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Geotechnical Properties of Innovative, Synthetic Lightweight Aggregates

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INTRODUCTION

From a practical perspective, sustainable development requires the optimization of current natural resources and the minimization of derived wastes. A major concern with respect to sustainable infrastructure development is the continued depletion of easily-available natural resources; e.g., construction aggregates. Aggregate production the United States has averaged over 2 billion metric tons in 1995 and 1996, and significant reserves still exist. However, current economic, political and environmental factors limit the access to the reserves [9].

The reuse of wastes traditionally disposed in landfills represents a potential aggregate resource. Potential wastes include coal combustion by-products, municipal solid waste, construction debris, waste sludge, and contaminated soils. Many efforts have been made to beneficially reuse these wastes as construction aggregates in roadways or concrete [1, 2, 3, 13, 14].

This paper presents an investigation of the geotechnical properties of innovative, synthetic lightweight aggregates (SLAs) composed of coal fly ash and high density polyethylene (HDPE). The fly ash and HDPE were compounded through a blend-extrusion process and granulated to form aggregates with fly ash:HDPE ratios of 70:30 and 80:20 by weight. Geotechnical tests performed on the resulting aggregates included specific gravity, grain size distribution, one-dimensional compression, direct shear and triaxial compression tests.

DESCRIPTION OF MATERIALS

Fly ash

Approximately 45 million metric tons of coal fly ash is produced annually in the United States [8]. Less than one-fourth of this fly ash is used for flowable and structural fill, filler in asphalt mixes, road base material, and in waste stabilization. The remaining fly ash is generally land disposed. Usually exempt from hazardous waste regulations, fly ash is placed in monofills rather than general landfills that may contain other solid wastes.

The fly ash used in this study was obtained from Boston Sand and Gravel in Charlestown, MA. It is classified as class F fly ash that is commonly used in concrete mixtures as an additive/substitute for Portland cement. Class F fly ash is normally produced from burning anthracite or bituminous coal and has pozzolanic properties (ASTM C618-96). Approximately 90.7% of the fly ash used in this investigation consisted of silicon dioxide (SiO_2), aluminum oxide (Al_2O_3) and iron oxide (Fe_2O_3). The fly ash's loss on ignition was 1.2%, and specific gravity was 2.41.

High Density Polyethylene (HDPE)

Fifty-nine percent of today's plastic packaging consists of high density polyethylene (HDPE). HDPE serves as an excellent protective barrier and has very good chemical resistance properties which is desirable for containing household chemicals and detergents. In 1994 HDPE made up approximately one-fifth of the 17 million metric tons of plastics discarded in landfills [6].

The HDPE used in this study was re-pelletized detergent bottles provided by EnviroPlastics Corp. in Auburn, MA. The pellets were slightly rounded, disk-shaped particles with a diameter of approximately 4 mm. The initial tensile modulus and ultimate tensile strength were measured to be 779 MPa and 24 MPa respectively, per testing in accordance with ASTM D238. Most HDPE has a specific gravity between 0.94 and 0.97 and melts at 126 - 136°C [11].

Granular Aggregates

Two natural aggregates were used for comparison to the behavior of the SLAs. The normal-weight aggregate (NWA) consisted of processed, granitic rock composed chiefly of feldspar and quartz. The lightweight aggregate (LWA) consisted of commercially-available expanded clay/shale/slate developed via heating in a rotary kiln. For both natural aggregates, grain shapes varied from angular to sub-rounded. The NWA and LWA were further processed, using mechanical sieves, to have similar grain size distributions as the SLAs. The resulting gradation is classified as poorly graded sand according to the United Soil Classification System (USCS).

CURRENT RESEARCH EFFORT

Development of synthetic aggregates

Given the relative abundance of fly ash, an effort was made to produce as high as possible fly ash content in the aggregates. Therefore, two aggregates were produced with fly ash:HDPE ratios of 70:30 and 80:20 (by weight). To develop the synthetic aggregates, pre-weighed mixtures of HDPE and fly ash were compounded and extruded in a co-rotating twin screw extruder (Werner Pfleiderer, Ramsey, NJ model ZSK30). Processing temperatures ranged from approximately 200 to 230°C. The compounded mixtures were extruded through a 3 mm opening which formed a continuous strand of co-mingled HDPE and fly ash which was allowed to cool and solidify. The solid strand was then cut into uniformly-sized particles with a rotating knife granulator equipped with a 6-mm screen openings. Approximately 600 grams of each of the aggregates were produced [4].

Laboratory Testing Program and Discussion

Figure 1 shows images of the resulting SLAs. The two produced aggregates are very similar in size, shape, color, and texture. Scanning electron microscopy (see Fig. 1) indicates the fly ash is well encapsulated by the HDPE and thus the SLAs can be considered a dual composite material consisting of rigid fly ash particles in a soft plastic matrix.

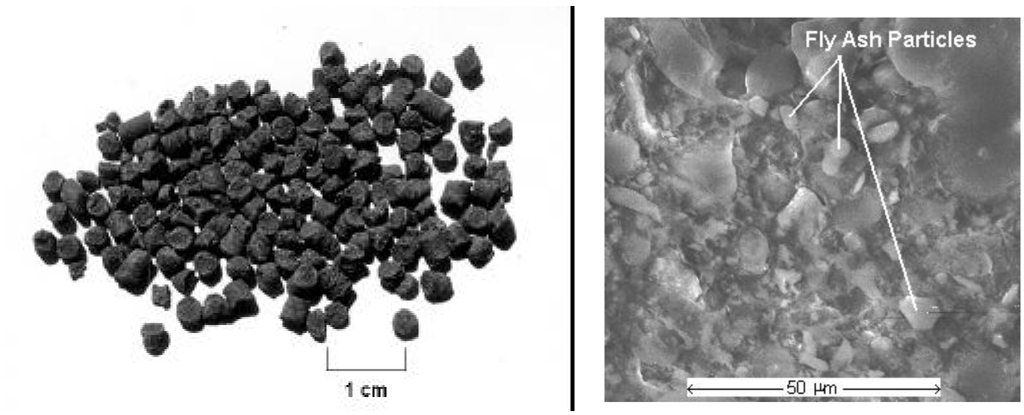

Figure 1 Images of 80:20 SLA (SEM image on right)

The SLAs have nearly identical, uniform grain size distributions. The coefficient of uniformity ($C_u = d_{60}/d_{10}$) was 1.73 for the 70:30 aggregate and 1.74 for the 80:20 aggregate. The coefficient of curvature ($C_c = \frac{d_{30}^2}{d_{10}d_{60}}$) was 1.01 and 1.04 for the 70:30 and 80:20 aggregates, respectively.

Specific gravity (G_s) analyses were performed in accordance with ASTM D854-92 for the two synthetic aggregates and the processed NWA and LWA. The 70:30 synthetic aggregates had average specific gravity of 1.67 (standard deviation, STD = 0.005; n = 4), and the 80:20 aggregate had a G_s of 1.90 (STD = 0.012; n = 6). These measured G_s values compare favorably with calculated values of 1.64 and 1.86 for the 70:30 and 80:20 synthetic aggregates, respectively. Calculated values are based on the specific gravities of the individual components (i.e., fly ash, G_s = 2.41; and HDPE, G_s = 0.97) and the volume fraction of each component. The processed NWA (predominantly coarse sand) had an average specific gravity of 2.67 (n = 2) and the LWA has an average G_s of 1.86 (n=3).

One-Dimensional Compression Tests

One-dimensional, incrementally-loaded, compression tests were performed on dry specimens of HDPE, NWA, LWA and both SLAs in general accordance with ASTM D2435-90. All specimens were 6.25 cm in diameter and were subjected to maximum stresses of approximately 2500 kPa. Given the cohesionless nature of the specimens, each load increment was maintained for one hour except for the maximum stress of 2500 kPa, which were maintained for at least 24 hours. Figure 2 shows semi-log plots of vertical strain (ε_v) versus applied normal stress (σ_N) for each of the five materials.

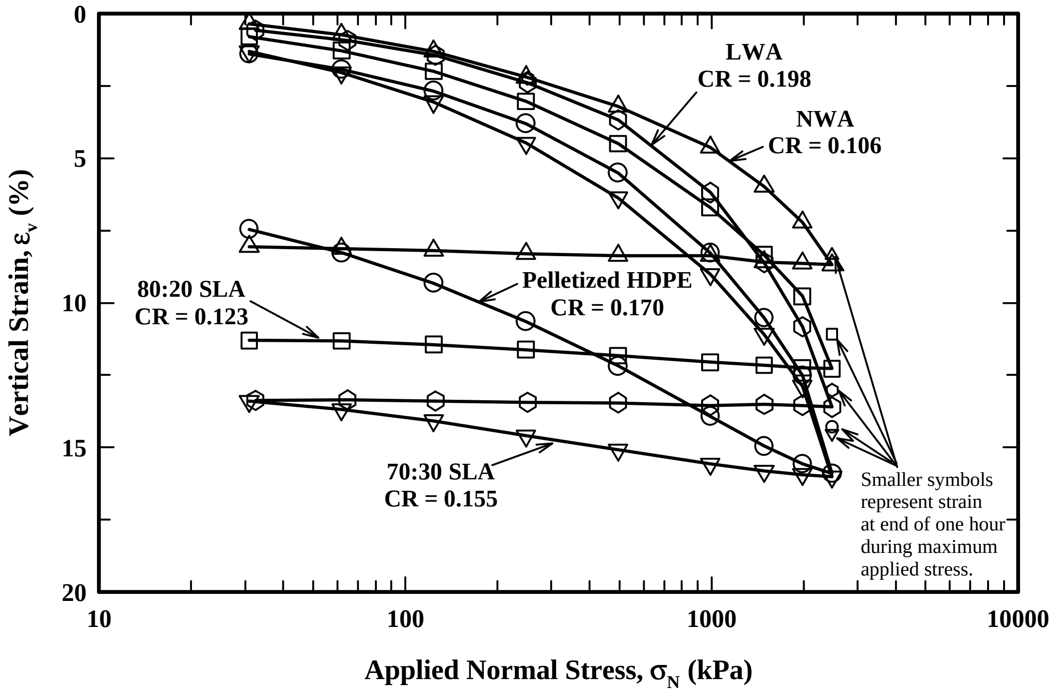

Figure 2 Vertical Strain versus Applied Normal Stress for SLAs, NWA, LWA and HDPE

All materials exhibited continuously curving responses with continued loading, much like a very disturbed natural soil sample. Except for HDPE, the relatively flat unloading response or rebound of the materials is also as expected for natural soils. The significant rebound of the HDPE indicates its higher range of elastic deformation. For the loading response, one indicator of a material's stiffness or rigidity, provided by the compression test, is the compression ratio, CR, which equals the slope of the loading curve at high stresses (i.e., $CR = \Delta\varepsilon_v/\Delta\log \sigma_N$, based on regressions through the data at the three highest applied stresses). Lower CR values indicate increased material stiffness. Values or CR for the five materials indicate that the NWA is the stiffest material, followed, in order, by the 80:20 SLA, 70:30 SLA, HDPE and LWA. As expected, the SLAs are stiffer than HDPE since the rigid fly ash particles are in the SLA's plastic matrix. The rebound behavior of the SLAs is surprising given that HDPE constitutes over 38% of the volume of the 80:20 aggregate and 51% of the volume of the 70:30 aggregate. This low rebound during unloading indicates that the individual SLA grains "interlock" to resist rebound. This hypothesis is supported by the fact that after testing, SLA specimens form highly porous cylindrical "cakes" that required forceful braking to recreate the originally separate particles. This "cementation" of the SLAs may be due to pressure melting of the HDPE at grain-to-grain contacts, which undergo significantly higher stresses than the applied maximum stress of 2500 kPa.

Shear Tests

Direct shear tests were performed on dry SLAs, NWA, LWA and HDPE specimens at various normal stresses. A Wynkam-Ferrance direct shear device with 6.25 cm diameter specimens was used for all tests. Figure 3 shows a plot of the peak shear stress versus applied normal stress for the various materials. The figure also shows failure envelopes for each material based on liner regression through the measured data. The resulting average friction angles range from 32.6° for the HDPE to 49.7° for the 70:30 synthetic aggregate. Both SLAs have slighter higher friction angles (ϕ = 47.7° to 49.7°) than the natural aggregates (ϕ = 46.1° to 47.7°). One possible reason for this behavior may be that the relatively ductile SLAs grains deform significantly (compared to NWA) and, as in the compression testing, develop larger, partially "cemented" grain-to-grain contacts which can now resist more shear stress. This could also help explain why the 70:30 synthetic aggregate had an even higher friction angle than the 80:20 aggregate. This requires more study. It is interesting to note that the HDPE has a lower friction angle (32.6°) compared to the SLAs, LWA, and NWA. This may be largely attributed to the normally smooth and rounded shape of its particles. Friction angles for SLAs are similar to those measured for other natural sands (Table 1).

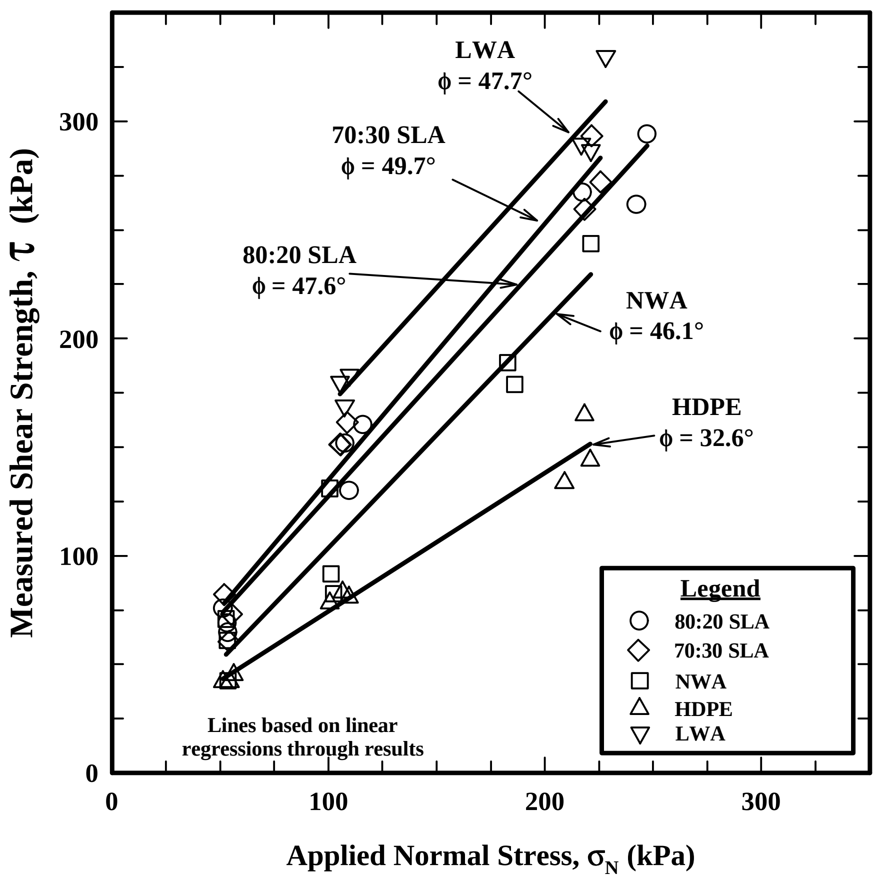

Figure 3 Summary of Direct Shear Test Results for SLAs, NWA, LWA, and HDPE

Table 1 Friction Angles of Various Cohesionless Soils

Material	Relative density	Particle shape	Friction angle Degrees	Type of test[1]	Source
Synthetic Aggregates 70:30 80:20	 Medium Medium	 subangular subangular	 49.7° 47.6°	 DS DS	 Current Study
Normal-Weight Lightweight	Medium Medium	Subangular Subangular	46.1° 44.5°	DS DS	Current Study
Manchester Fine Sand	Dense	Subangular	47° to 56°	TC	12
Monterey No. 0	very dense	-	48°	TC	7
River welland sand	Dense	-	45°	TC	10
Ottawa	Medium dense	generally rounded	44°	TC	5

1. DS - Direct Shear, TC Triaxial Compression tests

CONCLUSIONS

We conclude the following:

1. Synthetic aggregates were produced from recycled HDPE and coal combustion fly ash. Two different mixes were produced, one with 70% fly ash and 30% HDPE by weight (70:30) and one with 80% fly ash and 20% HDPE (80:20).
2. Both aggregates have similar uniform grain size distributions. Test results show that the 70:30 SLA has a specific gravity of 1.67 and the 80:20 SLA has a specific gravity of 1.9. These values are well below those typical of most natural soils ($G_s = 2.65 \pm 0.05$) and qualify the SLAs as lightweight.
3. One-dimensional compression tests show that upon loading, the ε versus log σ response of the SLAs have a similar response of HDPE, indicating the deformation properties of the plastic may governs the loading response. However, the unloading (rebound) response is relatively flat and is strongly influenced by the partially "cemented" granular particles.
4. Direct shear results indicate that the synthetic aggregates have slightly higher friction angles (ϕ = 47.7° to 49.7°) than NWA or LWA with similar grain size distributions (ϕ = 46.1° to 47.7°). It is likely that the higher strengths exhibited by the SLAs are a result of their ability to deform and create higher particle contact surfaces as well as the possibility of pressure melting at particle contacts. This requires further research for verification.
5. Based on these measured properties, the SLAs could be used in a variety of geotechnical applications including lightweight fill around foundations and embankments and high drainage material in utility trenches and around retaining walls.
6. Areas to be considered in future research include: a) examining the long term behavior of SLAs; b) examining other physical and chemical properties of SLAs; such as

mineral leachability, water absorption, behavior under high and low temperatures, and thermal or insulation characteristics; c) evaluating environmental and economic benefits associated with the use of SLAs; d) examining other potential manufacturing processes to combine plastics and fly ash; and e) evaluating SLAs created from other types of fly ashes and plastics.

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