762	4933	5920	6261	4220	5534	6768	7158
400	145	2628	3389	4025	4380	2949	3803	4490	4886
500	146.2	3022	3741	4556	4954	3326	4118	4911	5340
600	148.3	3336	4093	5088	5413	3737	4585	5705	6070
S200, T or B S100, M	138.6	2788	4015	4785	5168	3389	4496	5270	5683
S300, T or B S100, M	141.4	3217	4468	5352	5754	3712	4894	5903	6287

Table 4: Splitting-Tensile Resistance of Field Paving Slabs

Mixture No.	Soaked Splitting-Tensile Resistance (psi)				Air-Dry Splitting-Tensile Resistance (psi)			
	Pavement Age (Days)				Pavement Age (Days)			
	7	28	91	180	7	28	91	180
100	341	427	458	489	379	474	506	540
200	392	492	532	547	424	532	556	572
300	451	565	614	640	494	620	688	717
400	343	385	402	446	375	421	468	519
500	383	424	454	512	421	466	523	554
600	425	466	500	539	474	520	582	628
S200, T or B S100, M	378	468	493	516	406	516	539	564
S300, T or B S100, M	394	499	561	590	437	548	617	652

Table 5: Flexural Strength of Field Paving Slabs

Mixture No.	Pavement Age (days)	
	28	91
100	537	589
200	585	654
300	734	816
400	506	542
500	535	603
600	596	678
S200, T or B S100, M	561	622
S300, T or B S100, M	667	733

Table 6: Shrinkage Strain of Field Paving Slabs

Mixture No.	Shrinkage Strain (%) Exposure Duration (Days)					
	28	60	90	180	270	360
100	0.01	0.021	0.028	0.031	0.033	0.034
200	0.02	0.027	0.033	0.038	0.04	0.04
300	0.024	0.038	0.41	0.045	0.048	0.048
400	0.011	0.018	0.023	0.025	0.026	0.026
500	0.016	0.023	0.026	0.031	0.033	0.034
600	0.019	0.028	0.035	0.038	0.04	0.041

Table 7: Rapid Chloride Permeability of Field Paving Slabs

Mixture No.	Charge Passed (Coulombs)	Chloride Permeability
100	691	very low
200	288	very low
300	145	very low
400	3679	moderate
500	3001	moderate
600	2361	moderate

Table 8: Resistance to Abrasion of Field Paving Slabs

Mixture No.	Depth of Wear (x 10^ -4 in.) Testing Duration (Minutes)							
	0.5	1	3	5	7	10	15	20
100	100	125	200	232	251	276	305	330
200	75	100	167	193	213	229	256	290
300	83	96	137	159	178	194	230	253
400	81	104	135	161	178	206	235	269
500	57	70	108	136	148	173	206	243
600	42	55	95	109	121	139	168	205

Tabel 9: Absorption of Field Paving Slabs

Mixture No.	Absorption (%) Exposure Duration (Days)			
	1	2	3	7
100	1.70	1.82	1.93	2.03
200	1.63	1.7	1.78	1.83
300	1.28	1.33	1.37	1.40
400	2.50	2.60	2.68	2.73
500	2.08	2.20	2.33	2.45
600	1.93	2.07	2.19	2.21
S200, T or B S100, M	1.68	1.77	1.94	1.91
S300, T or B S100, M	1.30	1.41	1.45	1.58

Table 10: Resistance to Freezing and Thawing with Deicing Salts of Field Paving Slabs

Mixture No.	Mass Loss (%) and Surface Rating* Number of Cycles									
	5	10	15	20	25	30	35	40	45	50
100	0.23 (1)	0.79 (2)	1.52 (2)	2.35 (4)	3.22 (5)	4.2 (5)	4.99 (5)	5.91 (5)	6.72 (5)	7.59 (5)
200	0.06 (1)	0.09 (2)	0.24 (2)	0.37 (2)	0.52 (2)	0.70 (3)	0.96 (3)	1.17 (4)	1.41 (4)	1.54 (4)
300	0.04 (1)	0.06 (1)	0.07 (1)	0.14 (1)	0.25 (1)	0.36 (2)	0.50 (2)	0.64 (3)	0.85 (3)	0.96 (4)
400	0.03 (1)	0.06 (1)	0.12 (2)	0.19 (2)	0.31 (2)	0.44 (3)	0.56 (3)	0.81 (4)	1.03 (4)	1.18 (4)
500	0.03 (1)	0.07 (1)	0.12 (1)	0.18 (1)	0.24 (1)	0.41 (1)	0.49 (1)	0.60 (2)	0.75 (2)	0.89 (2)
600	0.04 (1)	0.05 (1)	0.1 (1)	0.16 (1)	0.24 (1)	0.32 (1)	0.46 (1)	0.58 (2)	0.64 (2)	0.71 (2)
S200, T or B S100, M	0.14(1,1)**	0.55 (2,1)	1.03 (3,2)	1.65 (4,2)	2.23 (5,3)	2.81 (5,3)	3.30 (5,4)	4.02 (5,4)	4.46 (5,4)	5.08 (5,5)
S300, T or B S100, M	6.09 (1,1)	0.44 (2,1)	0.82 (3,2)	1.2 (4,2)	1.67 (4,2)	1.89 (5,2)	2.29 (5,3)	2.77 (5,3)	3.24 (5,3)	3.97 (5,4)

* Surface Rating ( ): 0- No Scaling, 1- Very Light Scaling (1/8in. Depth, Max, no coarse aggyrate visible), 2- Slight to Moderate Scaling, 3- Moderate Scaling (some coarse aggyrate visible), 4- Moderate to Severe Scaling, and 5- Severe Scaling (coarse aggryate visible over entire surface)

** (Rating of Middle Section, Rating of Outer Section)

Table 11: Resistance to Rapid Freezing and Thawing of Field Paving Slabs

Mixture No.	Durability Factor (%)/ Mass Loss (%)/ Surface Rating* Number of Freezing and Thawing Cycles					
	50	100	150	200	250	300
100	100/ 0.03/ 0	100/ 0.07/ 1	98.84/ 0.14/ 2	98.84/ 0.17/ 2	97.67/ 0.30/ 3	96.51/ 0.41/ 4
200	100/ 0.03/ 0	100/ 0.05/ 0	99.42/ 0.08/ 1	99.12/ 0.13/ 1	98.27/ 0.21/ 2	97.39/ 0.29/ 3
300	100/ 0.02/ 0	100/ 0.03/ 0	99.68/ 0.08/ 1	99.28/ 0.12/ 1	98.63/ 0.18/ 2	97.71/ 0.23/ 2
400	100/ 0.04/ 0	100/ 0.06/ 1	98.70/ 0.13/ 1	98.34/ 0.18/ 2	96.13/ 0.26/ 3	95.43/ 0.31/ 3
500	100/ 0.03/ 0	100/ 0.05/ 0	98.90/ 0.08/ 1	98.35/ 0.13/ 1	96.70/ 0.18/ 2	96.15/ 0.23/ 2
600	100/ 0.0/ 0	100/ 0.03/ 0	99.45/ 0.05/ 1	99.01/ 0.10/ 1	98.81/ 0.15/ 1	97.92/ 0.18/ 2

* Surface Rating ( ): 0- No Scaling, 1- Very Light Scaling (1/8in. Depth, Max, no coarse aggyrate visible), 2- Slight to Moderate Scaling, 3- Moderate Scaling (some coarse aggyrate visible), 4- Moderate to Severe Scaling, and 5- Severe Scaling (Coarse aggryate visible over entire surface)

Table 12: Leachate Results of Portland Cement, PCC Bottom Ash, and Field Paving Slabs

Element (PPM)	Class 1 Standard	Class 2 Standard	Portland Cement	PCC Bottom Ash	Mixture No.					
					100	200	300	400	500	600
Ag	0.05	-	ND	ND	0.01	0.01	0.01	0	0	0.01
Al	-	-	0.09	1.06	0.39	0.6	1.63	0.19	0.12	0.1
As	0.05	0.2	ND	ND	0	0	0	0	0	0
B	2	2	0.017	0.36	0	0.01	0	0.12	0.06	0.02
Ba	2	-	1.19	0.12	1.52	1.09	0.69	1.12	1.27	1.06
Be	0.004	0.5	ND	ND	0	0	0	0	0	0
Ca	-	TDS=1200	960	60	465	348	22.2	513	635	690
Cd	0.005	0.05	ND	ND	0	0	0	0	0	0
Co	1	1	ND	ND	0	0	0	0	0	0
Cr	0.1	1	0.17	0.08	0.07	0.08	0.07	0.08	0.08	0.09
Cu	0.65	0.65	ND	ND	0	0	0.01	0.01	0	0
Fe	5	5	ND	ND	0.06	0.08	0.08	0	0	0
Mg	-	-	ND	ND	0.2	0.26	0.22	0.48	0.2	0.1
Mn	0.15	10	ND	ND	0	0	0	0	0	0
Mo	-	-	0.07	0.07	0	0	0	0	0	0
Ni	0.1	2	0.06	0.06	0.05	0.05	0.05	0.05	0.5	0.05
Pb	0.0075	0.1	ND	ND	0	0	0	0	0	0
Sb	0.006	0.024	0.04*	0.05*	0.03*	0.02*	0.02*	0.02*	0.03*	0.01*
Se	0.05	0.05	ND	0.01	0.02	0.03	0	0	0.02	0.01
Tl	0.002	0.02	0.03*	0.02*	0.01*	0.02*	0.01*	0.02*	0.02*	0.02*
V	-	-	ND	0.1	0	0	0	0	0	0
Zn	5	10	0.28	0.1	0.45	0.36	0.21	0.16	0.6	0.21
pH	-	-	NA	NA	12.08	12.12	11.82	12.23	12.31	11.57

- None, ND = Not Detectable, * Noise Level, and NA = Not Available

Table 13: Mixture Proprotions of Laboratory-Made Specimans

Mixture No.	Cement Content (lb/yd^3)	Natural Fine Aggregate (lb/yd^3)	PCC Bottom Ash (lb/yd^3)	Limestone Coarse Aggregate (lb/yd^3)	Added Water (lb/yd^3)	Water Cement Ratio	Water Reducer Admixture (oz/100 # of cement)	Air Entraining Admixture (oz/100 # of cement)	Air Content Designated (%)
100	550	0	1160	1878	247.5	0.54	9	5	6 +/- 1
200	650	0	1039	1878	260	0.4	9	5	6 +/- 1
300	750	0	906	1878	281.3	0.375	8	5	6 +/- 1
700*	550	1157	0	1936	118.4	0.45	0	1	6 +/- 1
800*	650	1040	0	1936	110	0.4	0	1	6 +/- 1
900*	750	899	0	1936	110.6	0.375	0	2	6 +/- 1

* Control Mixtures

Table 14: Fresh Properties of Laboratory-Made Specimans

Mixture No.	Slump (in.)	Air Content Measured (%)	Bleeding (%)	Initial Times of Setting (hrs)	Final Times of Setting (hrs)	Peak Adiabatic Temperature (degree F)	Time to Reach Peak Adiabatic Temperature (hrs)	One-Day Demoled Unit Weight (lb/ft^3)
100	4+/- 1/4	6.5	0	3.12	4.25	125	11	142.3
200	4+/- 1/4	5.5	0.01	2.73	3.93	131	10	143.1
300	4+/- 1/4	5.5	0.047	2.55	3.77	140	11	143.8
700	4+/- 1/4	6	0.305	3.63	4.75	120	10	145.9
800	4+/- 1/4	6	0.324	3.58	4.7	126	12	146.5
900	4+/- 1/4	6	0.352	3.23	4.68	136	12	147.1

Table 15: Hardened Properties of Laboratory-Made Samples

Mixture No.	Compressive Strength (psi)				Splitting Tensile Resistance (psi)				Flexural Stength (psi)	
	Curring Age (Days)				Curring Age (Days)				Curring Age (Days)	
	7	28	91	180	7	28	91	180	28	91
100	3635	4879	5805	6249	435	544	600	640	633	694
200	3963	5237	6069	6574	485	608	663	682	684	765
300	4244	5565	6700	7086	516	647	700	730	724	805
400	3342	4310	4960	5398	396	444	493	547	542	581
500	3742	4633	5406	5878	442	489	544	613	576	649
600	4051	4970	5815	6187	478	524	585	631	604	687

OBJECTIVES

This research investigation and its assigned tasks is designed to ascertain the constructability and performance of the concrete mixtures containing dry PCC bottom ash, identified during the four-year laboratory investigation, using vibratory and roller compacted techniques, under realistic climatic and traffic flow of field conditions. Eight different matrix proportions are considered for the construction of the experimental two-lane road. Seven major tasks are proposed. In the first assignment, physico-chemical characteristics of concrete constituents; such as pH, a complete chemical analyses, size gradation and fineness modulus, specific gravity and absorption, unit weight, and particle shape; are identified. The second and third tasks of the proposed project are devoted to (1) selection of combined aggregates and optimal mixture proportions identified during the laboratory studies, and (2) pavement thickness design, respectively. In the fourth task, the construction of the proposed experimental road is described in details. The fifth task of the proposed project is used to evaluate short-medium and long-term performance of the experimental slabs. Field cores will be tested at different stages for compression, splitting-tension, flexure, modulus of elasticity, shrinkage, abrasion, chloride permeability, and freezing and thawing tests. Task six is used to examine the engineering characteristics of on-site mixtures cast in the laboratory. These laboratory-made samples are subjected to various testings in order to identify the proper correlation between field and laboratory specimens. The seventh and final task addresses the issue of the groundwater contamination which is usually raised whenever coal combustion residues are utilized. Cores obtained from each experimental slab are tested for leaching of solid waste to obtain a solution that will determine the constituents that could enter into groundwater.

An experimental two-lane road consisted of eight different vibratory-placed concrete slabs was constructed. Each 24 x 24 ft section was 8 inches deep. In addition to longtudinal joints, shrinkage/construction joints were provided at 24 ft intervals. Dowels were used to transfer loads between slabs. A portion of the experimental road consisted of nine solid slab sections. Three of them were made with 100% PCC bottom ash as a fine aggregate component of concrete. The remaining three solid sections were the control concretes made with 100% natural siliceous fine aggregate. There were two sandwich sections made with 4 in. deep of a richer concrete encased between 2 in. leaner mixtures. Cement factors of 550, 650, and 750 lb/yd^3 were used. Concrete mixtures were prepared with a uniform consistency of 4± 1/4 inches and an air-entrainment of 6± 1%. Fresh properties of the field and laboratory mixtures are reported.

INTRODUCTION AND BACKGROUND

The coal and utility industries are the major source of mining and industrial wastes in the state of Illinois. The readily available supply of coal and its use in coal burning electric generating plants and co-generation pulverized coal combustion facilities has resulted in production and accumulation of large quantities of by-product residues (over five million tons per annum). Additionally, the use of scrubber sludge to facilitate sulfur reduction of Illinois high-sulfur coal also generates large quantities of scrubber sludge annually. With only 20% utilization, where the remaining by-products are disposed in landfills and ponds, and the expected growth in power generation; the industry is faced with a lack of available disposal space, storage cost, and environmental consequences for surrounding communities.

Over the past four years, the Department of Civil Engineering at SIUC has directed a laboratory program designed to investigate the basic engineering characteristics of PCC dry lignite and bituminous and their potential applications for various aspects of the construction industry. Both conventional (vibratory-placed) and roller compacted concretes were utilized. Over ten thousands of the laboratory-made samples were subjected to a comprehensive review of (1) fresh characteristics (early shrinkage, initial and final setting times, air content, vibration time, and demolded density); (2) hardened properties (strength, deformation, stiffness, expansion and shrinkage); and (3) long-term durability (external sulfate attack, rapid chloride permeability, abrasion wear, freezing and thawing with deicing salts, and rapid freezing and thawing).

While the four-year laboratory investigation has provided valuable scientific data on the performance of various PCC concrete mixtures and identified a number of potentially viable paving applications, field feasibility studies are needed to bring the laboratory investigation a step closer to reality. It is, therefore, the thrust of this research project to evaluate the constructability and performance of field experimental slabs utilizing Illinois PCC dry bottom ash as a filler aggregate of concrete matrix. Cored samples of hardened concretes are tested for a variety of mechanical properties and long-term performance under different climatic conditions and ages.

In summary, this proposed investigation and relevant tasks are intended to provide fundamental scientific data and strong argument for commercialization of PCC bottom ash derived from Illinois high-sulfur coal in surface course pavement applications. Construction, mining, power generation, and cogenerating industries within the state of Illinois are expected to benefit from the proposed study via the provision of an alternative solution for the productive disposal of large quantities of PCC wastes and by their utilization as a viable synthetic aggregate for a variety of structural grade highway-related applications. The goal of this investigation, regarding full substitution for natural fine aggregates, are threefold: (1) to recycle by-product wastes, and thus, reducing the overall disposal costs to utility and co-generation plants; (2) to develop a substitute material which will alleviate the shortage of natural resources; and (3) to lower the unit cost of highway construction by developing a cost-effective technology aimed at providing the construction industry with less expensive substitute materials. As a consequence, a successful implementation of new highway materials will be of joint benefit to the Illinois Clean Coal Institute, industry, and to the citizens of Illinois by contributing significantly to the economic well-being of the state.

EXPERIMENTAL PROCEDURES

Tests used for the evaluation of the test samples included ASTM C 143 (workability), ASTM C 232 (bleeding), ASTM C 403 (setting time), ASTM C 231 (air content), and ASTM C 39 (unit weight). For the measurement of adiabatic temperature, the fresh matrix was placed 5 inches in diameter by 5 inches in height cyclindrical insulated plastic container lined with a plastic bag. A type J thermocouple wire was inserted into the fresh mortar to a depth of 4 inches. The container was then securely sealed into a tightly sealed insulated 26 x 26 x 29 inches wooden box. The thermocouple wire was plugged into a data recorder which registered and logged the mortar temperature at 1 hour intervals over a period of 100 hours.

For each field paving slab, various tests were performed on both fresh and hardened materials. Consistency, bleeding, air content, early volume shrinkage, and time of settings were conducted in accordance with *ASTM C 143, C 232, C 231, C 826,* and *C 403,* respectively. Cylindrical cors for compressive strength, and splitting-tensile resistance were tested according to *ASTM C 39* and *C 496*, respectively. Flexural strengths using third-point loading were evaluated based on *ASTM C 78.* Tests for rapid chloride permeability, rapid freezing and thawing with deicing salts, sulfate durability, abrasion, freezing and thawing, and length change (shrinkage strain) were conducted in accordance with American Association of State Highway and Transportation Officicals *(AASHTO) T 277, CAN 3 – A231.2 - M85, ASTM C 1012, ASTM C 779* (procedure C, ball bearings), *ASTM C 666* (procedure A), and *ASTM C 157*, respectively.

RESULTS AND DISCUSSION

Short-Term Properties of Field Paving Slabs - Table 2 of the Technical Report documents the fresh properties of paving slabs. For a practically similar water-to-cement ratio and workability, the amount of bleeding water for the PCC bottom ash concrete was nearly 90% lower than that of the control mix. This is explained through the finer PCC bottom ash particles which attached themselves to the cement particles, reducing the channels for bleeding and leaving very little free water available in fresh concrete for bleeding. Table 2 of the Technical Reports also reveals that inclusion of PCC bottom ash improved initial and final setting times when compared to that of the control concretes. When the fine aggregate portion contained 100% bottom ash, the initial and final setting times of the field mixtures decreased, over those of equivalent control mixes, by 17 and 20%, respectively. Increases in cement factor reduced the initial and final setting times of both PCC bottom ash and natural fine aggregate concretes in an approximately linear fusion. The peak adiabatic temperature rise and the corresponding elapsed time for both PCC bottom ash and reference field mixes are shown in Table 2 of the Technical Report. Test results indicate that all mixtures under consideration produced peak temperature at a rate similar to each other. The number of hours elapsed to reach the maximum temperature was also similar for PCC bottom ash concretes and reference mixtures. And finally, Table 2 of the Technical Report displays the measured air content of the field freshly-mixed concretes which remained within the intended range of 6±1%.

Medium-Term Properties of Field Paving Slabs – As shown in Table 3 of the Technical Report, the unit weight of the PCC bottom ash concrete were slightly below that of the reference paving slabs. However, they remained in the range typically seen for normal weight concrete. Table 3 of the Technical Report also documents wet (soaked) and air-dry compressive strengths of both PCC bottom ash and natural fine aggregate (control) concretes. The PCC bottom concretes gained 75.6% of its 28-day compressive strength in the first seven days after casting, and the 28-day compressive strength was exceeded by an average of 19 and 28% for the pavement ages of 91 and 180 days respectively. The strength development of the control slabs followed a similar pattern, averaging 80% of the 28-day compressive strength by the first week. At the end of 91 and 180 days, additional gains of 21 and 31% were recorded over that observed after 28 days of pavement age. Under air-dry conditions, the compressive strength of the PCC bottom ash and natural sand concretes was nearly 11% higher than that obtained under soaked conditions. When compared against the control field slab specimens, the PCC bottom ash concrete exhibited a 9.2%, 10.41%, and 16.93% strength gain for the mixtures containing cement content of 550, 650, and 750 1b/yd^3, respectively.

The splitting-tensile strengths of the PCC bottom ash and natural sand paving slabs are illustrated in Table 4 of the Technical Report for both wet and air-dry conditions. The splitting-tensile strength improvements, over that of the reference concrete, were approximately 2.5%, 15.7%, 14.8%, 9.5% at pavement ages of 7, 28, 91, and 180 days, respectively. The splitting-tensile resistance under air-dry conditions was 9.5% and 12.6% higher than those tested in wet conditions for the PCC bottom ash and natural sand concretes, respectively. The splitting tensile-compressive strength ratios were in the range of 0.101 – 0.121 for the PCC bottom ash slabs, reproducing the results obtained for the control concretes (0.993 – 0.128).

The progression of flexural strength with respect to cement content and curing age is shown in Table 5 of the Technical Report. The flexural strength ratio of the PCC bottom ash to natural sand concretes was 1.08, 1.09, and 1.22 for the mixtures containing 550, 650, and 750 1b/yd^3 portland cement, respectively. The 91-day flexural strength exceeded the 28-day result by nearly 11 and 11.2% for the PCC bottom ash and reference mixes.

Table 6 of the Technical Report documents the shrinkage strain of the test mixtures containing 550, 650, and 750 1b/yd^3 portland cement. The drying shrinkage of the paving slabs increased with time and stabilized after roughly 180 days from the time of initial casting. PCC bottom ash slabs displayed higher ultimate drying shrinkage strains (30.8, 17.6, and 17.7% at cement factors of 550, 650, and 750 1b/yd^3, respectively) than the equivalent paving sections made with control concretes.

Long-Term Properties of Field Paving Slabs – The results of accelerated chloride permeability tests are shown in Table 7 of the Technical Report. The control mixtures allowed, on average, 970% higher current flow than the PCC bottom ash concretes. All reference slabs are considered moderately permeable, whereas the PCC bottom ash paving sections can be classified as having very low permeability to chloride.

The resistance to abrasion of the PCC bottom ash and natural sand concretes (for the saw-cut surface of the cross section) is shown in Table 8 of the Technical Report for the mixtures containing 550 through 750 lb/yd^3 portland cement. The abrasion resistance (via depth of wear) of the control mixtures improved by 9.7 and 23.8% when cement content increased from 550 to 650 to 750 1b/yd^3, respectively. The PCC bottom ash concretes also exhibited a similar trend, and resistance to abrasion improved by 12.2 and 23.4% when the same cement contents were utilized. The average depth of wear for the bottom ash mixes was nearly 18% higher than that of the natural sand (control) concretes.

The absorption, an indirect measure of moisture conductivity, of both PCC bottom ash and natural sand slabs is shown in Table 9 of the Technical Report. The higher amount of fines in PCC bottom ash, as compared to that of the natural sand, provided lower absorption for the bottom ash concrete slabs. The 7-day absorptions of the PCC bottom ash concrete was lower by nearly 30% than that of the equivalent control mixes.

The resistance to freezing and thawing with deicing salts expressed in mass loss and surface rating of the field paving slabs is shown in Table 10 of the Technical Report. Although the impermeability of the bottom ash concretes surpassed that of the control mixes, the porous nature of the less-densed PCC bottom ash aggregate and the higher water-cement ratio resulted in a greater resistance to freezing and thawing with deicing salts for the natural sand concrete slab sections.

As documented in Table 11 of the Technical Report, all field specimens completed 300 freezing and thawing cycles with the lowest durability factor recorded at 95.4%. The PCC bottom ash concretes exhibited a similar resistance to rapid freezing and thawing when compared to that of the control field samples. Although the failure criterion (relative dynamic modulus of elasticity of 60%) was never reached, a moderate amount of surface scaling was found (after 300 freezing and thawing cycles) in the bottom ash specimen containing a low cement content of 550 1b/yd^3. The mass loss and surface rating of all test specimens taken after 50 freezing and thawing cycles, up to 300 cycles, are shown in Table 11 of the Technical Reports.

Leachate Studies – The results of ASTM shake tests for portland cement, PCC bottom ash, and field paving slabs are reported in Table 12 of the Technical Report. In general, all paving slabs under consideration, complied with the requirements of Class I and II of IEPA Groundwater. However, elements Tl and Sb recorded nois levels and they may be closely examined under (1) recalibration of ASTM shake test or (2) graphite furnace atomic absorption test.

Fresh and Hardened Properties of Laboratory–Made Specimens – the matrix components and proportions, and the resulting water-to-cement ratios are shown in Table 13 of the Technical Report. The results of the tests conducted for fresh and hardened properties are documented in Tables 14 and 15 of the Technical Report, respectively, for the PCC bottom ash and natural sand concretes.

CONCLUSIONS AND RECOMMENDATIONS

PCC bottom ash concretes display excellent mixability, consolidability, and finishability, similar to that of control mixtures. Both laboratory and field results reveal that inclusion of bottom ash improves bleeding and initial and final setting times when compared to that of control concretes. All mixtures exhibited similar maximum adiabatic temperature and the corresponding elapsed time. PCC bottom ash concrete slab produces a nearly 20% higher shrinkage strain than that of the equivalent control pavement. The strength properties, absorption, and rapid chloride permeability of the PCC bottom ash concretes are superior to those of the companion control mixes. Under accelerated laboratory testings, the PCC bottom ash concretes perform slightly below the reference mixes when subjected to repeated freezing and thawing cycles (with or without deicing salts) and abrasion.

DISCLAIMER STATEMENT

"This report was prepared by Dr. Nader Ghafoori of Southern Illinois University at Carbondale with support, in part by grants made possible by the Illinois Department of Commerce and Community Affairs through the Illinois Coal Development Board and the Illinois Clean Coal Institute. Neither Dr. N. Ghafoori, or Southern Illinois University at Carbondale, nor any of its subcontractors, nor the Illinois Department of Commerce and Community Affairs, Illinois Coal Development Board, Illinois Clean Coal Institute, nor any person acting on behalf of either:

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PROJECT MANAGEMENT REPORT
September 1, 1996, through April 30, 1998

Project Title: **FIELD STUDIES OF ILLINOIS PCC BOTTOM ASH FOR STRUCTURAL GRADE CONCRETE PAVEMENTS**

ICCI Project Number:	96-1/3.1A-26
Principal Investigator:	Nader Ghafoori, Southern Illinois University at Carbondale
Project Manager:	Daniel Banerjee, ICCI

COMMENTS

Due to unavailability of the needed volume of PCC bottom ash and arrival of the winter climate (Winter 1996), with prior approval from ICCI, the road construction was postponed to Spring 1997. The low budget expenditure reflects this delay. In late March 1997, nearly 400 tons of PCC bottom ash was delivered. During the months of April-May 1997, they were sieved for proper gradation. In late May 1997, the grading of the site and the construction of the experimental road began. In early June 1997, an experimental two-lane road, consisting of fourteen 24-ft long solid and sandwich slab sections, was constructed. An 8-month project extention was granted by ICCI. All project milestones were completed before April 30, 1998.

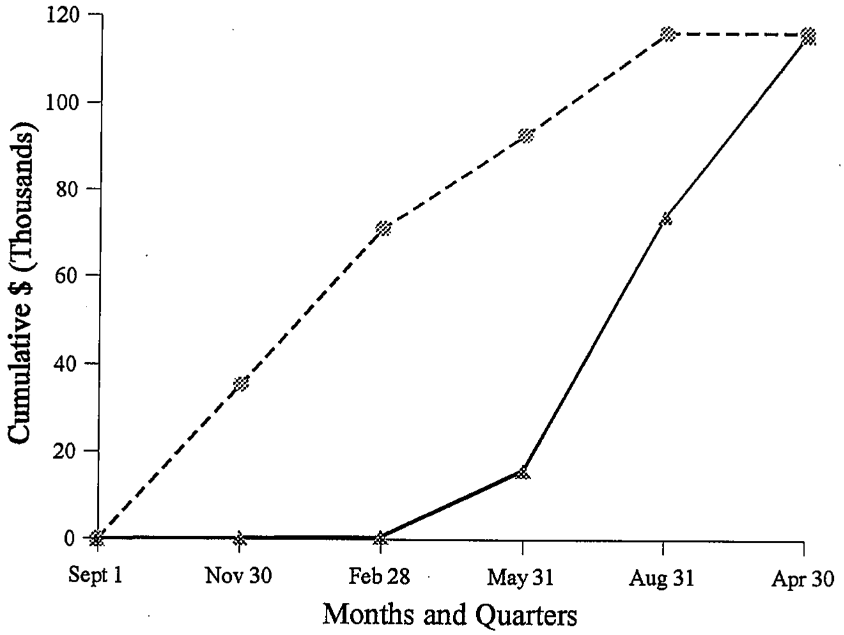
PROJECTED AND ESTIMATED EXPENDITURES BY QUARTER

Quarter*	Types of Cost	Direct Labor	Fringe Benefits	Materials and Supplies	Travel	Major Equipment	Other Direct Costs	Indirect Cost	Total
Sept. 1, 1996 to Nov. 30,1996	Projected	6,498	883	2,178	0	0	22,748	3,231	35,538
	Estimated	0	0	70	0	0	230	30	330
Sept. 1, 1996 to Feb. 28, 1997	Projected	12,995	1,766	4,356	0	0	45,496	6,461	71,074
	Estimated	0	0	282	80	0	282	64	708
Sept. 1, 1996 to May 31, 1997	Projected	19,492	2,649	5,445	0	0	56,870	8,446	92,902
	Estimated	3,839	312	623	499	0	9,173	1,453	15,899
Sept. 1, 1996 to April 30, 1998	Projected	25,990	3,534	6,535	1,200	0	68,245	10,550	116,054
	Estimated	25,980	3,534	6,432	1,200	0	67,948	10,550	115,644

*Cumulative by Quarter

CUMULATIVE COSTS BY QUARTER

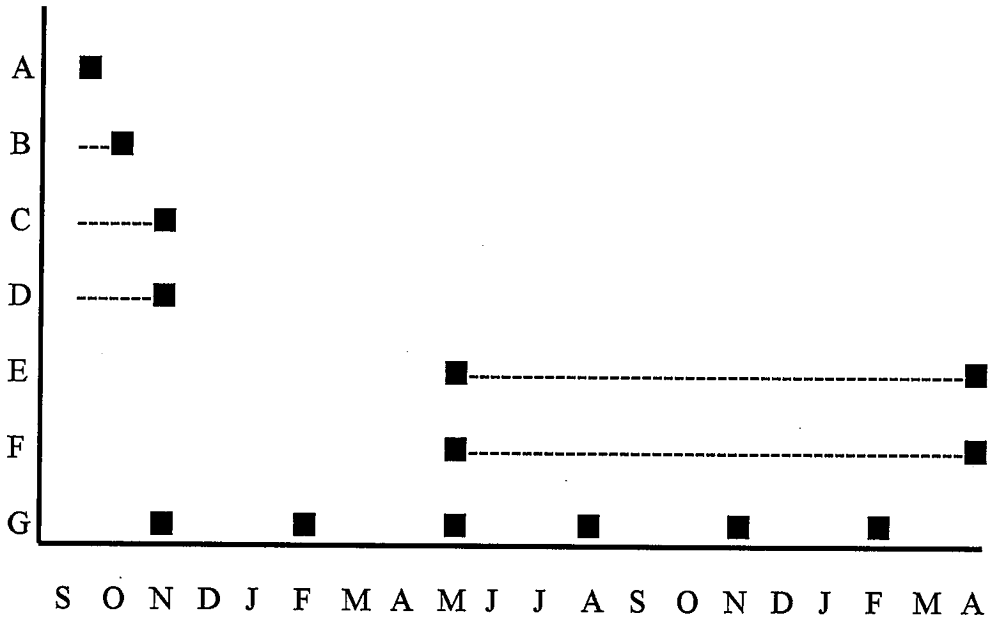
Field Studies of Illinois PCC Bottom Ash for Structural Grade Concrete Pavements



● = Projected Expenditures - - - - - - -
▲ = Actual Expenditures ________

Total Illinois Clean Coal Instutute Award $116,054

SCHEDULE OF PROJECT MILESTONES



Begin
September 1
1996

Milestones:

A. Research assistants employed.
B. Preparation of raw materials.
C. Physico-chemical properties of raw materials.
D. Preparation and grading of the site and construction of field slab pavements.
E. Evaluation of field-cored specimens for strength, deformation,