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Use of Class C Fly Ash For Stabilization of Soft Subgrade

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Abstract

This paper represents the results of a study aimed at using self-cementing Class C fly ash for the stabilization of soft subgrade of a city street in Cross Plains, Wisconsin, U.S.A. Both strength and modulus-based approaches were applied to estimate the optimum mix design and to determine the thickness of the stabilized layer. Stabilized soil samples were prepared mixing fly ash at three different contents at varying water contents. The samples were subjected to unconfined compression test after seven days of curing to develop water content-strength relationship. To evaluate the impact of compaction delay that commonly occurs in field construction, one set of the samples was compacted just after mixing with water, while the other set after two hours. CBR and resilient modulus tests were conducted and used to determine the thickness of the stabilized layer in pavement design. Some field tests were also performed after the construction, which showed that the fly ash stabilization improved the engineering properties significantly.

Introduction

Fly Ash is one of the most plentiful and versatile of the industrial by-products (Collins and Ciesielski 1992). It is generated in vast quantities (more than 65 million metric tons per year) as a by-product of burning coal at electric power plants. Combustion of sub-bituminous coal produces a fly ash (Class C) that has self-cementing characteristics and has been used in earthwork applications to improve the mechanical properties of soils for more than 20 years (Ferguson 1993). After the introduction of Clean Air Act Amendments of 1990, the utilities in the western and mid-western regions of the United States began burning sub-bituminous coal in their power plants to meet more stringent EPA sulfur emission standards, which increased the availability of Class C fly ash. The potential for using fly ash in soil stabilization has increased significantly in Wisconsin due to increased availability and the introduction of new environmental regulations (NR

538, Wisconsin Administrative Code) that encourage use of fly ash in geotechnical applications when it is environmentally safe.

Class C fly ash is usually recycled as an engineering material to take advantage of its pozzolanic characteristics. This type of fly ash provides the opportunity for applications where no other activators would be required and thus it offers more economical alternative for a wide range of stabilization applications. The primary objective of this paper is to study how Class C fly ash can be used in soil stabilization without using any other activator, and the performance of fly ash-stabilized subbase of a pavement system.

Ferguson (1993) investigated soil stabilization in a racetrack with Class C fly ash without any other activator, which showed encouraging results. Improved engineering properties of fly ash-stabilized soil are also reported by Turner (1997). Edil et al. (2002) conducted research on fly ash-stabilized subbase along with nine other stabilization alternatives, such as those using a subbase layer consisting of foundry sand, foundry slag, and bottom ash or geosynthetics-reinforcement. Based on the falling weight deflectometer (FWD) data, performance of Class C fly ash-stabilized subbase seemed to be equal or better than the other stabilization alternatives.

Fly Ash Chemistry

Fly ash is classified into two classes, F and C, based on the chemical composition of the fly ash according to ASTM C 618 Class F fly ash is produced from burning anthracite and bituminous coals and contains small amount of lime (CaO). This fly ash has siliceous and aluminous material (pozzolans), which itself possesses little or no cementitious value but in the presence of moisture, chemically reacts with lime at ordinary temperature to form cementitious compounds (Chu et al. 1993). Class C fly ash is normally produced from lignite and sub-bituminous coals, and usually contains significant amount of lime (Cockrell et al. 1970) along with pozzolanic materials.

Formation of cementitious material by the reaction of lime with the pozzolans (AlO_3, SiO_2, Fe_2O_3) in the presence of water is known as hydration of fly ash. The hydrated calcium silicate gel or calcium aluminate gel (cementitious material) can bind inert material together. The pozzolanic reactions for soil stabilization are as follows (TRB 1987):

$$CaO + H_2O \Rightarrow Ca(OH)_2 \quad (1)$$

$$Ca(OH)_2 \Rightarrow Ca^{++} + 2[OH]^- \quad (2)$$

$$Ca^{++} + 2[OH]^- + \underset{\text{(silica)}}{SiO_2} \Rightarrow \underset{\text{(gel)}}{CSH} \quad (3)$$

$$Ca^{++} + 2[OH]^- + \underset{\text{(alumina)}}{Al_2O_3} \Rightarrow \underset{\text{(gel)}}{CAH} \quad (4)$$

For Class C fly ash, the lime present in the fly ash reacts with the siliceous and aluminous materials (pozzolans) in the fly ash. A similar reaction can occur in Class F fly ash, but lime must be added because the lime content of the ash is too low. Lime stabilization of soils occurs in a similar manner, where the pozzolanic reactions depend on the siliceous and aluminous materials provided by the soil.

Background

A city street in Scenic Edge (a residential sub-division) at Cross Plains, Wisconsin, U.S.A., which is described in this study, was constructed in August 2000. The layout of the field sites is shown in Fig. 1. The length of this street is 0.7 km. The pavement was originally designed to have an excavation of soft soil to 750 mm below the subgrade and refilling with granular material before pavement construction (i.e., base course and asphalt). Due to the opposition of the residents of the neighboring sub-divisions to removal and replacement of large amounts of earthen materials in trucks through their sub-divisions, motivated the city authority to consider the alternative of *in situ* stabilization that would reduce the trucking by 95%. Technical assistance from the "Consortium for Fly Ash Use for Geotechnical Application" at the University of Wisconsin-Madison ensured development of fly ash stabilization rapidly.

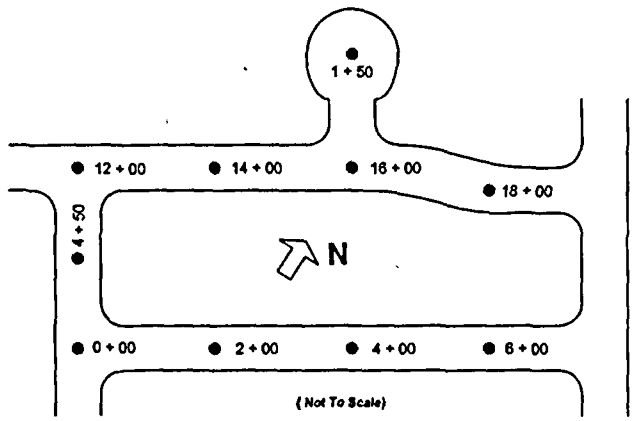

Figure 1 Layout of the Scenic Edge Field Site.

MATERIALS

Soil

Soil samples were collected along the centerline of the proposed roadway at the depth of the subgrade level using Shelby tubes. Index properties, compaction characteristics, classifications, and California bearing ratio (CBR) of the subgrade soil are shown in Table 1. The soil is low-plasticity clay. The maximum dry unit weight was 16.2 kN/m^3 and optimum water content was 20% at standard Proctor effort (ASTM D 698). CBR test was performed at the natural water content following ASTM D 1883. The CBR was 1, which indicates that the soil is very soft at natural water content. Particle size distribution curve for the soils is shown in Fig. 2. The percent fines (P_{200}) is 93%, and the 2-μm clay fraction is 20%.

Fly Ash

Class C Columbia fly ash from the Columbia Power Station (Unit 2) in Portage, Wisconsin, was used for soil stabilization. The specific gravity of the fly ash was 2.68 and the loss on ignition was 0.7%. Columbia fly ash contains 23% lime, which is very similar to typical Class C fly ash (FHWA 1995). Particle size distribution curve of the fly ash is shown in Fig. 2 along with the soil. Columbia fly ash contains some uniform silt size and a wide range of smaller particles. The percent fines of Columbia fly ash is 98% and the 2-μm clay fraction is 9%.

Table 1 Index Properties, Compaction Characteristics, Classification, and CBR of Soil.

Liquid Limit	Plasticity Index	Specific Gravity	LOI (%)	Classification		CBR	W_N (%)	$\gamma_{d(CBR)}$ (kN/m^3)	W_{OPT} (%)	γ_{dmax} (kN/m^3)
				USCS	AASHTO					
44	20	2.71	2	CL	A-7-6	1	27	14.6	20	16.2

Notes: LOI = Loss on Ignition, W_N = Natural Water Content, $\gamma_{d(CBR)}$ = Dry Unit Weight for CBR Samples, W_{OPT} = Optimum Water Content, and γ_{dmax} = Maximum Dry Unit Weight.

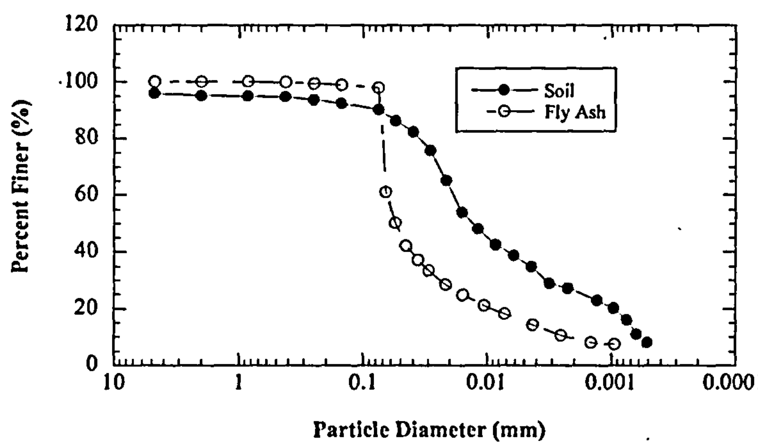

Figure 2 Particle Size Distributions of the Soil and Fly Ash.

Stabilized Soil

Compaction curves for stabilized soils determined using Harvard Miniature Compaction procedure (ASTM D 4609-94) are shown in Fig. 3 along with that of the untreated soil. The compaction effort was the standard Proctor effort (ASTM D 698). Mixtures were prepared with fly ash contents of 12%, 16%, and 20% on dry weight basis with the soil. Air-dried soil that passed a US No. 20 Standard sieve was mixed homogeneously with the required amount of fly ash and then the required amount of water was sprayed on soil-fly ash mixture. The first set of mixtures was compacted in a mold (35 mm-diameter and 70 mm-height) immediately after mixing with water (no delay) and the second set of mixtures was compacted 2 hr after mixing with water (2-hr delay) to simulate the typical duration between mixing and compaction that occurs in the field. The maximum dry unit weight and optimum water content for "no delay" stabilized soil are comparable with that for the soil alone. The maximum dry unit weight for "2-hr delay" stabilized soil is lower than that for the soil alone, and optimum water content of is slightly higher (1%). Additionally, the maximum dry unit weight decreases and the optimum water content increases as the fly ash content increases.

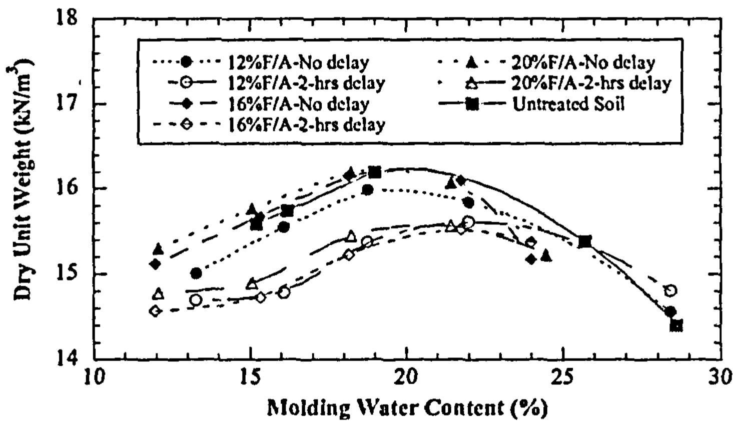

Figure 3 Compaction Curves for Fly Ash-Stabilized Soil and Untreated Soil.

Laboratory Tests

Unconfined Compression Tests

Unconfined compression tests were performed to develop a moisture content-strength relationship and to determine the effect of compaction delay. The specimens that were used for compaction characteristics of fly ash-stabilized soil were wrapped with saran wrap, allowed to cure for seven days in a wet room (100% relative humidity), and then subjected to unconfined compressive strength test following ASTM D 2166.

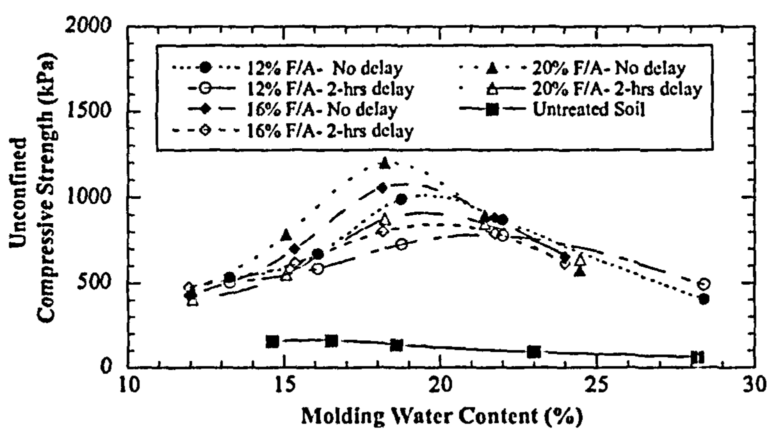

Figure 4 Unconfined Compressive Strength of Fly Ash-Stabilized and Untreated Soils at Different Molding Water Contents.

Unconfined compressive strength of fly ash-stabilized soils at different molding water contents is shown in Fig. 4 along with the untreated soil. Fly ash stabilization increases the strength significantly and the maximum strength increases with increasing fly ash content. The optimum strength was obtained at a specific water content, which was close to the optimum water content (1% wetter). The maximum strength was reduced by approximately 20% due to 2-hr compaction delay.

California Bearing Ratio (CBR) Tests

CBR tests were performed on stabilized soils at three different fly ash contents and at a molding water content of 1% wet of optimum, which corresponded to the maximum unconfined compressive strength. Air-dried soil that passed a US No. 4 Standard sieve was mixed homogeneously with the required amount of fly ash, and then the required amount of water was sprayed on soil-fly ash mixture. Similar to the unconfined compressive strength tests, some portion of the of soil-fly ash mixtures was compacted in a standard CBR mold immediately after mixing with water and the other portion of the mixtures was kept in a air-tight polythene bag and compacted 2hours after mixing with water. The CBR specimen was wrapped while in the mold with plastic wrap and allowed to cure for seven days in the wet room. Then the CBR tests were performed in accordance with ASTM D 1883-87.

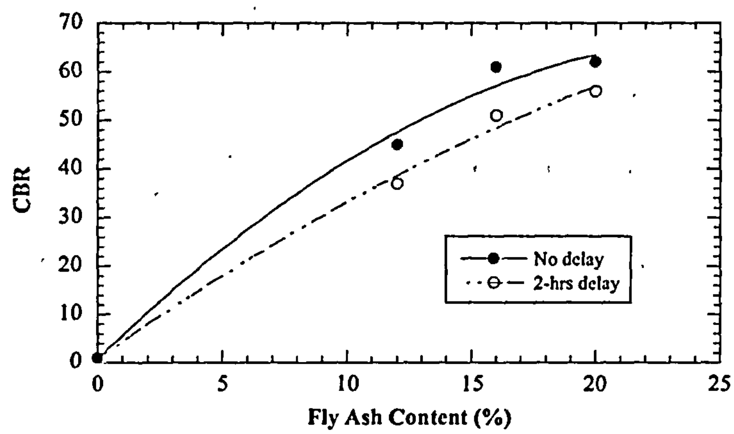

Figure 5 CBR of Fly Ash-Stabilized Soil at Different Fly Ash Contents.

CBR of the fly ash-stabilized soil prepared using different fly ash contents is shown in Fig. 5. Similar to unconfined compressive strength, CBR increases with increasing fly ash content and the rate of increase of CBR diminishes as the fly ash content increases. The CBR is also reduced (by approximately 18%) due to 2 hours of compaction delay.

Resilient Modulus Tests

The resilient modulus tests were conducted according to AASHTO Standard T 294-94 considering fly ash-stabilized soil as Type 2 material (cohesive soil). Resilient modulus tests were conducted at three different fly ash contents at a water content similar to that used in the CBR tests. Since the unconfined compressive strength and CBR test results showed a significant reduction of strength due to compaction delay, resilient modulus tests were conducted only on specimens that were compacted simulating 2-hr compaction delay. Soil-fly ash mixtures were prepared following the same procedure for CBR. Specimens of the resilient modulus tests were compacted in a split mold (100 mm-diameter and 200 mm-height) to achieve a dry unit weight corresponding to the standard Proctor compaction effort. Specimens were extruded and wrapped with plastic wrap, and allowed to cure for seven days in the wet room before performing the resilient modulus tests.

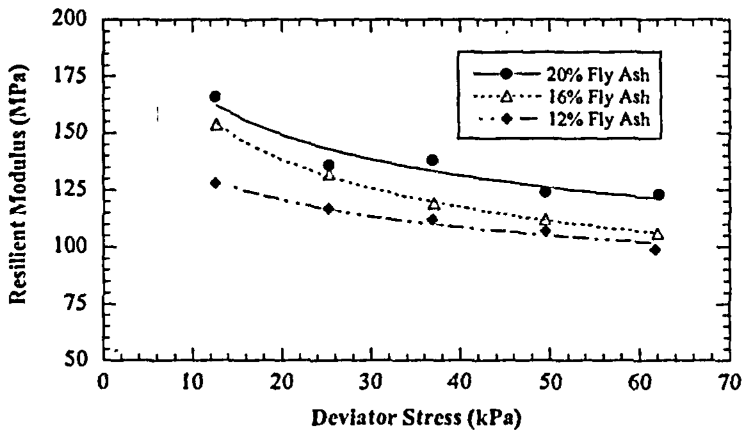

Figure 6 Resilient Modulus of Fly Ash-Stabilized Soil at Different Fly Ash Contents.

Resilient Modulus of the fly ash-stabilized soils prepared using different fly ash contents is shown in Fig. 6. Similar to unconfined compressive strength and CBR, resilient modulus increases with increasing fly ash content. Several attempts were taken to conduct resilient modulus test with the untreated soil at natural water content, but the specimen was too soft and failed during the test.

Field Construction

Based on the laboratory mix-design, the subgrade was stabilized using a fly ash content of 12% and the intended molding water content was 21% for the field site. Water content of the subgrade was measured prior to construction. For the Scenic Edge site, except from Stn. 12+00 to 18+00, an average water content of 23% was observed and no water was added in this section. But the average water content of the remainder section was 20%; therefore water was sprayed on the subgrade surface approximately an hour before construction so that the targeted water content (about 3 to 4% higher) can be achieved before mixing 12% fly ash. The required amount of fly ash was spread uniformly on the subgrade using a truck-mounted lay-down equipment designed specifically for fly ash application with minimal dust generation. After placing the fly ash approximately 200m, a reclaimer was used to mix the fly ash with the subgrade soil to a depth of 300 mm. Immediately after mixing, three different compactors (tamping foot, steel drum, and rubber tire) were used to compact the mixture in sequence to complete the stabilized process. Compaction to required density was verified by the nuclear density gauge survey.

Post Construction Tests

Unconfined Compression Tests

Shelby tube samples were collected before and after fly ash stabilization at different locations (Fig. 1). Both the untreated subgrade and fly ash-stabilized soil samples were extruded from the tube within 24 hrs and the stabilized soil samples were wrapped with plastic wrap and allowed to cure for seven days in the wet room. Specimens (50 mm in diameter and 100 mm high) were prepared by trimming Shelby tube samples and subjected to unconfined compression test following the method used for mix-design. Fly ash-stabilized soil is usually brittle and some of the samples were broken into pieces during sampling and extruding. Therefore, unconfined compressive strength could not be determined in several locations and it was estimated using the pocket penetrometer.

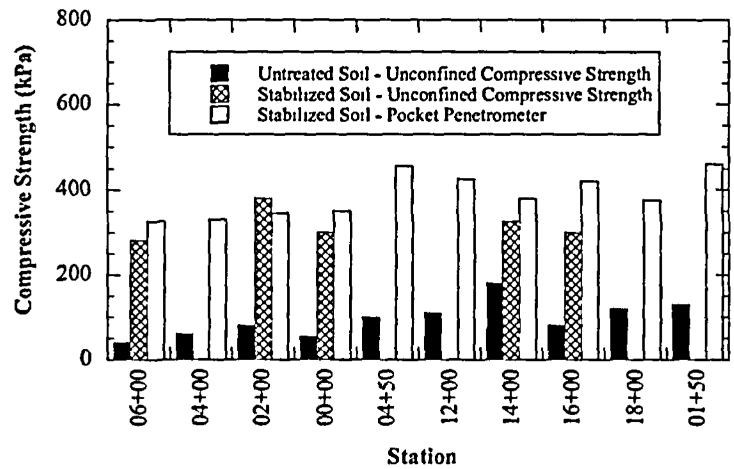

Figure 7 Compressive Strength of Fly Ash-Stabilized and Untreated Soils.

Compressive strength of fly ash-stabilized soil and untreated soil are shown in Fig. 7. Fly ash stabilization increased the compressive strength significantly.

California Bearing Ratio (CBR) Tests

Field-mixed soil-fly ash mixtures were collected from a specific location and compacted in a CBR mold at the same time when the mixture of that location was compacted. The specimens were compacted to a density similar to the average density of the stabilized soil in the field, which was monitored using a nuclear density gauge. Similar to the procedure used in the mix-design, the CBR specimens were allowed to cure for seven days in the wet room before the tests were performed.

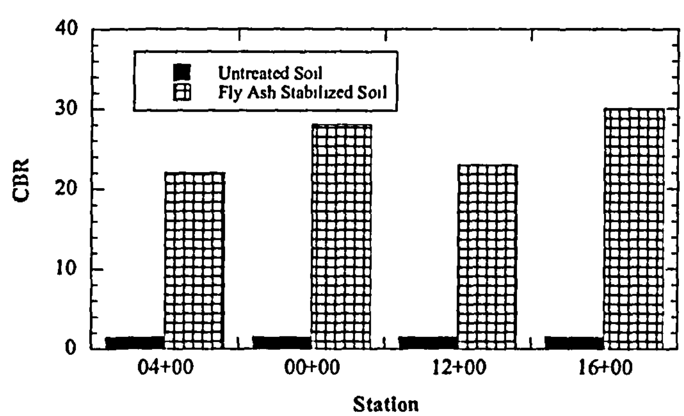

Figure 8 CBR of Fly Ash-Stabilized Soil and Untreated Soil.

CBR of the fly ash-stabilized soil collected during construction is shown in Fig. 8. CBR increased from 1 to approximately 25 due to stabilization.

Geo Gauge Stiffness Tests

Geo gauge stiffness (GGS) survey was conducted along the centerline of the test sections before stabilization and seven days after stabilization. Geo gauge is a device that measures stiffness using vibrations (Humboldt Mfg. Co. 1999). Results of the GGS survey on untreated subgrade and fly ash-stabilized subbase are shown in Fig. 9. Geo gauge stiffness increased after stabilization from an average stiffness of 5 MN/m to an average stiffness of 13 MN/m.

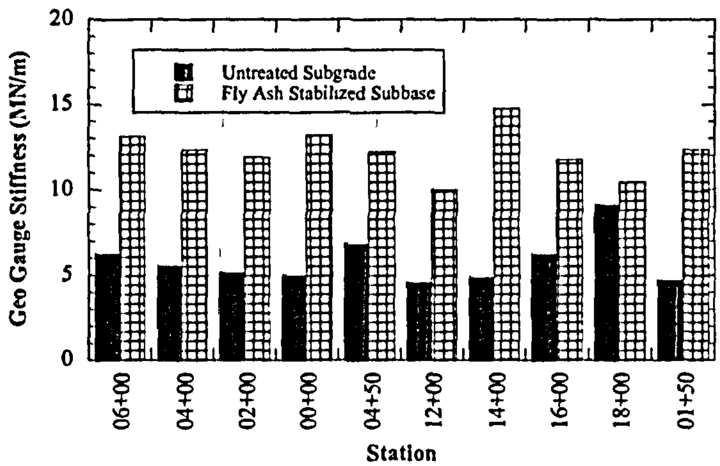

Figure 9 Geo Gauge Stiffness of Fly Ash-Stabilized and Untreated Subgrade.

Conclusions

In order to improve the engineering properties of soft subgrade soil, Class C fly ash can be used without any other activator. Engineering properties, such as unconfined compressive strength, CBR, and resilient modulus increase substantially after fly ash stabilization. The stabilized subbase layer provided adequate support for mobilization of construction equipments and materials over a soft subgrade in a field application. The stabilization process is construction sensitive and requires strict control of moisture content. The strength loss due to compaction delay is significant and must be considered in design and construction. The strength of fly ash-stabilized soil can be maximized by stabilizing at a specified water content and minimizing compaction delay in the field operation.

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