Beneficial Use of Off-Specification Fly Ash to Improve the Small-Strain Stiffness of Expansive Soil-Rubber Mixtures

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KEYWORDS: off-specification fly ash, scrap tire rubber, expansive soil, soil stabilization, stiffness, bender elements, triaxial test.

ABSTRACT

The potential use of off-specification fly ash to increase the small-strain stiffness of expansive soil-rubber (ESR) mixtures was investigated systematically in this study. Both high-sulfur content and high-carbon content off-specification fly ashes were tested. A standard Class C fly ash was also used as a control fly ash. The ESR mixture consisted of high-plasticity clay blended with 20% 6.7-mm granulated rubber (by dry weight). The off-specification fly ash content required to develop pozzolanic reactions was determined based on the lime fixation point concept and kept constant for all ESR-fly ash mixtures. At this selected off-specification fly ash content, ESR-fly ash mixtures were tested at a single relative compaction and curing time of seven days. Changes in small-strain stiffness due to fly ash addition were evaluated at mean effective stresses equal to 30, 50, 100 and 200 kPa using a bender element device incorporated to a conventional triaxial apparatus. Results suggest the small-strain stiffness improvement imparted by off-specification fly ashes is equal to or better than the improvement imparted by a standard Class C fly ash. Beneficial use of off-specification fly ashes restores the small-strain stiffness of the ESR mixtures to levels similar to or higher than those reported for the soil without rubber.

INTRODUCTION

In 2007 approximately 4.6 million tons of scrap tires were generated in the United States (Rubber Manufacturers Association 2009). In that same year, about 89% of the generated scrap tires went to end use markets. In areas such as Colorado, about 55 million waste tires remain in storage at designated waste tire facilities (Colorado Department of Public Health and Environment 2009). There is an obvious advantage in discovering and implementing alternative uses to expand the end use markets for scrap tire rubber (STR) and reduce the excessive number of scrap tires remaining in these designated waste tire facilities.

Currently, approximately 12% of the STR generated in the United States is beneficially used in end use markets in civil engineering projects (Rubber Manufacturers Association 2009). Beneficial use of STR in civil engineering applications is desirable not only from a sustainable point of view, but also since STR is a relatively light-weight material, which makes it an ideal candidate for use in embankment fills and retaining wall backfills. Early research on this topic investigated the use of STR as an alternative geomaterial in civil engineering applications (Humphrey et al. 1993). Later studies investigated the use of sand-rubber mixtures (Ahmed & Lovell 1993, Edil & Bosscher 1994, Lee et al. 1999, Youwai & Bergado 2003, Lee et al. 2007, Kim & Santamarina 2008), while other studies have focused on the use of clay-rubber mixtures (Ozkul & Baykal 2001, Cetin et al. 2006). None of the previous studies have investigated the more specific case of expansive soil-rubber (ESR) mixtures. With expansive soils being a major cause of damages to structures each year (Puppala & Cerato 2009), additional mitigation techniques may be advantageous to reduce costly damages caused by heaving of expansive soil.

A recent systematic study conducted at Colorado State University (CSU), which has focused on the swell potential of an ESR mixture, has shown that STR addition reduced both the swell percent and the swell pressure of an expansive soil from Colorado (Seda et al. 2007). Another comprehensive study recently completed at CSU indicates that the shear strength of ESR mixtures may be slightly higher than the shear strength of the untreated expansive soil (Dunham-Friel 2009). However, that same study showed that a significant reduction in stiffness might also take place due to STR addition (Dunham-Friel 2009).

The beneficial use of STR mixed to expansive soils is of interest to civil engineering applications since the swell percent and the swell pressure can be potentially reduced with no deleterious effect to the shear strength of the mixture (Seda et al. 2007, Dunham-Friel 2009). However, for applications whose design and analysis rely upon the stiffness characteristics of the materials used (e.g. roadways and foundations), a more stringent stiffness requirement may be in order. Consequently, the focus of this study was to investigate the feasibility of using off-specification fly ash to increase the stiffness of ESR mixtures so that the final mixture can have acceptable shear strength, stiffness and swell potential characteristics, and, at the same time, be developed entirely using alternative, sustainable materials.

MATERIALS

Soil

The soil used in this study is a residual soil from the Pierre Shale formation obtained from the expansive soil test site at CSU in Fort Collins, Colorado (Dunham-Friel 2009). Soil index properties determined in accordance with ASTM D 4318, ASTM C 117 and ASTM C 136 are summarized in Table 1. According to the Unified Soil Classification System (USCS), the soil classifies as highly plastic clay (CH).

Table 1. Soil index properties

Liquid Limit, w_L	Plasticity Index, I_P	Specific Gravity, G_s	% Finer No. 4	% Finer No. 200	USCS
54%	33%	2.72	100	93	CH

Rubber

The STR material used in this study was provided by Caliber Recycled Products Inc. and consists of granulated rubber with nominal maximum particle size of 6.7 mm and specific gravity equal to 1.16.

Fly Ash

Fly ash is typically classified based on its chemical/physical constituents. The main classes of fly ash for use in Portland cement concrete include Class N, Class F, and Class C (ASTM C 618). Class C fly ash is normally produced from lignite or subituminous coal combustion and is desirable for soil stabilization due to its pozzolanic and self-cementing characteristics. In this study, fly ash not conforming to ASTM C 618 is referred to as off-specification fly ash.

Fly ashes used in this study were obtained from three different sources. The standard Class C fly ash was produced at the Laramie River Station in Wheatland, Wyoming. The off-specification fly ashes were produced at the Rawhide Energy Station, which is located north of Fort Collins, Colorado, and at the Drake Power Plant in Colorado Springs, Colorado. The chemical composition of the fly ashes tested is shown in Table 2. The Laramie River Station ash is a Class C fly ash. The Drake 5 ash is an off-specification fly ash due to its high loss on ignition (LOI). The Rawhide ash is an off-specification ash based on its high sulfur trioxide (SO_3) content and relatively low amount of pozzolanic materials (<50%). For this study, the 20% 6.7-mm ESR mixture was blended with the Laramie River Station fly ash, with the Rawhide Energy Station fly ash, or with a mixture of 40% Drake 5 and 60% Laramie River Station ashes. Hereafter, the Laramie River Station ash, the Rawhide Energy Station ash and the Drake 5-Laramie River ash blend will be referred to as L, R and DL fly ashes, respectively.

Table 2. Chemical composition and classification of the fly ashes tested

Chemical Constituent	ASTM C 618 Requirements	Laramie River Ash (L)	Rawhide Ash (R)	Drake 5 Ash	40% Drake 5 / 60% Laramie River Blend (DL)
Silicon Dioxide (SiO_2), %		33.7	26.6	35.1	34.3
Aluminum Oxide (Al_2O_3), %		18.6	12.8	17.5	18.1
Iron Oxide (Fe_2O_3), %		5.7	5.4	3.4	4.8
Sum of SiO_2, Al_2O_3, Fe_2O_3, %	50.0 Min.	58.0	44.8	56.0	57.2
Calcium Oxide (CaO), %		27.9	29.7	12.3	21.7
Magnesium Oxide (MgO), %		6.1	5.5	3.2	4.9
Sulfur Trioxide (SO_3), %	5.0 Max.	1.8	12.4	1.4	1.7
Sodium Oxide (Na_2O), %		2.0	1.6	1.2	1.7
Potassium Oxide (K_2O), %		0.4	0.4	0.6	0.5
Loss on Ignition, %	6.0 Max.	0.2	2.5	22.8	9.3
Specific Gravity		2.60	2.41	1.76	2.18
ASTM Classification	Class C	Class C	Off-Spec	Off-Spec	Off-Spec

EXPERIMENTAL PROGRAM

This study was carried out using a single type of soil and rubber and three different types of fly ash, as described previously. The rubber content, which was defined as the ratio of dry mass of rubber to the dry mass of rubber and soil (or dry mass of rubber, soil and fly ash for mixtures stabilized with fly ash), was kept constant and equal to 20% for all specimens (Dunham-Friel 2009, Wiechert 2011). For the ESR mixtures stabilized with fly ash, the fly ash content (*FAC*), which was defined as the ratio of dry mass of fly ash to the dry mass of fly ash and soil, was determined and kept equal to 14% (Wiechert 2011). This selected *FAC* was determined systematically according to the Lime Fixation Point concept (Hilt & Davidson 1960). The mixture design approach used to determine the *FAC* of the mixtures is described in detail in Wiechert (2011).

Specimens used in the stiffness tests were prepared by statically compacting predetermined amounts of soil, rubber and/or fly ash (depending upon whether specimens of the soil alone, ESR, or ESR-fly ash mixtures were prepared, respectively) according to the AASHTO T 307 method. Specimens were compacted to target soil states corresponding to approximately 95% of the standard Proctor maximum dry density and optimum water content determined for each of the mixtures tested according to ASTM D 698. ESR specimens were subjected to further laboratory testing immediately after compaction. Specimens containing fly ash were compacted two hours after fly ash addition to simulate typical field compaction conditions and then allowed to cure inside the split compaction mold for 7 days at approximately 22±1.5 ˚C. During curing, the mold was kept inside three impermeable flexible polyethylene plastic bags to minimize water content changes. After curing, specimens containing fly ash were removed from the split compaction mold by initially applying an axial load on one end of the specimen to overcome any bonding that may have developed between the specimen and the mold. Once the specimen was relatively free within the mold, the split mold lateral restraints were removed. Then the specimen was removed from the split mold by sliding the opposing halves of the split mold in opposite directions (removing the specimen in this fashion minimized sample disturbance and lateral strains).

Specimens prepared as described above were then placed inside a rubber membrane, in accordance with ASTM D 4767, and placed in a standard triaxial apparatus. The triaxial cell was then filled with de-aired, de-ionized water and an initial radial (or cell) pressure (σ_r) of 30 kPa was applied. Next, the specimen was flushed with de-aired, de-ionized water from bottom to top. After flushing, back pressure saturation of specimens was completed based on the protocol outlined by ASTM D 4767. The level of saturation was indirectly evaluated by measuring the Skempton's pore pressure coefficient B (Skempton 1954). All specimens were deemed saturated when a $B \geq 0.98$ was achieved. Volumetric changes and height changes were monitored during each stage of the test for determination of the specimen's state properties. Once saturation was achieved through back pressure saturation, specimens were isotropically consolidated to mean effective stress (p') levels of 30, 50, 100 and 200 kPa. The very small-strain stiffness was evaluated at each level of p' based on measurement of the shear wave velocity (V_s) using bender elements (Shirley & Hampton 1977) mounted in the triaxial platens.

STIFFNESS RESPONSE AT VERY SMALL STRAINS

Soil stiffness at axial strains between 0.0001 and 0.001% is referred to as very small-strain stiffness (Atkinson 2000). At very small strains, stiffness can be assessed through shear wave velocity (V_s) methods. Soil shear stiffness in the very small-strain range (also referred to as $G_{\max}$ or G_0) can be deduced from simple one-dimensional wave propagation analysis as:

$$G_{\max} = \rho V_s^2 \qquad \text{(Equation 1)}$$

where ρ is the total density of the material.

Shear wave velocity can be measured experimentally using bender elements (Shirley & Hampton 1977). In the present study, a bender element apparatus manufactured by GDS Instruments Limited (Hook, Hampshire, United Kingdom) was used to evaluate the V_s of the specimens under p' levels equal to 30, 50, 100 and 200 kPa. V_s depends on the time required for the shear wave to propagate through the specimen. The travel time of the shear wave may be determined as the difference between the time when the input wave is applied and the arrival time associated with the first major reversal of the received signal (Viggiani & Atkinson 1995; Jovicic et al. 1996). The distance of propagation of the shear wave was taken as the distance between the tips of the bender elements (Viggiani & Atkinson 1995). Sinusoidal input shear waves were used with 14-V input signal amplitude and periods of 0.3 to 0.5 mV. Acquisition of the received wave was obtained using a sampling frequency of 2,000 kamp/s and a sampling interval of 1 ms which were empirically selected to provide a received signal with optimal resolution.

The V_s of the ESR and ESR-fly ash specimens was determined after the specimens were isotropically consolidated to the target mean effective stress levels described above. After V_s was measured, the very small-strain stiffness was determined according to Equation 1. The variation of the very small-strain stiffness of ESR and

ESR-fly ash specimens cured for 7 days are shown in Figure 1 for p'=30, 50, 100 and 200 kPa. The results obtained for the untreated soil (dashed line) are also shown in Figure 1, for comparison.

Results indicate rubber addition reduces the very small-strain stiffness of the soil. Conversely, fly ash addition to the ESR restores the small-strain stiffness of the ESR mixtures to values that are equal to or greater than the stiffness of the soil alone. On average, the very small-strain stiffness of the ESR-fly ash specimens was approximately 227, 242, 228 and 206% greater than the stiffness of the ESR at p'=30, 50, 100 and 200 kPa, respectively.

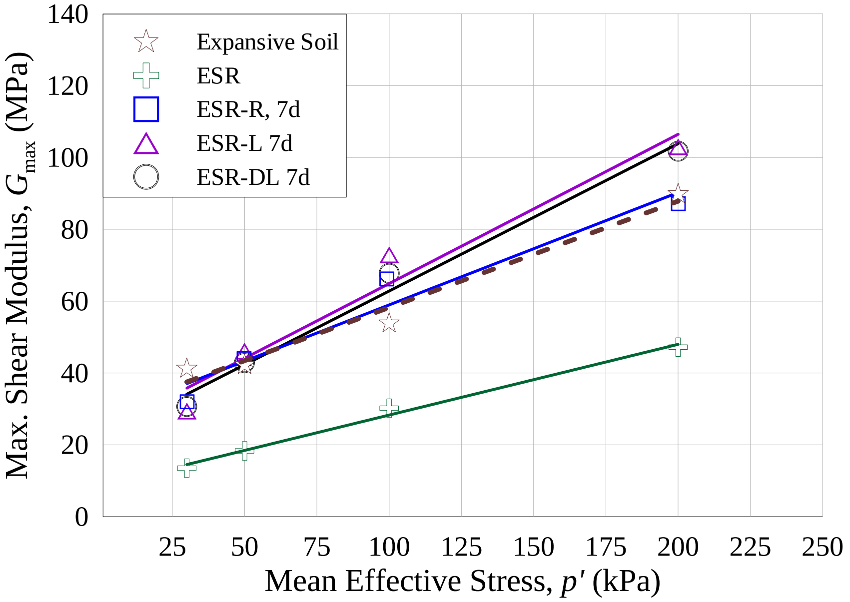

Figure 1. Variation of maximum shear modulus with mean effective stress for expansive soil, ESR and ESR-fly ash specimens cured for 7 days

CONCLUSIONS

The experimental results discussed in this paper derive from a more comprehensive study that focused on the stiffness improvement of ESR mixtures stabilized with off-specification fly ash (Wiechert 2011). The main findings related to the results presented in this paper are summarized below.

1) The very-small strain stiffness of the ESR mixtures stabilized with fly ash is equal to or higher than the stiffness of the expansive soil alone and higher than the stiffness of the ESR mixture.

2) The very small-strain stiffness improvements attained through stabilization using the off-specification fly ashes were similar to, or, in some cases, better than those observed for the standard Class C fly ash.

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