CENTER FOR TRANSPORTATION INFRASTRUCTURE AND SAFETY

Development and Testing of Synthetic Riprap Constructed from Coal Combustion Products (CCPs)

by

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16. Abstract

Even with an increase in the amount of coal combustion products (CCPs) used in concrete con-struction, soil stabilization, and other applications, the coal power industry must dispose of a sig-nificant amount of fly ash and bottom ash. One potential avenue for the material is to develop a riprap to armor shorelines, streambeds, bridge abutments, and pilings against scour and ice dam-age. The ***objective*** of this research project was to evaluate the feasibility of constructing riprap containing 90% CCPs such as fly ash and bottom ash. Since the 1930's, fly ash – a pozzolanic material – has been used as a partial replacement of port-land cement in concrete to improve the material's strength and durability, while also limiting the amount of early heat generation. From an environmental perspective, replacing cement with fly ash reduces concrete's overall carbon footprint and diverts an industrial by-product from the sol-id waste stream. Unfortunately, only about 40% of fly ash is reclaimed for beneficial reuse, with the remaining 60% disposed of in landfills. In some instances, the reason for only a 40% use rate is the lack of a viable market, but in other instances, it is because the fly ash does not meet the required specification for use in concrete or as soil stabilization. For instance, current specifications limit the carbon content of fly ashes used as partial replacement of cement in concrete to less than 6%. However, Ameren Corporation's (Ameren) Sioux Power Plant and other plants containing cyclone-fired boilers produce ash with very high levels of unburned carbon, often in the 20 to 50% range. Furthermore, activated carbon injection for mercury control will usually increase the carbon content of fly ashes from conven-tional boilers, reducing potential sales of ashes from these plants as well. In general, higher car-bon contents reduce the reactivity of the ash and the efficacy of air-entraining admixtures. The study included evaluation of CCPs from several Ameren power plants, mix design develop-ment, and small-scale specimen construction and testing. The intent of this project was to serve as a proof-of-concept for synthetic riprap constructed from 90% CCPs.

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Chapter 1

Introduction

Even with an increase in the amount of coal combustion products (CCPs) used in concrete construction, soil stabilization, and other applications, the coal power industry must dispose of a significant amount of fly ash and bottom ash. One potential avenue for the material is to develop a riprap to armor shorelines, streambeds, bridge abutments, and pilings against scour and ice damage. The ***objective*** of this research project was to evaluate the feasibility of constructing riprap containing 90% CCPs such as fly ash and bottom ash.

Since the 1930's, fly ash – a pozzolanic material – has been used as a partial replacement of portland cement in concrete to improve the material's strength and durability, while also limiting the amount of early heat generation. From an environmental perspective, replacing cement with fly ash reduces concrete's overall carbon footprint and diverts an industrial by-product from the solid waste stream. Unfortunately, only about 40% of fly ash is reclaimed for beneficial reuse, with the remaining 60% disposed of in landfills.

In some instances, the reason for only a 40% use rate is the lack of a viable market, but in other instances, it is because the fly ash does not meet the required specification for use in concrete or as soil stabilization. For instance, current specifications limit the carbon content of fly ashes used as partial replacement of cement in concrete to less than 6%. However, Ameren Corporation's (Ameren) Sioux Power Plant and other plants containing cyclone-fired boilers produce ash with very high levels of unburned carbon, often in the 20 to 50% range. Furthermore, activated carbon injection for mercury control will usually increase the carbon content of fly ashes from conventional boilers, reducing potential sales of ashes from these plants as well. In general, higher carbon contents reduce the reactivity of the ash and the efficacy of air-entraining admixtures.

The study included evaluation of CCPs from several Ameren power plants, mix design development, and small-scale specimen construction and testing. The intent of this project was to serve as a proof-of-concept for synthetic riprap constructed from 90% CCPs.

Chapter 2

Evaluation of Coal Combustion Products

The first task of the research project involved collecting and testing samples of fly ash and bottom ash from several of Ameren's coal-fired power plants. Results of the Class C fly ash chemical and physical testing are shown in Table 2.1. Note that fly ash samples 4 and 5 do not meet the ASTM requirements for use in concrete due to the high LOI (loss of ignition) values. Results of the bottom ash physical testing are shown in Table 2.2.

Table 2.1 – Fly Ash Chemical and Physical Analyses

	Fly Ash Samples				
	1	2	3	4	5
SiO_2	33.72	33.34	35.42	30.55	32.26
Al_2O_3	21.90	20.57	16.88	18.78	19.03
Fe_2O_3	7.15	6.15	7.97	7.48	6.24
CaO	25.31	26.34	23.21	28.43	27.94
SO_3	2.25	1.87	3.46	3.33	2.40
Na_2O	1.40	1.63	1.40	1.50	2.20
K_2O	0.41	0.43	0.56	0.45	0.33
Eq. Alk.	1.68	1.92	1.78	1.81	2.43
Retained #325	11.16	11.17	19.37	10.17	13.04
LOI	0.37	0.49	3.05	9.40	11.21

Table 2.2 – Bottom Ash Chemical and Physical Analyses

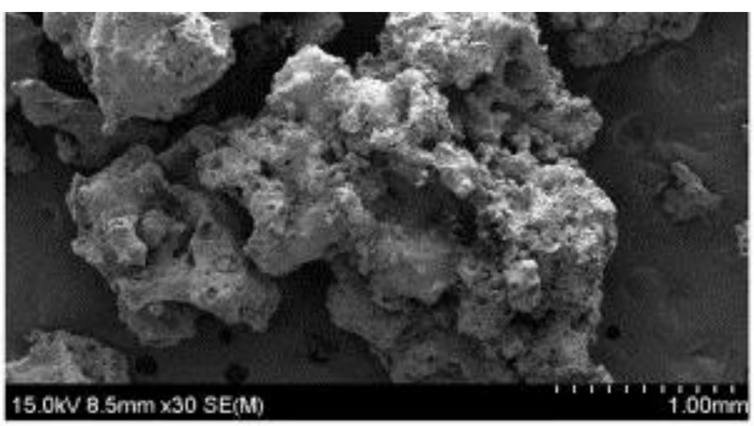
	Bottom Ash Samples				
	1	2	3	4	5
SiO_2	53.60	45.40	40.50	42.09	47.72
Al_2O_3	25.21	19.33	13.81	21.03	16.11
Fe_2O_3	10.27	9.78	14.25	10.58	13.07
CaO	4.76	15.30	22.44	17.03	11.50
MgO	3.10	4.77	5.60	2.33	5.20
Na_2O	0.70	1.30	1.70	1.30	1.50
K_2O	0.21	0.10	1.10	0.50	0.93
Density (lb/ft^3)	83.5	77.7	75.6	81.4	82.1
Los Angeles Abrasion	47	43	49	44	51

Chapter 3

Effect of Bottom Ash on Physical Properties

The next step in the study dealt with determining the effect of bottom ash on the physical properties of potential mixes. Even with its high crystalline silica composition, bottom ash is generally non-reactive compared to fly ash. Bottom ash is also "softer" than limestone aggregate and has a higher porosity, typically 5% to 7% for bottom ash compared to 0.5% to 0.9% for limestone. A photograph of one of the bottom ash samples is shown in Fig. 3.1(a) with an SEM image shown in Fig. 3.1(b).

(a) Coarse Aggregate Bottom Ash



(b) SEM Image of Bottom Ash

Figure 3.1 – Coarse Aggregate Bottom Ash

A conventional concrete mix design was used to evaluate whether there were any noticeable differences between the five bottom ash samples. The research team performed mechanical property testing on the mix design shown in Table 3.1 using each of the five bottom ash samples, which included compressive strength, modulus of rupture, and modulus of elasticity. The results are shown in Table 3.2, with each value representing the average of three test specimens. As shown in Table 3.2, all five bottom ash samples behaved similarly. Both parametric (paired *t*-test) and nonparametric (Wilcoxon signed-rank test) statistical evaluations confirmed that the mechanical property results for all five bottom ash samples are statistically the same (i.e., the values are within the sampling mean).

Table 3.1 – Concrete Mix Proportions

Constituent	Amount (lb/yd^3)
Cement (Type I)	650
Water	292
Bottom Ash	1630
Sand	1350

Table 3.2 – Mechanical Properties

	Bottom Ash Samples				
	1	2	3	4	5
Compressive Strength (psi)	3,750	3,570	3,495	3,670	3,705
Modulus of Rupture (psi)	434	422	410	426	431
Modulus of Elasticity (ksi)	3,307	3,218	3,109	3,320	3,340

Chapter 4

Effect of Fly Ash on Physical Properties

The next step in the study dealt with determining the effect of fly ash on the physical properties of potential mixes. In general, Class C fly ash is both pozzolanic and self-cementing. The degree of self-cementing is a property of the reactive portions of the crystalline silica composition and varies between coal types and even between specific boilers at a coal-fired power plant. To determine the degree of reactivity of the five fly ash samples, the research team used the conventional concrete mix design shown in Table 4.1 and varied the fly ash substitution rate. The reactivity was measured as a function of compressive strength at 28 days. The results are shown in Table 4.2, with each value representing the average of three test specimens.

Table 4.1 – Concrete Mix Proportions

Constituent	Amount (lb/yd^3)
Cement (Type I)	650
Water	292
Bottom Ash	1820
Sand	1350

Table 4.2 – Compressive Strength (psi)

Fly Ash Percentage	Fly Ash Samples				
	1	2	3	4	5
0	4,790	4,790	4,790	4,790	4,790
25	5,030	4,300	4,860	4,900	3,840
50	4,795	3,970	4,620	4,805	3,410
75	3,825	2,360	3,310	3,200	1,750
90	2,705	995	2,120	2,360	790
100	1,550	305	950	1,005	195

Of the five different fly ash samples, No. 1 performed the best at all replacement levels, followed closely by Nos. 3 and 4. Fly ash sample No. 5 was the lowest performing, while No. 2 was only slightly better, particularly at the highest replacement levels, 90% and 100%. In order to increase performance, the research team examined adding both gypsum and lime to increase the reactivity of the mixes at the high replacement rates. The gypsum reduces the possibility of sulfate depletion during the initial hydration stage, while the lime supplements the calcium oxide not present due to the low amount of portland cement. The research team added 5% gypsum and 10% lime to the 75%, 90%, and 100% fly ash mixes. The percentages of gypsum and lime were based on the amount of fly ash. The results are shown in Table 4.3, with each value representing the average of three test specimens.

Table 4.3 – Compressive Strength (psi)

Fly Ash Percentage	Fly Ash Samples				
	1	2	3	4	5
75	4,570	3,810	4,100	3,700	2,285
90	3,150	1,580	2,440	2,770	990
100	1,810	555	1,190	1,270	235

In general, fly ash sample No. 1 and No. 4 responded well to the gypsum and lime additions, with No. 3 following slightly behind. Sample Nos. 2 and 5 showed modest gains, with No. 5 exhibiting the worst. The result for fly ash sample No. 5 is likely the result of the high amount of carbon, which can interfere with the reactivity of the silica portions.

These results indicate that samples Nos. 1, 3, and 4 can use a lower amount of cement to obtain acceptable strengths, on the order of 10% to 15%, and thus facilitate the highest amount of CCPs in the synthetic riprap. Fly ash samples Nos. 2 and 5, on the other hand, would likely require at least 25% cement to reach acceptable levels of behavior.

Chapter 5

Synthetic Riprap Prototype Mix Evaluation

The final step in this proof-of-concept study of synthetic riprap constructed from CCPs involved developing and testing a mix design that utilized the highest percentage of fly ash and bottom ash that would result in a viable product. The research team used fly ash sample No. 1 with bottom ash sample No. 1. The mix design utilized 90% fly ash and 100% replacement of coarse aggregate with bottom ash. Both gypsum and lime were added to the mix at 5% and 10% of the fly ash amount, respectively, to augment strength development and behavior of the material. The mix design is shown in Table 5.1. Mechanical property test results are shown in Table 5.2, which included compressive strength, modulus of rupture, and modulus of elasticity. The values represent the average of three test specimens. The results indicate that it is possible to develop a viable material for use in constructing riprap while using up to 60% CCPs. This value can potentially increase to 90% if fine sieved bottom ash is also used to replace the natural sand.

Table 5.1 – Riprap Prototype Mix Proportions

Constituent	Amount (lb/yd^3)
Cement (Type I)	65
Fly Ash	500
Gypsum	25
Lime	50
Water	292
Bottom Ash	1630
Sand	1350

Table 5.2 – Mechanical Properties

Property	Test Value
Compressive Strength (psi)	3,005
Modulus of Rupture (psi)	347
Modulus of Elasticity (ksi)	2,810