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MODIFYING A PLASTIC CLAY WITH CRUSHED GLASS: IMPLICATIONS FOR CONSTRUCTED FILLS

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ABSTRACT

A laboratory study was conducted to evaluate the potential of 9.5mm-minus crushed glass (CG) to improve the physical and strength properties of a high plasticity soil (CH). The model soil used in this study, a kaolinite-bentonite mixture or ''model'' clay (MC), was chosen to represent the properties of naturally occurring fat clays, as well as to provide baseline data for future comparison of site-specific CH soils. Tests were performed on 100% MC and 80/20, 60/40, 40/60, 20/80 CG-MC (dry CG weight% reported first) blends using the CG previously evaluated by Grubb et al. (2006a). The most significant incremental increases in maximum dry density for standard (2.8 kN/m^3) and modified (2.5 kN/m^3) Proctor compactive effort and decreases in moisture sensitivity (14 and 12%), respectively, were observed to occur with the addition of 40% CG. By a CG content of 40%, the effective friction angle increased by about 5° while the compressibility decreased by about 33%. Similar improvements of lesser magnitude occurred with additional incremental (20%) increases in CG content.

Key words: clay, compaction, consolidation, engineering development, laboratory tests, physio-chemical properties, soil stabilization, soil structure, special soil, triaxial compression test (**IGC**: D2/D3/D9)

INTRODUCTION

This paper reports on a laboratory evaluation of blending crushed glass (CG) and with a high plasticity fat clay, or CH soil, according to the Unified Soil Classification System (USCS). The CH soil used in this study was created by blending kaolinite with bentonite on a 3:1 dry weight basis. This ''model clay,'' or MC, was intentionally selected because its stress-strain behavior is similar to a slightly sensitive natural fine-grained material (Wartman and Reimer, 2005).

This work is part of a series of papers related to Wartman et al. (2004a, b) and Grubb et al. (2006a, b, 2007a, b) aimed at increasing the recycling rates of 9.5 mm minus crushed curbside-collected glass, or CG, including its blends with fine-grained materials such as pure kaolinite (ML soil), quarry fines (CL/ML soil) and dredged material (DM; OH soil). The historical, social, technical and economic challenges associated with the beneficial use of these glass materials and fines (naturally- or industrially-produced) will not be repeated here. Briefly, these studies illustrated that CG could significantly enhance the properties of fine-grained soils for use in several aspects of construction.

This work constitutes a parallel study to the CG-DM blending conducted by Grubb et al. (2006a) in that the original motivation for undertaking CG-MC blending was to increase the beneficial use of DM classifying as a CH soil, since the majority of the DM fines in disposal basins typically classifies as a ML, MH, OH or CH soil. Owing to their high plasticity, the latter two soils (OH, CH) were taken to represent a worst case scenario for benchmarking soil improvements through CG blending. If CG could substantially improve OH and CH soils for a range of construction applications, then CG blending with soils of less or moderate plasticity would be even more viable and successful. Hence, preliminary decision making would likely begin with data interpolation to approximate behavior, followed by focused testing to finalize blend design.

The MC was originally developed by Seed and Clough (1963) and has been the focus of numerous physical modeling studies in the geotechnical literature (e.g., Sultan and Seed, 1967; Kovacs et al., 1971; Arango and Seed, 1974; Bray et al., 1994; Lazarte and Bray, 1996; Wartman et al., 2003, 2005). Thus, instead of trying to identify a DM classifying as a CH soil that would be considered as ''representative,'' the choice of the MC also

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facilitated repeatability of results in the laboratory and the transferability of the CG-MC blending results. Accordingly, the intent of the joint studies was to provide a basis for the general application of the CG blending approach for a wide range of marginal soils, and to bracket the soil improvements provided by CG.

The results have broad implications for developing fines or residuals management approaches across several market sectors, and to implement *sustainable geotechnics* practices. Well-developed countries find themselves at the intersection of several pressing issues. Landfill space for municipal waste is decreasing; therefore, it is practical and can be cost effective to recycle construction and demolition debris and other solids. New aggregate quarries and fill sources are becoming more difficult to identify, locate, permit and expand, as well as being increasingly distant from the regions where construction is highly concentrated. Also, the urban sites with the most competent soils and favorable topography have already been developed, and the geotechnical designer is confronted with continual challenges for site improvement.

Sources of naturally-occurring and processed fine-grained materials (e.g., soils, DM, spoils, slimes, tailings, quarry fines, red muds, fly ash, kiln dusts) are found throughout many parts of the world, including the urban coastal environment. The low shear strength, high compressibility, high natural water content, and low hydraulic conductivity of fine-grained media make them some of the least desirable construction materials for infrastructure development, except for waste repositories. Likewise, recycled materials and industrial byproducts are often generated in the same metropolitan areas, and increased use of these materials is enabling them to be more cost effective than traditional aggregates and fill materials.

Since CG is chemically inert, its effects on MC appear to be purely geomechanical aside from the potential effects of aging. Traditional methods for improving the physical and mechanical characteristics of soft plastic soils has involved pozzolanic stabilization/solidification using the addition of calcium-rich materials such as fly ash, lime, cement, cement kiln dust, etc (Ingles and Metcalf, 1973; Mitchell, 1981, 1986; TRB, 1976). When blended with fine-grained soils, these materials generate cation exchange on the surface of the clay mineral and the formation of new silicate materials, resulting in changes in soil plasticity and strength characteristics. Such materials were observed also act as drying agents, reduce or eliminate plasticity, and increase short- and long-term shear strength (Ferguson, 1993). When used, calcium-rich materials are typically added at 3 to 7% lime content (Keshawarz and Dutta, 1993; Nicholson and Kashyap, 1994) and 10 to 25% fly ash content (Ferguson, 1993; Keshawarz and Dutta, 1993; Chu and Kao, 1993) by weight. A similar study, evaluating the use of fly ash to improve the low strain shear modulus of MC was performed by Wartman and Reimer (2005). The chief advantage of using CG for the geomechanical stabilization of soft clays is that it is potentially less expensive, requires no curing time, and is without the complications of ettringite/thaumasite formation (Dermatas, 1995).

LABORATORY STUDY

Materials

City of Philadelphia curbside-collected glass was the source of glass materials for this study, as described in Grubb et al. (2006a). A detailed description of the physical and chemical properties of the 100% CG is presented in Grubb et al. (2006a,b). The artificial soil, model clay (MC), used in this study was composed of a 3:1 kaolinite:bentonite blend (by dry weight). Kaolinite (Hydrated Aluminum Silicate 35, Huber Engineered Materials, Georgia, USA) and bentonite, a sodium montmorillonite (The American Colloid Company, Illinois, USA) are packaged and sold in a milled powder form.

A series of tests were performed on 100% CG and 100 % MC specimens to establish a baseline performance. The following CG-MC blends were evaluated (CG/MC ratio by % dry wt.): 20/80, 40/60, 60/40 and 80/20. CG and MC bulk samples were respectively oven and air-dried. Kaolinite and bentonite have an elevated affinity for water and possess a typical air-dry moisture content of ~1%, and ~5%, respectively. This moisture was calculated for each bag of kaolinite and bentonite and accounted for prior to mixing the MC. The 100% MC and CG-MC blends were blended to specified proportions by hand in a mixing tub until they visually appeared to be of uniform consistency. Samples were then preserved in the sealed buckets for experimentation.

Physical Properties

A series of laboratory tests was performed to evaluate the basic physical properties of the CG and MC, including as-received moisture content, specific gravity (G_s), loss on ignition (LOI), grain size distribution and Atterberg limits. The soils were then classified according to the USCS and the American Association of State Highway Transportation Officials (AASHTO) systems. Table 1 summarizes the physical properties of the CG, MC and the CG-MC blends and the applicable ASTM testing methods. All results are reported on the basis of triplicate tests except ASTM D422 (single test), unless otherwise noted.

The moisture contents shown in Table 1 reflect the ''as-received'' moisture of the pure CG in the sealed drums from the material recovery facility and laboratory-batched MC from the supplier bagged kaolinite and bentonite. Moisture contents of the blended materials were obtained immediately after mixing. The water content of the CG was 0.4%, while the water content of the 100% MC was 0.1%. The G_s of the MC was 2.72. The G_s values for the CG-MC blends were interpolated by using the 100% MC and 100% CG values in the analysis of consolidation data.

Loss on ignition (LOI) was used to determine the organic matter content of the CG, MC and CG-MC blends. The tests were performed in two stages using ASTM D2974 (Method D). First, the samples were oven dried for

Table 1. Classification and physical properties of CG, MC and CG-MC blends

Media Tested		Water Content	Specific Gravity	Loss on Ignition	Particle Size			Plasticity Indices			USCS	AASHTO
		D2974	D854	D2974	D422			D4318			D2487	D3284
		%	(−)	%	%Gravel	%Sand	%Fines	LL	PL	PI		
Crushed Glass (CG)*		0.4	2.48	3.1	29.2	70.4	0.4	NP	NP	NP	SP	A-1-a
Blends	80/20 CG-MC	—	—	—	12.4	68.1	19.5	94	32	62	SC	A-1-a
	60/40 CG-MC	—	—	—	10.2	47.3	42.5	90	32	58	SC	A-2-7
	40/60 CG-MC	—	—	—	14.3	39.5	51.6	116	33	83	CH	A-7-5
	20/80 CG-MC	—	—	—	2.1	20.6	77.3	102	35	67	CH	A-7-5
Model Clay (MC)		0.1	2.72	0.0	0.0	0.0	100.0	122	42	80	CH	A-7-6

ASTM designations shown where relevant
*Summarized from Grubb et al. (2006a).

16 hours at 105°C for the water content determination (Method A). The samples were then transferred to a muffle furnace (440°C) for 12 hours for the LOI determination. The LOIs of the pure CG and MC were 3.1 and 0 %, respectively. The organic content of the CG is attributed to debris such as paper, glue and plastic cap fragments, and other carbonaceous materials associated with the recycling stream.

The grain size distributions of the CG, MC and CG-MC blends were determined in accordance with ASTM D421 and ASTM D422 (mechanical sieving only). The grain size distribution curves are presented in Fig. 1 and the percent gravel, sand and fines are summarized in Table 1. As expected, the grain size distribution of the CG-MC blends grew progressively coarser with the addition of CG. However, the actual fines content of the CG-MC blends differed from their target values due to losses of MC during sample preparation, airborne MC dust, and from the MC clinging to the sieve nest and CG particles during blending.

The crushing of 100% CG was investigated by Wartman et al. (2004), who found that modified Proctor compaction resulted in only limited particle breakage (i.e., generation of less than 10% additional finer material). Moreover, measured changes in grain size distribution (GSD) were not sufficient to change the original USCS designation of the soil blend (SP). Therefore, it is unlikely that the GSD of the current study were significantly impacted by particle crushing occurring during laboratory compaction.

The plasticity indices for the CG-MC blends are summarized in Table 1. The CG does not strongly influence the Atterberg limits of the CG-MC through blending chiefly because the fraction of the non-plastic CG passing the 0.425 mm sieve was less than 5% (Grubb et al., 2006a). Measured variations in the PI of the CG-MC blends are likely due material heterogeneity (i.e., small differences in percentage of CG passing the No. 40 sieve) and the semi-qualitative nature of the experimental procedure.

The USCS and AASHTO soil classifications for CG,

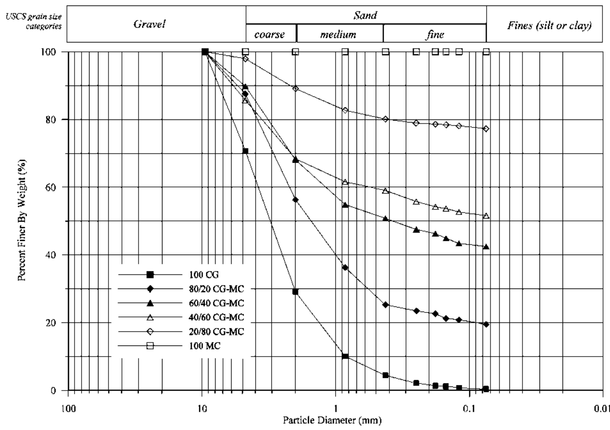

Fig. 1. Grain size distribution for Crushed Glass (CG), Model Clay (MC) and CG-MC blends

MC and their blends were also determined. In general, the CG classifies as poorly graded (well sorted) sand (SP) and the MC as high plasticity clay (CH). The raw materials defined the limits of the classification for the CG-MC blends. The 60/40 and 80/20 CG-MC blends classified as clayey sand (SC). The 20/40 and 40/60 blends classified as CH. The corresponding AASHTO soil classifications are shown in Table 1. The 100% CG closely resembles an AASHTO No. 9 aggregate gradation (ASTM D448).

Compaction Characteristics

Laboratory moisture-density relationships were developed for CG, MC and CG-MC blends following the standard (ASTM D698) and modified (ASTM D1557) Proctor methods using 5 or 6 moisture-density points. Table 2 summarizes the maximum dry densities ($\gamma_{d,\,max}$) in both SI (kN/m^3) and English (lbs/ft^3) units and the optimum moisture content (w_{opt}) for both compactive efforts. Figures 2 and 3 show the compaction curves for the standard and modified Proctor efforts, respectively. Zero air voids (ZAV) curves for specific gravities of 2.48 (CG) and 2.72 (MC) are shown for comparative purposes.

The moisture-density curves for the 100% MC exhibit

Table 2. Compaction and shear strength parameters of CG, MC and CG-MC blends

Media Tested		Standard Compaction		Modified Compaction		Direct Shear		UU Triaxial		CIU Triaxial	
		D698		D1557		D3080		D2850		D4767	
		$\gamma_{d,\,max}$ kN/m^3 (lb/ft^3)	w_{opt} (%)	$\gamma_{d,\,max}$ kN/m^3 (lb/ft^3)	w_{opt} (%)	c kPa (lb/ft^3)	ϕ (°)	c kPa (lb/ft^3)	ϕ (°)	c' kPa (lb/ft^3)	ϕ' (°)
Crushed Glass (CG)*		17.1 (109.0)	8	18.7 (119.0)	8	0 (0)	42	11 (225)	40.2	0 (0)	37.2
Blends	80/20 CG-MC	18.1 (115)	9	19.7 (125.2)	8	26 (543)	43.3	87 (1,817)	29	0 (0)	30.9
	60/40 CG-MC	17.7 (113)	11	18.8 (120)	9	29 (606)	37	195 (4,080)	24.8	0 (0)	29.1
	40/60 CG-MC	15.9 (101.5)	13	17.6 (112)	9.5	28 (585)	31	202 (4,214)	23	0 (0)	27.6
	20/80 CG-MC	14.4 (92)	21.5	16.2 (103)	16	42 (877)	24.5	121 (2,534)	23.7	1.7 (36)	21.2
Model Clay (MC)		13.1 (83.5)	27	15.1 (96)	22	43 (898)	26	193 (4,032)	13.1	1.7 (36)	22.9

ASTM designations shown where relevant
*Summarized from Grubb et al. (2006a).

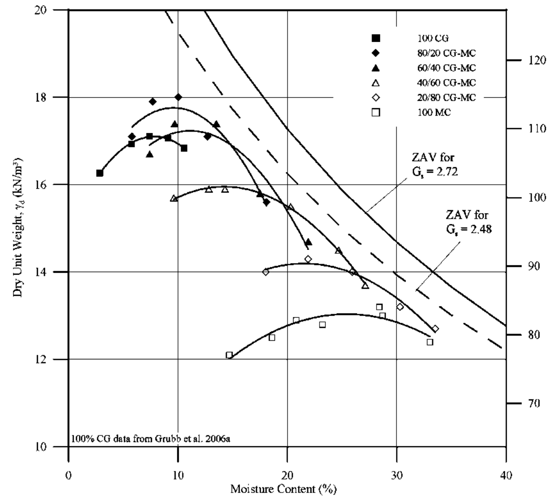

Fig. 2. Standard proctor compaction results for CG, MC and CG-MC blends

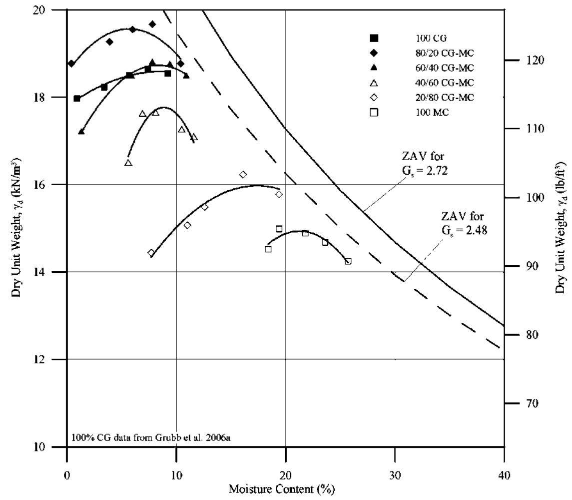

Fig. 3. Modified proctor compaction results for CG, MC and CG-MC blends

the characteristic convex shape typical of CH soils. With increased CG content, w_{opt} decreased and $\gamma_{d,\,max}$ increased, and the shape of the compaction curve trend flattened. The trends in the line of optimums for the CG-MC blends are summarized in Fig. 4. The impact of CG on the compaction characteristics of 100% MC was the most significant for CG contents of 20% and 40%. Incremental decreases in w_{opt} of 5 to 9 percentage points and increases in $\gamma_{d,\,max}$ by approximately 1 to 1.5 kN/m^3 (6 to 9 lb/ft^3) occurred in both the standard and modified levels of compaction for each 20% CG increment. Although incremental increases in $\gamma_{d,\,max}$ continued up to 80% CG, w_{opt} was not significantly impacted thereafter.

As shown in Fig. 4, the values of $\gamma_{d,\,max}$ increase in a relatively linear trend, peaking for the 80/20 CG-MC blend. This trend is consistent with the results obtained when CG was blended with pure kaolinite (K) and quarry fines (QF) (Wartman et al., 2004b), illustrating that the CG-K and CG-QF blends were denser than the raw materials, despite the significant difference in the specific gravities of the raw materials [2.48 (CG) vs. ~2.65 (K, QF)]. Wartman et al. (2004b) attributed the increased densities of the CG-K and CG-QF blends above the raw materials themselves to the better packing of the blends, a trend not observed with blending with OH soils (Grubb et al., 2006a).

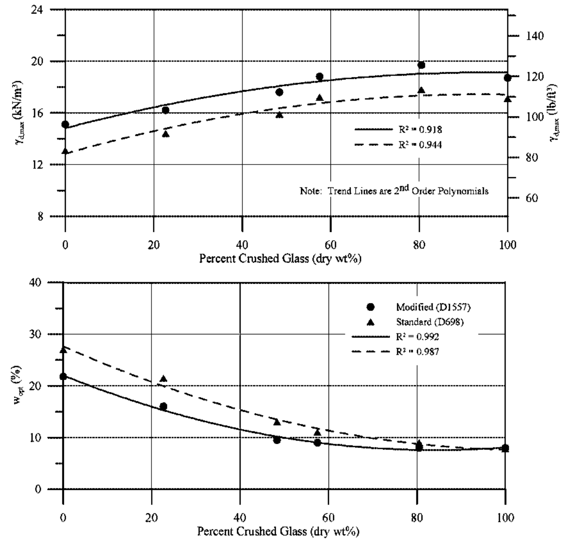

Fig. 4. Line of optimums for compacted CG, MC and CG-MC blends

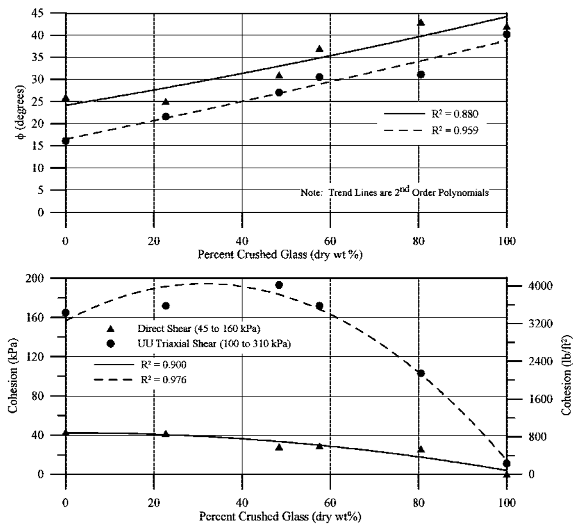

Fig. 5. Strength properties (ϕ, c) for compacted CG, MC and CG-MC blends

Direct Shear and Unconsolidated Undrained Triaxial Strength Testing

Direct (DS) and unconsolidated undrained triaxial (UU) shear tests were performed on CG, MC and CG-MC blend samples in general accordance with ASTM D3080 and ASTM D2850 standards, respectively. The DS and UU shearing results are summarized in Table 2 and Fig. 5. The specimens were placed in the molds using thin lifts and were compacted using a rubber-tipped pestle to a minimum of 95% relative compaction (RC) and within ±2% of w_{opt} based on ASTM D1557. The selected normal stresses ($\sigma_n = 45$ to 160 kPa) and confining pressures ($\sigma_c = 100$ to 345 kPa) corresponded to shallow to moderate depth overburden conditions for DS and for UU. The higher pressure range was chosen for the UU specimens to exceed the pressures induced by specimen compaction (over consolidation). The DS and UU tests were performed under as-compacted (partially saturated), total stress conditions. Shear rates were selected as 2 mm/minute and 1%/minute for the DS and UU tests, respectively. In most of the specimens tested, there was a defined peak stress which could be taken to denote failure. A less pronounced (or no) peak was observed at the lowest normal stress and confining stress for DS and UU, respectively. Strain hardening behavior was not observed in any specimen.

Figure 5 shows the variations in friction angle and cohesion as a function of CG content for each blend. As expected, the total stress friction angle of the blends generally increased with addition of CG. For both the DS and UU specimens, the friction angle increase is rather linear, with the DS friction angle typically 5 to 7 degrees higher than that of the UU for each respective blend. However, cohesion was relatively constant for all CG-MC blends up to a CG content of 60% for the UU specimens. Sharp decreases in c_{UU} were observed for the 80/20 CG-MC blend and 100% CG. With respect to the DS results, the cohesion value peaked around a CG content of 40%. Unlike the friction angle results, the DS and UU cohesion values show varied significantly due to differences in the strain rate and boundary conditions of the two tests. Wartman et al. (2004b) suggested that the impacts of CG on the strength of fine-grained soils may be delayed until the CG particles cease floating in the fine-grained matrix and develop particle-to-particle interactions which subsequently dominate strength behavior. Similarly, Grubb et al. (2006a) showed that significant changes in ϕ_{DS} and c_{DS} were delayed until a CG content of 60% or greater. This trend likewise occurs for the CG-MC cohesion results, however, the friction angle increases were relatively independent of this mechanism.

CIŪ Strength Testing

Isotropically consolidated, undrained triaxial (CIŪ) shear tests with pore pressure measurements were performed on CG, MC and CG-MC blend samples in general accordance with ASTM D4757. A specimen preparation procedure was developed to account for the very low hydraulic conductivity of MC and the long times required to adequately saturate the specimens is described below.

A split mold was assembled and lined with a nonwoven geotextile, to ultimately facilitate separation of the mold from the specimen. A premeasured sample was then moistened until a stiff consistency was achieved. The resulting moisture content varied from roughly w_{opt} + 10% for the 80/20 CG-MC blend to as much as w_{opt} + 25% for 100% MC. This excess water was necessary to achieve a specimen consistency that could be efficiently and adequately saturated. The wet specimen was placed in the mold with a spatula in 5 to 7 lifts to ensure intimate contact with the mold. Each lift was compacted by placing a rubber stopper on top of the wet specimen material, and then the lift was tamped to achieve a uniformly dense specimen. The top of the specimen was trimmed using a metal spatula to remove excess material.

After each specimen was compacted, the split mold was

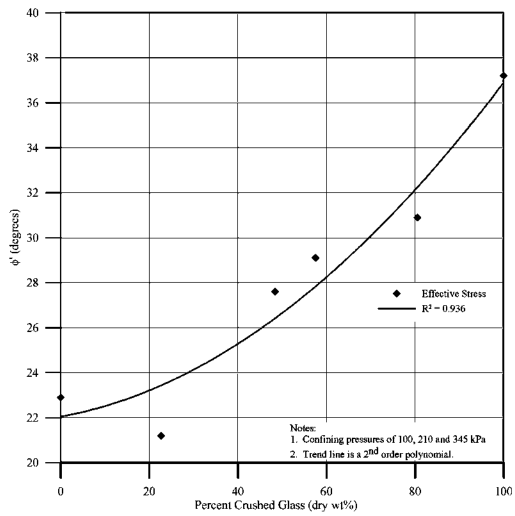

Fig. 6. Isotropically consolidated undrained (CIU) triaxial results for compacted CG, MC and CG-MC blends

removed and the geotextile was carefully peeled off and replaced with a filter paper to accelerate back pressure saturation and consolidation of the specimen. The filter paper was fashioned with spiraling strips making it unable to provide compressive strength to the specimen. A single rubber membrane was then placed on the specimen. Mounted samples in the triaxial device were then flushed with CO_2 for about 20 minutes and de-aired water for another 120 minutes. Finally, backpressure saturation was applied until a *B*-value of at least 0.95 was achieved to verify saturation.

Confining pressures (σ_c) of 100, 210 and 345 kPa were selected to place the specimens in the normally consolidated range. Given the very low hydraulic conductivity of the specimens (*see* Figure 7), the strain rates were not selected based on t_{50} values (ASTM 4767). These rates were excessively slow (>24 hrs) and were observed to produce creep strength loss during testing. Alternatively, a strain rate of 0.5% per hour was chosen and observed to provide adequate pore pressure dissipation without creep strength loss. In all cases there was no definitive peak stress, so failure was defined by the maximum stress obliquity criterion.

The effective stress strength parameters are summarized in Table 2 and Fig. 6. The 100% MC had a $c'_{\mathrm{CI\bar{U}}}$ of about 1.7 kPa. The addition of CG to the MC caused a gradual increase in $\phi'_{\mathrm{CI\bar{U}}}$ from approximately 23° (100% MC) to 31° at a CG content of 80%. The $\phi'_{\mathrm{CI\bar{U}}}$ reported the pure CG for this study was determined to be 37° using the same failure criterion (Grubb et al., 2006a).

Observed soil behavior in the form of *p-q* and deviator stress-axial strain curves are provided in Fig. 7. As expected, the 80/20 CG-MC blend showed increased dilatancy with increasing confining stress. This blend also exhibited post-peak strain hardening. In contrast, the other blends showed no peak stress or strain hardening behavior, thus indicating the dominance of the clay phase of each blend on soil behavior. Overall, these specimens (MC content >40%) exhibited stress-strain behavior characteristic of normally to lightly overconsolidated clay.

Hydraulic Conductivity

The hydraulic conductivities (*k*) of the 100% MC and CG-MC blends were determined in accordance with ASTM D5084. Specimens were compacted in three lifts to a minimum of 95% RC and between 0 and plus 2% of w_{opt} based on ASTM D1557. Tests were performed under fully saturated conditions at 20°C with confining pressures on the order of 35 kPa. The results are summarized in Table 3 and Fig. 8. Figure 8 illustrates that the CG-MC blends maintain a k less than 10^{-7} cm/s for CG contents below approximately 60%. As expected, the impact of the MC on the CG was significant. The addition of 20 % MC to CG reduced the hydraulic conductivity of the 100% CG by approximately five orders of magnitude.

These results are generally consistent with results reported by Shelley and Daniel (1993). Shelley and Daniel (1993) used specimens compacted to $\gamma_{d,\max}$ and 2 to 4% above w_{opt} based on ASTM D698. Shelley and Daniel (1993) found that the addition of gravel had little impact on the hydraulic conductivity of the blends at gravel contents less than 60%. However, when the gravel content increased above 60% there was only an order of magnitude increase in (*k*) for the mine spoil-gravel and kaolinite-gravel blends.

Consolidation Properties

One-dimensional consolidation properties of the CG and MC materials were determined in accordance with ASTM D2435, as summarized in Table 3. Specimens were compacted in molds in three lifts to a minimum of 95% RC and between 0 and plus 2% of w_{opt} by ASTM D1557. The response of the 100% MC to loading conditions is consistent with that of high compressible CH soil; i.e., $C_c > 0.4$ (Mitchell and Soga, 2005). Figure 9 illustrates incremental reductions in settlement with increasing CG contents, likely due to the emergence of a granular soil skeleton or network of relatively incompressible particles (CG).

As expected, the C_c of the CG-MC blends decreased significantly as the CG content increased, as shown in Fig. 9. Compression indices decreased by roughly 15 to 20% for the first three 20% CG increments. Thereafter, the percentage decrease was nearly 40% between CG contents of 60% to 80%. There was a generally decreasing trend in C_r with increasing CG content. The ratio of C_c/C_r increased from approximately 2 for the 100% MC, to approximately 4 for the 80/20 CG-MC blend.

The values of the coefficients of consolidation, C_v, were obtained at two pressures (400 kPa and 800 kPa) from the 1-D consolidation data shown in Table 3 and Fig. 10. As expected, C_v generally increased with increasing CG content, the scatter in the data reflecting that C_v is a complex function of *k*, unit weight and compressibility. The shape of both trend lines resembles that of the hydraulic conductivity curve, i.e., a stable C_v value until a CG content of 60%. The secondary compression, C_α, was obtained from the 1,500 kPa increment of the 1-D consoli-

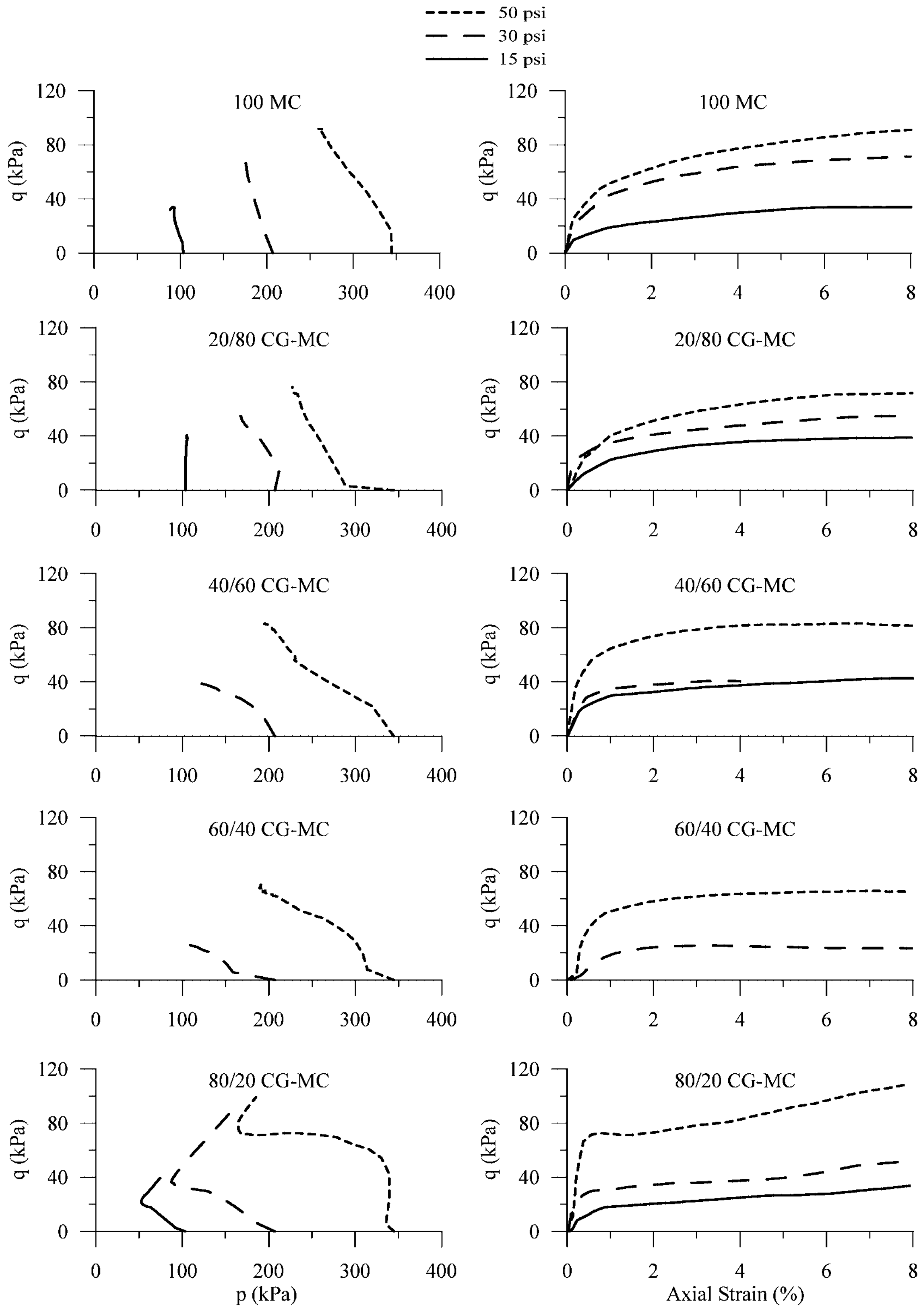

Fig. 7. *p-q* **and stress-strain response for CG, MC and CG-MC blends**

dation test. This increment was substantially longer than t_{100} ($\sim$24 hr.) in order to develop a linear secondary compression curve. Table 3 and Fig. 11 indicate a generally constant C_α for each CG-MC blend. Only slight increases in secondary compression indices occurred with increasing MC content.

DISCUSSION

The addition of CG caused significant changes in the physical properties of MC, including reductions in moisture content and plasticity index, as well as the coarsening of the grain size distribution. These changes are generally recognized to improve the workability of MC.

Table 3. Hydraulic and consolidation properties of CG, MC and CG-MC blends

Media Tested		Hydraulic Conductivity		1-D Consolidation				
		D5084		D2435				
		cm/s	in/s	c_v @400 kPa (cm^2/s)	c_v @800 kPa (cm^2/s)	C_c (−)	C_r (−)	C_α (−)
Crushed Glass (CG)*		6.20E-02	2.44E-02	0.1451	0.0896	0.042	0.005	0.0016
Blends	80/20 CG-MC	8.60E-07	3.39E-07	0.0132	0.0192	0.166	0.042	0.0054
	60/40 CG-MC	8.50E-08	3.35E-08	0.0098	0.0130	0.266	0.071	0.0049
	40/60 CG-MC	8.00E-08	3.15E-08	0.0088	0.0096	0.312	0.100	0.006
	20/80 CG-MC	1.20E-08	4.72E-09	0.0072	0.0110	0.402	0.149	0.007
Model Clay (MC)		1.20E-08	4.72E-09	0.0061	0.0062	0.465	0.249	0.008

ASTM designations shown where relevant
*Summarized from Grubb et al. (2006a).

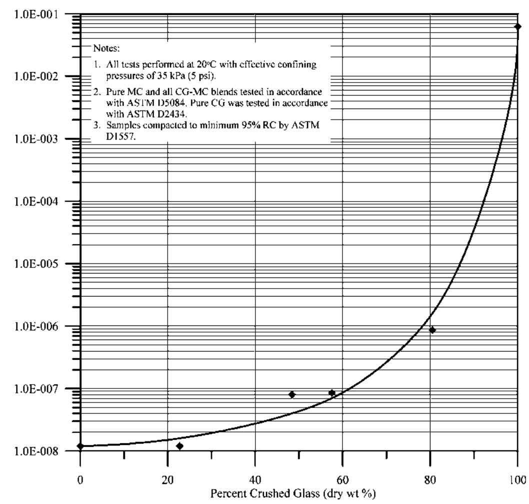

Fig. 8. Hydraulic conductivity (cm/s) vs. CG content

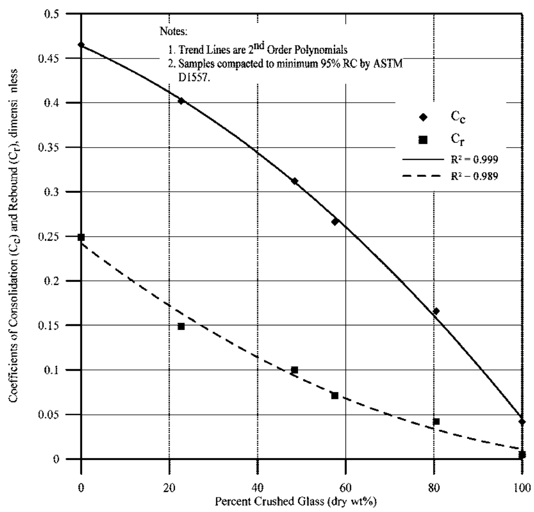

Fig. 9. Coefficients of consolidation (C_c) and rebound (C_r) for CG, MC and CG-MC blends

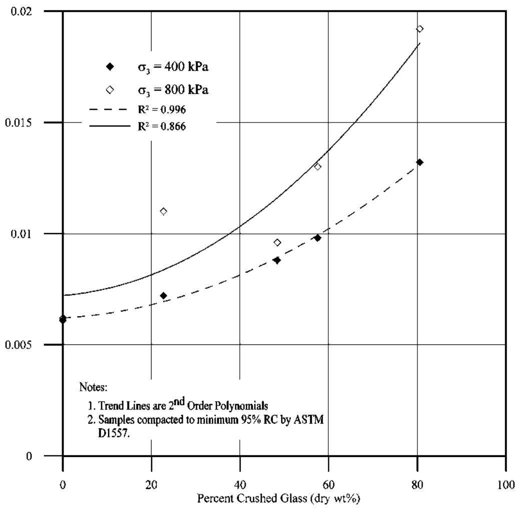

Fig. 10. C_v for compacted CG, MC and CG-MC blends

In addition, there are significant incremental improvements in $\gamma_{d,\max}$ (increased) and w_{opt} (reduced) of all of the CG-MC blends. A CG content of 40% produced a decrease in w_{opt} of 14 and 12 percentage points and increased $\gamma_{d,\max}$ by 21 and 11% at standard and modified levels of compaction, respectively.

These observations are consistent with the results of CG-DM blending (Grubb et al., 2006a) where a CG content as little 20% produced significant initial improvements to the 100% DM, which classified as an OH material. These effects were delayed in the MC until CG a content of about 40%, which is attributed to the higher plasticity of the MC, as well as the likely presence of higher quantities of colloidal-sized particles in the MC. A direct comparison of select behavior of the CG-DM and CG-MC blends is provided in Grubb et al., 2007b.

Overall, the effect of strength of the CG-MC blends was the result of the combined effects of increases in friction angle and density, decreases in compressibility, and the influence of added cohesion from the MC. Figure 5 shows a maximum increase in the effective friction angle on the order of roughly 11° between the 100% MC and

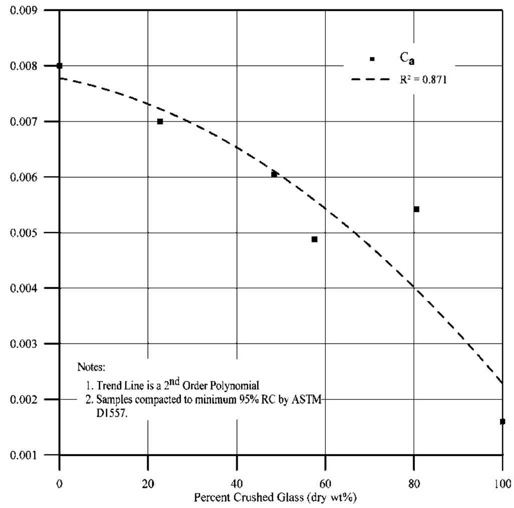

Fig. 11. Coefficients of secondary compression (C_a) for CG, MC and CG-MC blends

60/40 CG-MC blend. Wartman et al. (2004b) showed similar increases ($\sim 12°$) in the friction angles of CG-K blend when blending 50% CG with kaolinite. Despite significant differences in PI (K ~ 20; MC ~ 80), the increases in ϕ_{DS} by CG addition were surprisingly similar.

Despite improvements in workability, shear strength, and compressibility, the hydraulic conductivity of the CG-MC blends was largely unaffected by the CG content and remained below 10^{-6} cm/s even at a CG content of 80%. This result can be considered advantageous for use in compacted clay liners, as improvements in shear strength are achieved without compromising the low hydraulic conductivity. In addition, reduced compressibility from the addition of CG mitigates concerns of liner consolidation during the operational timeline of a landfill. A comparison of the hydraulic conductivity of the CG-MC blends versus other ''coarse-fine'' material blends is provided in Grubb et al., 2007b.

There are several design considerations that can be evaluated and optimized for improving construction with marginal high plasticity materials, the first of which is the ratio of available CG to MC. This may drive many choices, but the major changes in MC physical behavior occur at CG contents of 40% or greater. For example, increasing the CG content above 40% results in only a 1% to 4% reduction in w_{opt} with similarly diminishing returns in increased $\gamma_{d,\max}$. However, incremental increases in total and effective friction angles are observed with each increase in CG content. Similarly compressibility parameters are improved with each increase in CG content resulting in both decreased settlement and time to the end of primary consolidation.

The stress-strain behavior of the CG-MC blends is that of a ductile material. With the exception of UU testing (i.e., high strain rate), the CG-MC blends exhibited a stress-strain behavior analogous to loose sand; i.e., no prominent peak in stress and/or distinguished failure plane occurred. For this reason, applications of modifying a CH material with CG are highly advantageous over in-situ compressible soils which may potentially undergo long-term and differential settlement. Ductile material behavior would allow for larger magnitudes of long-term deformation when compared to admixture-stabilized soils (stiff/brittle) while maintaining structural integrity.

CONCLUSIONS

A laboratory evaluation was completed on the blending 9.5 mm minus curbside-collected crushed glass (CG) with model clay (MC) to address the effect of improved strength and workability of marginal materials (MC) by the addition of coarse grained material (CG). Tests were performed on 100% CG (SP) and 100% MC (CH) specimens and 20/80, 40/60, 60/40 and 80/20 CG-MC blends. The most notable improvement was in workability. The addition of 20% CG resulted in a 5 to 9 point reduction in w_{opt} while increasing the dry density approximately 1 to 1.5 kN/m^3 (6 to 9 lb/ft^3) for standard and modified Proctor levels of compaction, respectively. Also, a loss of moisture sensitivity was observed at CG contents greater than 40%. Effective friction angles and compressibility values obtained from this study show the dominance of clay-like behavior (low $\phi'_{CI\bar{U}}$ and high C_c) occurred at 20% or less high-plasticity material (MC), with relatively small incremental changes for each increase in clay content. However, overall improvement of the effective friction angle (8°) above the 100% MC at a CG content of 80% was significant. Likewise, the C_c values for 60/40 and 80/20 CG-MC blends were reduced roughly 43 and 65%, respectively. MC-dominant behavior was also evident for hydraulic conductivity, with the most significant impacts occurring with the first 20% MC increment.

The range of properties obtainable by CG-MC blends offers a versatility to improve marginal high plasticity materials for the design of fills using recycled crushed glass that can optimize on multiple design parameters (e.g., maximum strength, maximum density, compressibility).

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project sponsors.

NOTATION

The following symbols are used in this paper:

C_c = compression index, dimensionless
C_r = recompression index, dimensionless
c_v = coefficient of consolidation, cm^2/s
C_α = coefficient of secondary compression, dimensionless
c = cohesion, kPa
G_s = specific gravity, dimensionless
k = hydraulic conductivity, cm/s
wt.% = percent by weight
$\gamma_{d, max}$ = maximum dry density, kN/m^3
w_{opt} = optimum water content, %
σn = applied effective normal stress during direct shear testing, kPa
σ_c, p = effective normal stress during triaxial shear testing, kPa
q = effective deviator stress during triaxial shear testing, kPa

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