

Time Dependent Strength and Stiffness of PCC Bottom Ash-Bentonite Mixtures

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Utilization of bottom ash from burning of pulverized coal in construction-related applications has received some attention within the last decade. Its use in geotechnical engineering applications is still very limited, however. Within the last few years several studies have been completed to evaluate strength, stiffness, and durability properties of pulverized coal combustion (PCC) bottom ash mixed with various admixtures. Studies have shown that the physical properties of bottom ash obtained from burning of pulverized coal are similar to that of natural sand with particle sizes ranging from fine gravel to fine sand and low percentages of silt and clay sized particles. However, unlike sand, chemical composition of bottom ash results in change of strength and stiffness characteristics of Illinois PCC bottom ash and bentonite mixtures with time are evaluated. A series of unconfined compression tests on bottom ash-bentonite mixtures at various curing ages was performed in the laboratory. Results presented show that strength and stiffness of bottom ash-bentonite mixtures changed significantly with time.

Keywords Bottom ash, coal combustion, modulus, shear strength, stiffness.

Introduction

Burning of pulverized coal to produce electricity generates large quantities of coal combustion products (CCPs) every year all over the world. During 2001, about 900 million metric tons (Mt) of coal were burned in the United States, and about 107 Mt of coal combustion byproducts were generated by electric utilities and non-utilities (Kalyoncu, 2003). According to Dube (1994), only 10 percent of the total ash generated was being used in the early '90s. In 2001, approximately 33 percent of the total CCPs was used in various applications (Kalyoncu, 2003) whereas in 2000 approximately 29 percent (28.59 Mt) of CCPs was used (Kelly and Kalyoncu, 2002). Because of the increasing costs associated with the disposal of CCPs and environmental regulations in place, development of profitable and environmentally safe uses of this waste material is required. Out of several types of CCPs, beneficial use of bottom ash is very limited so far. Not much effort has been made in the

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past to evaluate strength and stiffness characteristics of bottom ash mixed with admixtures. As a consequence, its use in geotechnical engineering applications is still very limited, if any.

Coal utilization is one area in which the handling and disposal of waste can be especially costly since large volume of waste is generated. Therefore, there is a strong economic incentive to develop improved methods of utilizing coal combustion byproducts (Shirey *et al.*, 1999). The high cost of transporting the low unit-value CCPs and competition from locally available natural materials are the two most important economic barriers for CCPs utilization (Kalyoncu, 2003). Federal, state and local agencies, as well as the private sector, have been taking an active part in sponsoring and promoting a growing number of programs and research studies to develop alternative methods to make profitable and environmentally safe uses of these residues.

The major utilization of CCPs has been in construction-related applications. Within the past 30 years, the concrete industry has given special attention to the safe and economical utilization of these residues (Helmuth, 1987). Current research on the beneficial use of CCPs as building and highway construction materials has identified several promising uses for these materials. In addition to use in concrete, CCPs have been successfully used in the agricultural industry, blasting grit and roofing material, cement clinker raw feed, flowable fill, grout, mineral filler, mining applications, snow and ice control, wallboard, roller compacted concrete, structural fill, embankments, and soil stabilization (Kalyoncu, 2003). Several case histories of utilization of coal combustion byproducts in construction projects are available (ACAA, 2001; GAI, 1988; Golden, 1986; Korcak, 1998; Kumar *et al.*, 2001, 2003; Kumar and Stewart, 2003a, and b; Lovell *et al.*, 1997; Naik *et al.*, 1997; Schroeder, 1994; Seals *et al.*, 1972; Tikalsky and Carrasquillo, 1989).

Studies have shown that the physical properties of bottom ash are similar to that of natural sand with particles sizes ranging from fine gravel to fine sand and low percentages of silt and clay-sized particles. The particles of PCC bottom ash appear to be internally porous when-examined under magnification. In addition, the PCC dry bottom ash is light gray in color and has a sandpaper-like surface texture. Chemical composition of PCC dry bottom ash shows some cementitious/pozzolanic properties, which can result in time-dependent change in the properties of products made using this type of bottom ash.

Natural sands are commonly used inplace of cohesive soils after amending with admixtures such as bentonite, clay, and lime, and several studies have been done to evaluate the properties of mixtures of sand and admixtures. Since physical properties of PCC bottom ash are similar to that of sands, this study was conducted on bottom ash-bentonite mixtures. For any geotechnical project, strength and stiffness are the most important parameters required for design. Because of the chemical composition of bottom ash, the strength and stiffness of the bottom ash-bentonite mixtures may change with time. Therefore, this study was initiated with an objective to evaluate change in the strength and stiffness characteristics of bottom ash-bentonite mixtures with time. The goals of this study were accomplished by conducting a series of unconfined compression tests with stressstrain measurements in the laboratory. The strength was measured in terms of unconfined compression strength and the stiffness was measured in terms of initial tangent modulus and secant modulus. The samples were prepared at four different bentonite contents (5, 10, 15, and 20 percent by dry weight of the total sample) and were tested at four curing ages (0, 7, 28, and 60 days). The detailed test procedure and results are presented herein.

Testing Procedure and Materials Used

The bottom ash used for this study was obtained from City Water Light and Power Company (CWLPC) in Springfield, Illinois. The CWLPC uses coal from Elkhart, Illinois coal mine. Table 1 shows the chemical composition of bottom ash used in this study. Prior to use, the bottom ash was air dried at room temperature $(77 \pm 3^{\circ}F)$ and was sieved using a U.S. standard No. 40 sieve. The bentonite used in this investigation is sodium montmorillonite, which has a liquid limit of 550 and plastic limit of 55. The bentonite was obtained from Central Mine Equipment Company, St. Louis, Missouri.

All laboratory tests were performed in general accordance with the applicable procedures outlined by the American Society for Testing and Materials (ASTM D-2166). The samples were prepared at four different bentonite contents (5, 10, 15, and 20 percent by dry weight of the total sample). Samples from each bottom ash-bentonite mixture were tested at curing ages of 0, 7, 28, and 60 days. The samples were prepared by thoroughly mixing required weight of bentonite, bottom ash and water, and compacting the mixture to obtain 72 mm (2.82 in) diameter and 142 mm (5.60 in) high samples. A mold 190 mm (7.50 in) in height and 72 mm (2.82 in) in diameter and small compaction hammer were used to compact the samples. The goal was to create 142 mm (5.60 in) high samples by compacting the material in three equal layers. Each layer was compacted till the height of the layer reached the required height of that layer. In order to obtain a level horizontal surface at the top of the sample, it was decided to compact the samples 147 mm (5.80 in) in height and trim the samples to a height of 142 mm (5.60 in) after extrusion from the mold. All the samples were targeted for a dry unit weight of 15.70 kN/m³ (100 pcf) and moisture content of 20 percent.

A total of eight samples were prepared from each bottom ash-bentonite mixture. Two samples of each bottom ash-bentonite mixture were tested in unconfined compression immediately after completion of sample preparation. The rest of the samples were wrapped with plastic and sealed in two ziplock bags. All the wrapped and sealed samples were placed in water to prevent any moisture loss. Samples in water were monitored at a regular basis

Chemical properties of illinois PCC bottom ash		
Chemical Composition	PCC Bottom Ash (%)	Standard Limits (ASTM C 618)
Silicon dioxide (SiO2)	46.84	_
Aluminum Oxide (Al2O3)	14.36	
Iron Oxide (Fe2O3)	18.65	
Total (SiO2 + Al2O3 + Fe2O3)	79.85	50% Min
Sulfur Trioxide (SO3)	0.33	5.0% Max
Calcium Oxide (CaO)	7.24	
Magnesium Oxide (MgO)	1.04	
Loss on Ignition	4.21	6% Max
Free Moisture	N/A	3% Max
Available Alkalies as Na2O	1.73	1.5% Max
Potassium Oxide (K2O)	1.20	
Others (P2O5, TiO2, and etc.)	2.10	—

 Table 1

 Chemical properties of illinois PCC bottom ash

to check for any leakage of water. After each required curing period, samples were taken out of water and tested in unconfined compression. Moisture content of the samples was measured after the tests to determine loss or gain of moisture content, if any. All samples, except one, showed practically no change in the moisture content. Results from the sample that showed significant change in the moisture content were discarded. Testing of the specimens in unconfined compression was performed using an unconfined compression testing apparatus. All the samples were tested by loading the samples at a constant strain rate of approximately 0.5 percent per minute. Load-deformation characteristics of all samples were measured and recorded using an automatic data acquisition system for further analysis. Each test was continued until a vertical strain of approximately 15 percent was obtained or a sample failed in shear. Load-deformation data was collected and recorded for further analysis.

Results and Discussion

Although, an extensive laboratory investigation was conducted as a part of this study, test results from selected tests, directly relevant to the scope of this paper, are presented herein. As discussed in the previous section, several samples with various amounts of bentonite were tested at various curing ages to study the time-dependent strength and stiffness characteristics of bottom ash-bentonite mixtures.

Figures 1 and 2 show typical stress-strain response of samples with 10 and 20 percent bentonite, respectively, tested immediately after completion of sample preparation, i.e., 0 days curing age. These tests were performed to establish base strength and stiffness of the mixtures so that change in strength characteristics with time could be studied. Two samples of each bottom ash-bentonite mix were tested at each curing age. Figures 1 and 2 show that the stress-strain responses of both the samples of each type of bottom ash-bentonite mixture are similar and are nonlinear, which are typical of most soils. Failure strain of samples with 10 percent bentonite the failure strain was observed to be approximately 4 percent, whereas for samples with 20 percent bentonite the failure strain was observed to be approximately 9 percent. In general, the failure strain increased with the increase in bentonite content and decreased with the curing age. Figures 1 and 2 also show how the initial tangent and secant modulii were calculated from the stress-stain data.



Figure 1. Stress-strain response of a mixture with 10 percent bentonite tested at 0 days.



Figure 2. Stress-strain response of a mixture with 20 percent bentonite tested at 0 days.

Unconfined Compression Strength Response

Figure 3 shows the unconfined compression strength response with percent bentonite content at various curing ages. It is evident from Figure 3 that the unconfined compression strength changed marginally when the bentonite content increased from 5 to 10 percent, irrespective of the curing age. However, beyond 10 percent bentonite, the unconfined compression strength increased almost linearly with the increase in percent bentonite in the bottom ash. Figure 4 shows the effect of curing age on the unconfined compression strength of all bottom ash-bentonite mixtures tested. Figure 4 clearly shows a significant increase in the unconfined compression strength of all the mixtures. The unconfined compression strength of mixtures with 5, 10, 15, and 20 percent bentonite, after 60 days of curing, was 46, 57, 59, and 49 percent, respectively, more than the unconfined compression strength at 0 days of curing. It is also evident from Figure 4 that a significant portion of the total strength gain occurred within the first 7 days of curing. For mixtures with 5 and 10 percent bentonite, 80 to 90 percent of the total gain in unconfined compression strength occurred within the first seven days of curing, whereas for mixtures with 15 and 20 percent bentonite, 44 to



Figure 3. Unconfined compression strength versus bentonite for each curing period.



Figure 4. Unconfined compression strength versus curing period for each bentonite content.

47 percent of the total strength, gain was observed during the first seven days. Beyond 7 days of curing, samples with 15 and 20 percent bentonite show continued increase in the unconfined compression strength, whereas samples with 5 and 10 percent bentonite show minimal change in the unconfined compression strength. Based on the results obtained, it was concluded that most of the unconfined compression strength gain occurred within first 7 days after preparation of the samples and beyond 7 days of curing, the rate of change of unconfined compression strength is significantly less than the rate during the first 7 days of curing.

Initial Tangent Modulus Response

Initial tangent modulus was obtained from the initial portion of the stress-strain curves as shown in Figures 1 and 2. Figure 5 shows the initial tangent modulus response with percent bentonite content at all curing ages. Results presented in Figure 5 clearly show almost linear increase in initial tangent modulus with the increase in percent bentonite content. However, the rate of increase of initial tangent modulus with percent bentonite is significantly higher for samples cured for 7, 28, and 60 days compared to those tested



Figure 5. Initial tangent versus percentage of bentonite for each curing period.

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Figure 6. Initial tangent versus curing period for each percentage of bentonite.

immediately after sample preparation was completed, i.e., 0 days of curing. Figure 6 shows the effect of curing on initial tangent modulus of bottom ash-bentonite mixtures tested in this study. The initial tangent modulus results also show significant increase in the initial tangent modulus with time. The initial tangent modulus after 60 days of curing was observed to be more than double the initial tangent modulus measured from samples tested immediately after sample preparation (0 days of curing). Similar to the observations made from the unconfined compression strength response, a significant portion of the total increase in initial tangent modulus was observed within first 7 days of curing. For mixtures with 5 to 15 percent bentonite, approximately 51 percent of the total increase in modulus was observed within the first 7 days of curing, whereas for mixture with 20 percent bentonite, approximately 61 percent of the total increase in modulus was observed within the first 7 days of curing. Beyond 7 days of curing, rate of increase in the initial tangent modulus was significantly less than that observed during the first 7 days of curing. Based on the results presented in Figures 5 and 6, it was concluded that if the samples are made to the same dry unit weight and moisture content, the initial tangent modulus from unconfined compression tests increase linearly with the percent bentonite content. In addition, most of the gain in initial tangent modulus occurs during first 7 days of curing.



Figure 7. Secant modulus versus percentage of bentonite for each curing period.



Figure 8. Secant modulus versus curing period for each percentage of bentonite.

Secant Modulus Response

In this study secant modulus was computed as the ratio of stress and strain at failure as shown in Figures 1 and 2. Figure 7 shows the effect of adding bentonite on the secant modulus response at all curing ages obtained from unconfined compression strength tests. Comparison of secant modulus response (Figure 7) with unconfined compression strength (Figure 3) and initial tangent modulus (Figure 5) shows a significantly different trend. Figure 7 shows that at all curing ages, secant modulus decreased with the increase in bentonite content up to 15 percent and increased slightly beyond 15 percent bentonite. From the results shown in Figure 7, it can also be interpreted that with the increase in bentonite content the mixture became more plastic which resulted in an increase in failure strain. Beyond 15 percent bentonite content the failure strain remained fairly constant but a slight increase in unconfined compression strength resulted in a higher value of secant modulus.

Figure 8 shows the effect of curing age on secant modulus response of the mixtures tested at all curing ages. Similar to observations made from unconfined compression strength and initial tangent modulus response, Figure 8 shows that the secant modulus of all mixtures increased significantly with time. The total increase in the secant modulus after 60 days of curing for mixtures with 5, 10, 15, and 20 percent bentonite was measured to be 95, 134, 339, and 235 percent, respectively, more than the secant modulus measured from samples tested immediately after sample preparation (0 days of curing). Similar to the observations made from the unconfined compression strength and initial tangent modulus responses, a significant portion of the total increase in secant modulus was observed within the first 7 days of curing. For mixture containing 5 percent bentonite, 51 percent of the secant modulus increase occurred within the first 7 days of curing. For mixtures containing 10 or more percent of bentonite, the increase in secant modulus within the first 7 days was observed to be between 42 and 50 percent.

Conclusions

A detailed experimental study was conducted to evaluate the effects of adding bentonite and curing age on the strength and stiffness properties of bottom ash-bentonite mixtures. Results are presented to show that addition of bentonite increased the unconfined compression strength and initial tangent modulus of the mixtures, whereas the secant modulus of the

mixtures decreased with the addition of bentonite up to 15 percent. Results presented also show that the unconfined compression strength, initial tangent modulus, and secant modulus of all mixtures increased significantly with time and most of the strength and stiffness gain occurred within the first 7 days of curing. Beyond 7 days, the rate of change in the unconfined compression strength, initial tangent modulus, and secant modulus is very small compared to the rate of change during the first 7 days of curing. These observations are important for use of these mixtures in geotechnical engineering applications. Further investigation is in progress to evaluate the chemical changes in the mixtures with curing age.

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