Geotechnical Properties of Fly Ash and Soil Mixtures for Use in Highway Embankments

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ABSTRACT

Fly ash has a potential to be beneficially used in roadway constructions, including embankments and pavement structural layers such as base/sub-base layers, shoulders, asphalt concrete, and Portland cement concrete, to create longer lasting and sustainable infrastructure. The paper describes a study of the optimization of fly ash-soil mixture for highway embankment construction. The fly ash was collected from a utility power plant in Mississippi. Tests were conducted on soils and fly ash-soil mixtures prepared at optimum water content, including compaction, permeability, and unconfined compressive strength (q_u). Addition of fly ash into soil resulted in appreciable increases in the q_u of the inorganic soil. After 14 days of curing, the q_u of the samples compacted from the fly ash/soil mixtures ranged between 900 kN/m^2 and 9300 kN/m^2, whereas the soil alone had a q_u of 1 to 200 kN/m^2. The effect of mixing ratio and compaction water content on the geotechnical properties of fly ash/soil mixtures was discussed.

INTRODUCTION

According to the American Coal Ash Association, in 2007, the United States produced 131 million tons of coal combustion products annually. About 43% of the ashes were use beneficially, while nearly 75 million tons of ashes were disposed of as waste.[1] Due to the high cost of solid waste disposal, there has been an increased awareness of beneficial use technologies. Embankment construction is of particular interest because of the large volume of virgin materials being consumed annually. The beneficial use of fly ash for embankment construction is one of the promising solutions to reduce the disposal problem.

An embankment refers to a volume of earthen material that is placed and compacted for the purpose of raising the grade of a roadway above the level of the existing surrounding ground surface. Recent experience with the use of fly ash as embankment material has demonstrated that fly ash is an excellent engineering fill material, the performance is comparable to natural borrow materials.[2] Some of the geotechnical properties of fly ash that are of particular interest in embankment are its moisture-density relationship, particle size distribution, permeability, and strength.[3] The main objective of this paper is to optimize fly ash-soil mixture for embankment construction through laboratory tests. The compaction properties, density, compressive strength, and permeability were used as measures for the optimization. The optimum moisture content, fly ash-soil ratio, and curing condition were targeted in the study.

MATERIALS

Fly Ash

The fly ash was collected from the Red Hills Generation Facility (RHGF) located in Ackerman, Mississippi. It is a power plant that uses lignite coal from adjacent Red Hills Mine as its source of fuel. The RHGF utilizes a modern circulating fluidized bed (CFB) boiler technology. CFB units have an advantage over the conventional pulverized coal units in burning low-grade or high-sulfur content coal.[4] Few data has been published regarding the applicability of CFB fly ash for soil improvement applications.

Based on the chemical composition requirement stipulated in ASTM C 618 or AASHTO M 295, the RHGF fly ash does not meet either Class C or Class F, therefore it is considered as off-specification fly ash. The RHGF fly ash chemical composition is given in Table 1 alongside those for Class C and Class F fly ash specified in ASTM C 618.

Table 1. Chemical Composition of RHGF Fly Ash* and ASTM C 618 Specification Requirements

		ASTM C 618-08 Specification	
Chemical Composition	**RHGF Fly Ash**	**Class C**	**Class F**
Sum of SiO_2, Al_2O_3, Fe_2O_3, (%)	68.03	50 Min.	70 Min.
Sulfur Trioxide (SO_3), (%)	5.44	5.0 Max.	5.0 Max.
Moisture Content	0.13	3.0 Max.	3.0 Max.
Loss of Ignition	0.55	6.0 Max.	6.0 Max.
Calcium Oxide (CaO), (%)	19.32		

* The chemical analysis was carried out by Headwaters Resources on February 19, 2010, from a sample obtained on December 2009.

The RHGF fly ash does not meet the ASTM C 618 requirement because of its high sulfur trioxide (SO_3) content.

Soils

The soils were collected based on the type of borrow material generally used by the Mississippi Department of Transportation (MDOT) for embankment construction. The soils were attained from a construction site on the Jackson State University campus in Jackson, Mississippi and from a borrow excavation site in Pearl, Mississippi. The soil from the Pearl site has been used by MDOT for roadway construction purpose.

METHODS

Soil Characterization

Sieve analysis, hydrometer analysis, and Atterberg limits were performed to classify the soil samples. The Index properties, compaction characteristics, and classifications for each soil were obtained in these tests. The soils were classified in accordance with ASTM D2487 Standard Classification of Soils for Engineering Purposes, USCS Unified Soil Classification System, and AASHTO Classification of Materials for Subgrades and Granular Type Roads.

Geotechnical Properties of Fly Ash-Soil Mixtures

Fly ash-soil mixtures were prepared at several fly ash-soil ratios (i.e. 0, 20, 40, 60, and 100% fly ash content by weight), and then tested for their engineering properties relevant to embankment construction, including the compaction properties, compressive strength, and permeability.

Compaction

The unit weight of fly ash-soil mixture is an important parameter since it controls the strength, compressibility, and permeability. Densification of ash improves the engineering properties.[5] The unit weight of the compacted mixtures depends on the method of energy application, amount of energy applied, grain size distribution, plasticity characteristics, and moisture content at compaction. Gray and Lin have reported the engineering properties of compacted fly ash and found that properly compacted and stabilized fly ash has the requisite properties for use in load-bearing fills or highway sub-bases.[6]

Standard proctor compaction tests were performed on the fly ash-soil mixtures at different fly ash-soil ratios following ASTM D 698. A premeasured amount of fly ash, measured as percent of dry soil by weight, was mixed thoroughly to produce a homogeneous fly ash-soil mixture. Water was added slowly during mixing. The samples were compacted in 101.6 mm diameter molds.

Curing of Samples

Although there is no standardized protocol for testing fly ash-soil mixtures, there have been reports that compaction of samples of fly ash-soil mixtures should be done two hours after blending to simulate field compaction delay.[7] The samples were compacted in accordance to ASTM D 698. Each specimen was sealed in one gallon zip-loc bag and placed in an oven at 38°C ± 3°C immediately after compaction. The samples were cured for 14 or 28 days and subsequently tested for unconfined compressive strength.

Unconfined Compressive Strength (UCS)

Compressive strength is one of the most important geotechnical properties that a material like fly ash must possess when being considered for the different geotechnical applications. The unconfined compressive strength (UCS) varies with the fly ash-soil mixing ratio and water content. In order to find the optimum water content, the unconfined compressive strengths at different compaction water content for 20% fly ash-soil mixture and 100% fly ash samples were tested. For the 20% fly ash-soil mixture the starting water content was the optimum water content attained from the standard proctor compaction test. For the optimization of 100% fly ash, the starting water content was below the optimum water content attained from the standard proctor compaction test. The samples used for the optimization were cured for 14 days. The UCS test was conducted in accordance to ASTM D 2166 specification.

Permeability

Permeability is the measure of the rate at which a fluid passes through a material. Along with the pollutant leaching data, it may be used to estimate possible impacts on groundwater quality. Permeability data for CFB fly ash has been shown to range from about 10^{-5} to 10^{-9} cm/s or lower.[3] The permeability of fly ash depends upon the grain size, degree of compaction, and pozzolanic activity.[5] Since fly ash consists almost entirely of spherical shaped particles, the particles are able to be densely packed during compaction, resulting in comparatively low permeability values and minimize seepage of water through a fly ash embankment.[3] The soil permeability was measured by falling head test using a flexible-wall permeameter in accordance to ASTM D 5084.

RESULTS AND DISCUSSION

Soil Characterization

The USCS classification group names and AASHTO group index values are provided in Table 2. Both soils are low plasticity clays. The maximum dry unit weight ($\gamma_{d,max}$) and optimum compaction water content (W_{opt}) for the Campus soil, determined using ASTM D698 Standard Proctor Compaction, were 17.9 kN/m^3 and 14%, respectively.

Table 2. Index Properties, Compaction Characteristics, and Classification of Soil Samples

			Classification			
Soil Sample	**Liquid Limit**	**Plasticity Index**	**USCS**	**AASHTO**	W_{opt} **(%)**	$\gamma_{d, max}$ **(kN/m³)**
Campus Soil	37.0	20	CL	A-6	14	17.9
Pearl Soil	40.0	23	CL	A-6	NA	NA

Particle Size Analysis

The particle size distribution for each soil is shown in Figure 1. The Campus soil is slightly finer than the Pearl soil. The distribution shows that the soils are well graded. The percent of fines (P200) range between 76 and 87%. Since the two soils are similar, they are mixed to use in the following tests.

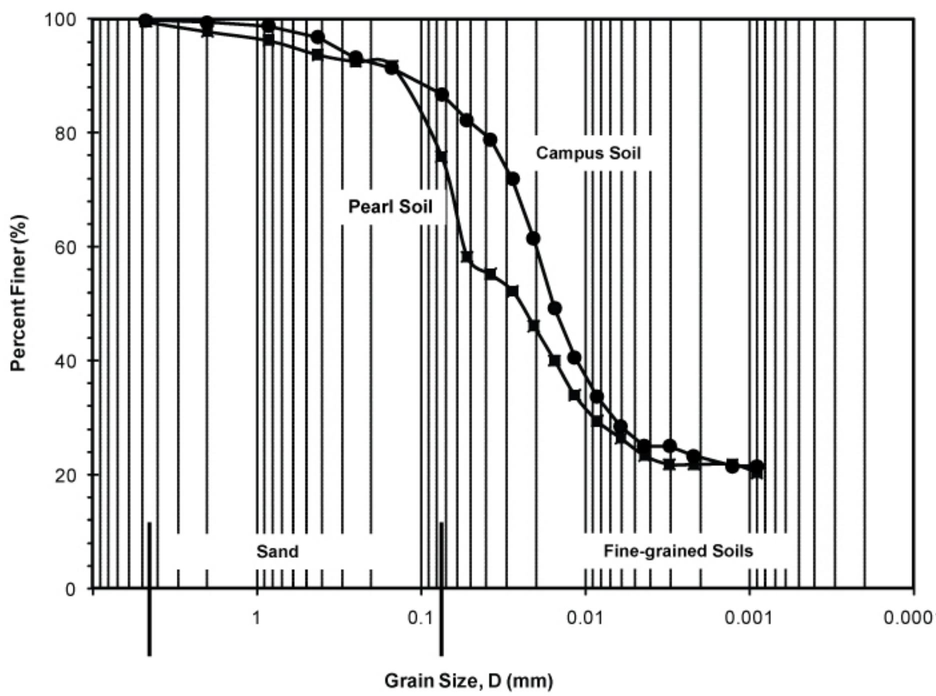

Figure 1. Particle Size Distribution Curves for Soil Samples

Compaction

The results of dry unit weight as function of fly ash-soil mixture ratios and moisture contents are shown in Figure 2. Table 3 summarizes the optimum water contents and maximum dry densities. The soil has the highest maximum dry unit weight (17.9 kN/m^3) at the lowest optimum water content (14%). The pure fly ash sample exhibits the lowest maximum dry density (10.4 kN/m^3) and highest optimum moisture content (45.5%). The 20, 40, and 60% fly ash-soil mixtures exhibit a decrease of the maximum dry density with increasing optimum water content. The results show that as the fly ash content increases, the maximum dry unit weight decrease and the optimum water content increase. The decrease in maximum dry unit weight as fly ash content increase is associated with the notion that fly ash is lightweight compared to soil only. The higher optimum water content associated with higher fly ash content follows from the need of hydration reaction for cementitious fly ash, and to release the capillary tension from the greater exposed surface of the finer fly ash particles.[9] The maximum dry unit weight as well as the optimum water content shows a significant dependence upon the fly ash content. The maximum dry unit weight values of fly ash-soil mixture are generally lower than those of soils, which typically range from 17 to 20 kN/m^3.[10]

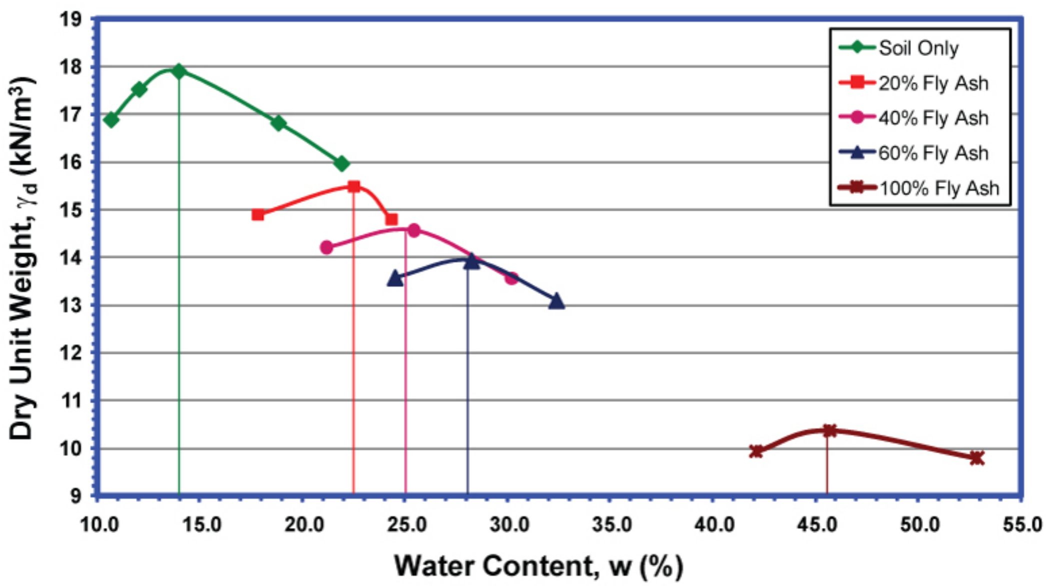

Figure 2. Moisture-Density Relationship of the Fly Ash-Soil Mixtures

Table 3. Summary of Fly Ash-Soil Mixture Optimum Water Contents and Maximum Dry Unit Weight

Fly Ash-Soil Mixture	Optimum Water Content, W_{opt} (%)	Maximum Dry Density, $\gamma_{d, max}$, (kN/m^3)
Soil Only	14.0	17.9
20% Fly Ash	22.5	15.5
40% Fly Ash	25.0	14.6
60% Fly Ash	28.0	13.9
100% Fly Ash	45.5	10.4

Compressive Strength

Figure 3 shows the unconfined compressive strength of 20% fly ash-soil mixture at different water contents. It can be seen that, as water content exceeded the compaction optimum water content (22.5%), the compressive strength decreased. Therefore, for the 20% fly ash-soil mixture, the optimum water content for maximum strength is the same as optimum compaction water content.

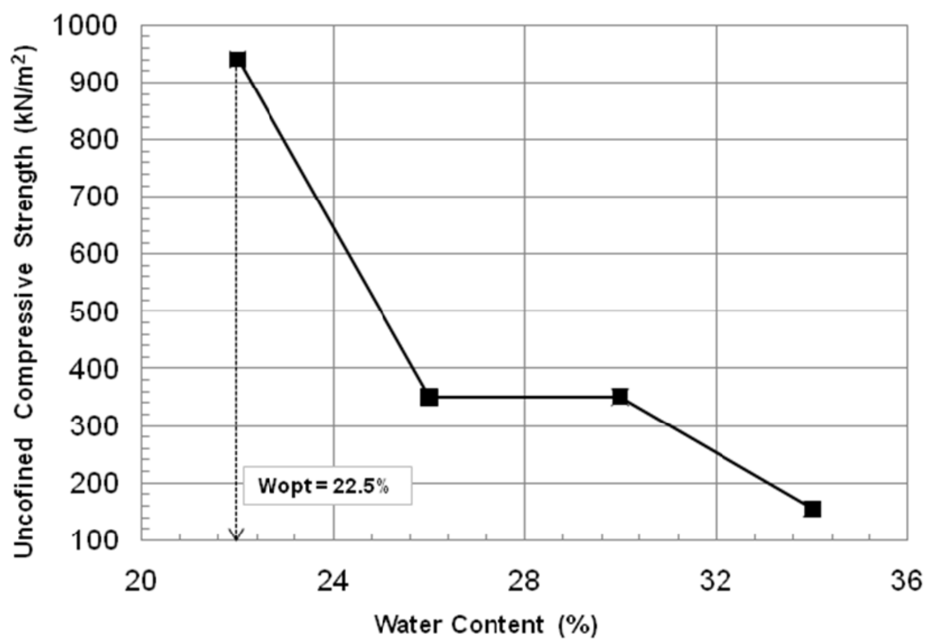

Figure 3. Unconfined Compressive Strength Optimization at Different Compaction Water Content for the 20% Fly Ash-Soil Mixture Cured for 14 Days

Figure 4 shows the unconfined compressive strength of 100% fly ash samples at different water contents. The strength increased with the increase of water content up to a certain level, and then decreased. The optimum water content for maximum strength (50%) is slightly higher that of the compaction optimum water content (45.5%). The results show that the maximum strength cannot be obtained if only based on the optimum compaction water content. The optimum water content for maximum strength should be used for embankment construction.

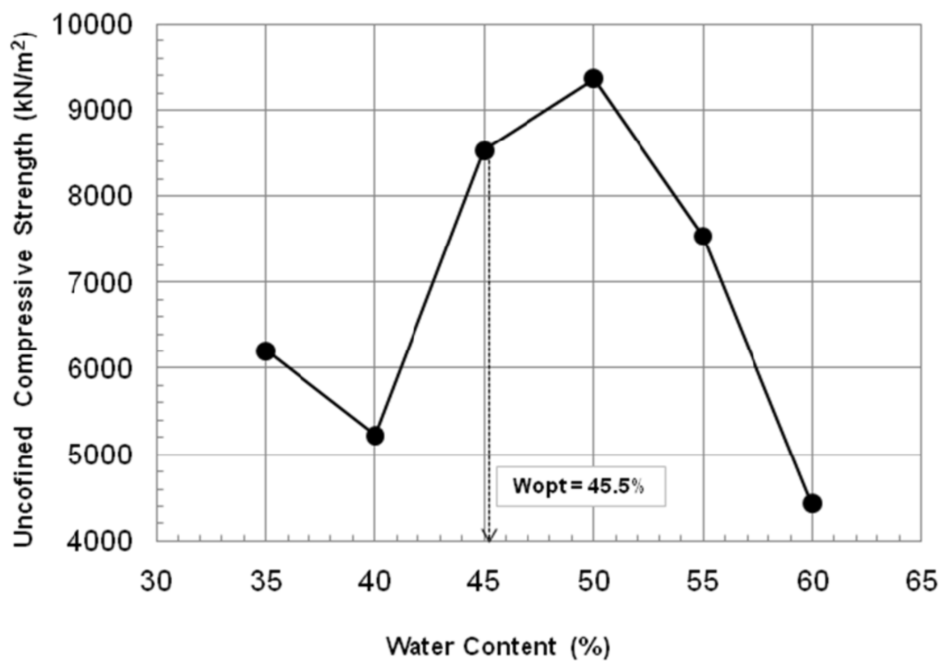

Figure 4. Unconfined Compressive Strengths at Different Compaction Water Content for 100% Fly Ash Cured for 14 Days

The unconfined compressive strengths obtained at the optimum compaction water contents for other fly ash-soil mixtures are given in Table 3. Note that some samples were cured for both 14 days and 28 days. The results show that 100% fly ash has the highest strength of 9365 kN/m^2. The strength increased with the increase fly ash-soil ratios. The minimum strength 940 kN/m^2 (for 20% fly ash-soil), which meets MDOT minimum requirement of 35.9 kN/m^2 for embankment construction[8].

Table 3. Summary of Fly Ash-Soil Mixture Water Contents and Maximum Compressive Strength

Fly Ash-Soil Ratio	Water Content W_c (%)	Maximum Strength	
		14 Days Curing (kN/m^2)	28 Days Curing (kN/m^2)
100	50.0	9365	NA
60	28.0	2536	2665
40	25.0	2258	2648
20	22.5	940	1353

Permeability

After establishing the compaction curves, compacted clay specimens were prepared for hydraulic conductivity testing. The specimens were compacted in a 71 mm diameter mold at an optimum water content of 14%. After compaction, the compacted specimens were extruded from the compaction mold and placed into flexible-wall permeameters. The assembled specimens then were back-pressured, maintaining an effective stress of 34.5 kPa until a minimum B value of 0.95 was established in accordance with ASTM D5084. At the end of back-pressure stage, the cell (confining) pressure was 294.4 kPa and the back pressure was 259.9 kPa.

Following the back-pressure stage, specimens were permeated with tap water as the permanent liquid. The falling headwater-rising tailwater method was used for permeation (ASTM D5084). Flow was induced from bottom to top of the specimen by changing the headwater pressure to 292.3 kPa and the tailwater pressure to 275.8 kPa, resulting in a pressure difference of 16.5 kPa, an average effective stress of 10.3 kPa, and a hydraulic gradient on the order of 16.5. The tests were not terminated before both of the following criteria were achieved (ASTM D5084): (1) at least four consecutive volumetric flow ratios of outflow relative to inflow were within 1.00±0.25 and (2) at least four consecutive *k* values were within ±25% of the mean value for $k \geq 1x10^{-8}$ cm/s or within ±50% for $k < 1x10^{-8}$ cm/s. The result of the hydraulic conductivity test was $2.45x10^{-8}$ cm/s.

CONCLUSIONS

Laboratory tests performed in this research suggest that the off-specification fly ash from the Red Hills Generation Facility is an effective material suitable for use in embankment construction.

Fly ash-soil mixtures exhibit relatively well defined moisture-density relationships, varying with mixture ratios. As fly ash content increases, optimum water content increases and the dry unit weight decreases. The dry unit weight for fly ash-soil mixtures is lower than those of typical compacted soils.

The unconfined compressive strength of fly ash-soil mixtures increases with the increase of fly ash content. The pure fly ash samples can attain a UCS of 9365 kN/m^2. The effect of longer curing time (from 14 to 28 days) has greater effect on the 20% fly ash content mixture, but insignificant effect on other mixtures. The result of the hydraulic conductivity test was 2.45×10^{-8} cm/s.

Based on the results of this research, it appears that fly ash-soil mixtures and pure fly ash are suitable for use in highway embankments. Fly ash can provide fill materials of comparable strength to most soil while having the advantage of lesser dry unit weights.

ACKNOWLEDGEMENTS

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