Laboratory Evaluation of Crushed Glass–Dredged Material Blends

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Abstract: A comprehensive laboratory evaluation of blending 9.5 mm (3/8 in.) minus curbside-collected crushed glass (CG) with dredged material (DM) was conducted to evaluate their potential for beneficial use as fill materials for urban applications. Tests were performed on 100% CG (USCS classification SP) and 100% DM (OH) specimens and 20/80, 40/60, 50/50, 60/40, and 80/20 CG–DM blends (dry weight percent CG content reported first). The addition of 20% CG resulted in a 10–20 point (33–67%) reduction in w_{opt} while increasing the dry density by approximately 1–3 kN/m^3 for standard and modified levels of compaction, respectively. Simultaneously, the compressibility of the DM was reduced by approximately 50% and the hydraulic conductivity was reduced by $\frac{1}{2}$ order of magnitude. The addition of 20% CG significantly decreased the moisture content and significantly improved the workability of the 100% DM, where workability refers to the ease of handling, transport, placement, and compaction of the CG–DM blends (compared to 100% DM). CI$\bar{\mathrm{U}}$ triaxial strength testing indicated effective friction angles of 34 and 37° for 100% DM and CG compacted to a minimum of 95% relative compaction by *ASTM D1557*, respectively. A peak effective friction angle of 39° occurred for the 60/40 and 80/20 CG–DM blends which were also 1 and 3 orders of magnitude more permeable than 100% DM, respectively. Related increases in c_v resulted in decreased times required for consolidation. The range of properties obtainable by the CG–DM blends offers a versatility that allows for the design of fills that can be potentially optimized to meet multiple design parameters (e.g. strength, settlement, drainage, or higher CG or DM content).

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Introduction

This paper reports on a laboratory evaluation of blending crushed glass (CG) and dredged material (DM) and the suitability of the blended products as general, embankment, and structural fill materials for transportation, airport, building and maritime construction, land reclamation, and brownfields and portfields redevelopment in urban areas. This study was motivated by the need for a pragmatic solution for two compelling long-term problems: the disposal of DM and beneficial use options for curbside-collected glass, which can be produced in coastal metropolitan cities at rates of millions and hundreds of thousands of tons per year, respectively. The U.S. Army Corps of Engineers (USACE) has major challenges maintaining long-term disposal capacity for DM in its confined disposal facilities (CDFs) in or near many metropolitan areas, and other upland disposal options are limited, cost prohibitive or difficult to permit. In addition, state Departments of the Environment have emphasized the curbside collection of glass without making comparable investments in beneficial use markets. This has resulted in a glut of glass (especially glass not suitable for bottling applications) at Material Recovery Facilities (MRFs) in states without bottle bills.

With regard to DM disposal, renewable capacity approaches that emphasize the mining/excavation of materials from CDFs have been pursued (to avoid the construction of new CDFs), but this often requires beneficial use permits. Except for large fill projects (>76,000 m^3 or 100,000 yd^3), the associated environmental testing costs either price DM out of the conventional fill market, or the use restrictions and need for permits are often too aggravating (time, delays, effort) for the construction industry. Moreover, while the construction industry is frequently interested in mining the gravel and/or sand fraction from CDFs, the majority of the DM in CDFs typically classifies as ML, MH, OH, and CH soil by the Unified Soil Classification System (USCS), which are commonly recognized as being among the poorest earthwork construction materials (USBR 1963). Hence, the construction industry has shown little interest in them except for landfill cover. Meanwhile, state Departments of Transportation (DOT) and the construction industry are the largest consumers of virgin materials, including fill, which tends to be expensive in metropolitan areas due to the costs of transporting large volumes of fill material from outlying areas.

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With regard to CG, limited glass recycling opportunities exist, and those relating to color-sorted (clear, amber, brown) opportunities such as bottling are both sporadic and dwindling from the increasing use of plastic containers. Yet in some cases (liquor, beer, certain foods), glass remains the container material of choice and it will thus remain in the recycling stream because its weight makes it the leading candidate for attaining community based recycling target objectives (% by weight basis). In addition, mixed color broken glass continues to accumulate at MRFs and must be disposed of at costs up to $50/t (landfill) due to the lack of beneficial use markets in certain regions. One application is to crush curbside-collected glass for freely draining geotechnical fill applications; however, CG has received extremely limited use due to unfamiliarity, negative perception, and lack of approved specifications (Wartman et al. 2004a).

An interesting and potentially cost-effective solution to both recycling challenges is presented by blending CG with DM to improve the geotechnical and workability characteristics of both materials for urban fill applications. Here, the term workability is used describe the ease of handling, transport, placement, and compaction of the CG–DM blends. Accordingly, a comprehensive evaluation of CG, DM, and CG–DM blends was undertaken to provide a basis for the geotechnical design and construction communities to utilize CG–DM blends in general, embankment, and structural fill applications. A companion paper (Grubb et al. 2006) reports on the associated field evaluation of three constructed CG–DM blend embankments, and includes information on specifications, blending operations and economics, construction, and geotechnical performance. Jointly, these papers (and Wartman et al. 2004b) are intended to provide a basis for the general application of the CG blending/soil improvement results to a wide range of marginal soils.

Previous Studies

Disposal and reuse of DM is the single greatest challenge for most dredging projects (Alcorn 2002). Accordingly, researchers have considered a wide range of reuse alternatives for DM including plasma vitrification, aggregate and construction materials manufacturing, stabilization and solidification, soil blending, and direct use as construction fill. In general, most of the previous research on the beneficial use of DM has focused on the technical rather than economic aspects of material reuse. McLaughlin et al. (1999) completed a demonstration project where plasma vitrification was used to melt DM into a salable glass product, but the process is currently limited by high costs. Recognizing that DM contains Al_2O_3, SiO_2, and FeO_3, which are important components of Portland cement, Dalton et al. (2001) and Weimer et al. (2002) studied the feasibility of using DM as feedstock material for cement manufacturing. Their preliminary findings suggested that DM can be substituted for other raw materials in the cement manufacturing process. Others such as Derman and Schlieper (1999), Tay et al. (2001), and Elkins and Thompson (1997) combined DM with other materials such as cements and polymers, which were then sintered to produce construction aggregates having compressive strengths comparable to natural aggregates. In each case, the principal limitation was the expense of the thermal processes.

Several investigators have studied Portland cement (PC) and/or lime stabilization of DM or similar materials. Bennert et al. (2000) conducted a laboratory and field investigation of PC-stabilized DM. They compared the resilient modulus of stabilized DM (8% PC by wet weight) with that of more conventional fill materials such as silty sands and sandy silts. They found that the stabilized DM had resilient modulus values that were about 30–60% higher than the natural soils. The field component of the investigation showed a reliable correlation between cone penetrometer test (CPT) tip resistance and soil density. Kukko (2000) considered the use of different cementitious materials such as PC, blast furnace slag, and fly ash to enhance the strength of several different clays and concluded that the strength of the stabilized materials was highly dependent on the "water-binder ratio," a parameter that effectively represents the cementitious material content. Dermatas et al. (2003a,b) evaluated the engineering characteristics of DM stabilized with 9, 11, and 13% PC (by wet weight). They found that PC had the following effects on DM: (1) it reduced plasticity, and consequently, improved workability; (2) it decreased compacted maximum dry density and increased optimum water content; (3) it increased unconfined compression strengths in the range of 14–96% depending on water and cement content; (4) it increased strength of up to 90% in the specimens having the lowest water contents; and (5) it reduced compressibility. Dermatas et al. (2003a,b) concluded that PC-stabilized DM could satisfactorily serve as nonstructural fill for transportation projects. Baxter et al. (2005) stabilized DM by adding 3–7% lime (dry % by weight), which resulted in significant increases in unconfined compressive strength. The writers concluded that lime-amended DM could serve as a capping material for brownfield sites and/or landfills. Tanal et al. (1995) and Vaghar et al. (1997) used 7% lime (wet % by weight) to stabilize DM as part of the Boston Central Artery project. These researchers showed increases in the unconfined compressive strength of the treated materials, but noted practical concerns such as odor and dust emissions with the field mixing of these materials.

Tsuchida et al. (2001) performed a laboratory and field investigation of different mixtures of DM, expanded polystyrol (EPS), beads and PC and developed empirical relationships between the strength and stiffness of these materials for different EPS and PC contents. The relatively low unit weight of EPS yielded a lightweight material mixture. The field component of the study demonstrated a successful pilot-scale application of this material, though the researchers noted that its durability under a wider range of climatic conditions (e.g., freezing) required further evaluation.

Recently, Wartman et al. (2004b) conducted a laboratory study to evaluate the feasibility of using CG to improve the engineering characteristics of fine-grained, marginal materials such as kaolin and quarry fines (i.e., the fines from a concrete sand quarry). Wartman et al. (2004b) found that frictional strength of the fine-grained soils was considerably increased by addition of CG and suggested that this concept could be used to improve the engineering properties of other marginal materials (e.g., dredged material, mining, and quarry spoils). In a similar vein, Baxter et al. (2005) suggested blending gravelly construction debris with DM at a 3:1 ratio to create a structural fill material that meets the gradation requirements of a local DOT; however, they noted obtaining such a large quantity of construction debris required for blending may be a practical limitation.

Laboratory Study

Materials

City of Philadelphia curbside-collected glass was the source of glass materials for this study. The glass was crushed and sieved

Table 1. Physical Properties and Classification of CG, DM, and CG–DM Blends

Media tested	Water content *D2974* (%)	Specific gravity *D854*	LOI *D2974* (%)	Particle size *D422* Gravel (%)	Sand (%)	Fines (%)	Plasticity indices *D4318* LL (%)	PL (%)	PI (%)	USCS *D2487*	AASHTO *D3282*
100% crushed glass (CG)											
Blends	1.7	2.48	3.1	29.2	70.4	0.4	NP	NP	NP	SP	A-1-a
80/20 CG–DM	11.9	—	2.9	26.6	59	14.4	71	48	23	SM	A-2-7
60/40 CG–DM	18.5	—	4.0	20	43.6	36.4	74	49	25	SM	A-7-5
50/50 CG–DM	24.5	—	5.7	6.8	44.8	48.4	73	46	27	SM	A-7-5
40/60 CG–DM	27.0	—	5.6	14.3	34.1	51.6	75	44	31	OH	A-7-5
20/80 CG–DM	32.9	—	8.7	6.4	18.3	75.3	80	51	29	OH	A-7-5
100% dredged material (DM)	45.8	2.40	11.0	0	3.4	96.6	81	53	28	OH	A-7-5
Pedricktown/Oldmans CDF material	50.8	2.50	6.6	0	9.7	90.3	83	47	36	OH	A-7-5
Wilmington Harbor North CDF material	39.6	2.43	7.2	0	1	99	83	38	45	CH	A-7-5

Note: All blends were made using Fort Mifflin DM. ASTM test designations shown where applicable.

through a 9.5 mm (3/8 in.) sieve, a size that does not generally represent a physical handling hazard (i.e., no shards). The USACE-Philadelphia District maintains (at least) three active CDFs for the dredging of the lower Schuylkill, Delaware, and Christina Rivers: Fort Mifflin (Philadelphia); Pedricktown/Oldmans (Salem County, N.J.); and, Wilmington Harbor North (Wilmington, Del.), respectively. While these CDFs accept hydraulically placed DM from different navigational projects (rivers), the materials in the CDFs are similar in composition, primarily silts (MH, OH). The principal source of DM for this project was Basin A at the USACE Fort Mifflin CDF. Six 55 gal sealed drums were used for the collection, transportation, and storage of the CG and DM materials. Additional DM samples (three 55 gal drums each) were collected from the Pedricktown and Wilmington Harbor North CDFs to illustrate the similarity between the DM materials from these CDFs and, accordingly, the applicability of the results to potential DM beneficial use projects in southern New Jersey and northern Delaware.

A series of tests was performed on 100% CG and 100% DM specimens to establish properties at the endpoints of the spectrum. Then, using the Fort Mifflin DM materials only, the following CG–DM blends were evaluated (CG/DM ratio by% by dry wt.): 20/80, 40/60, 50/50, 60/40, and 80/20. CG and DM bulk samples were blended in their as-received condition. The moisture contents of each material were measured and then the weights of each component were calculated to ensure the proportions were correct based on dry weight. The blends were mixed either by hand in a mixing bowl or in a cement mixer until they visually appeared to be of uniform consistency. Samples were then preserved in the sealed drums for experimentation.

Physical Properties

A series of laboratory tests were performed to evaluate the basic physical properties of the CG, DM, and their blends 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, DM, and CG–DM blends and the applicable ASTM standards. All results are reported as the average of triplicate tests except *D422*, unless otherwise noted.

The moisture contents shown in Table 1 reflect the "as-received" moisture of the 100% CG and 100% DM in the sealed drums from the MRF and respective CDFs, and in the case of the blends, immediately after mixing. The water content of the CG was 1.7%, while the water content of the three DMs ranged from 39.6 to 50.8%. The water content of the CG–DM blends decreased from 32.9 to 11.9% as the percentage of CG increased from 20 to 80%, respectively.

The G_s of the CG was 2.48, which was consistent with the results of previous studies (Schmitt et al. 1997; Wartman et al. 2004a). The G_s of the DM from Fort Mifflin, Wilmington Harbor North, and Pedricktown/Oldmans CDFs were 2.40, 2.43, and 2.50, respectively. These results are consistent with the values determined in regional CDFs (SAIC 2002; Weston 2002).

LOI was used to determine the organic matter content of the CG, DM, and CG–DM blends. The tests were performed in two stages using *ASTM D2974* (Method D). First, the samples were oven dried for 16 h at 105°C for the water content determination. The samples were then transferred to a muffle furnace (440°C) for 12 h for the LOI determination. The LOIs of the 100% CG and 100% DM were 3 and 11%, respectively, with the CG–DM blends containing slightly less organic matter than would be predicted by weight averaging. The organic content of the CG is attributed to debris such as paper, glue, and plastic cap fragments, whereas the organic matter in DM is comprised of decaying leaves, roots, branches, and other detritus.

The grain size distributions of the CG, DM, and CG–DM blends were determined in accordance with *ASTM D421* and *ASTM D422* (mechanical sieving only) (ASTM 1998b). 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 DM grew progressively coarser with the addition of CG.

Test specimens for the Atterberg limit determinations were prepared on a % by dry weight basis using the material passing the 0.425 mm (Number 40) sieve. Table 1 summarizes the plasticity indices. The CG does not strongly influence the Atterberg limits of the DM through blending mainly because the amount of the nonplastic CG passing the 0.425 mm sieve is generally on the order of 5% or less (Wartman et al. 2004a).

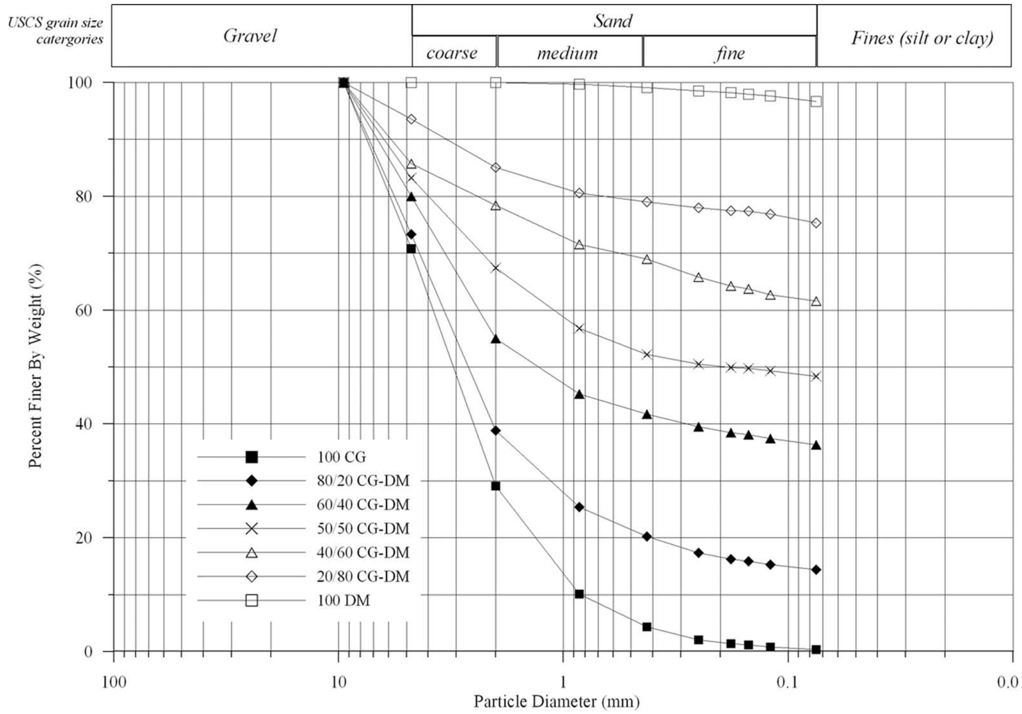

Fig. 1. Grain size distributions for CG, DM, and CG–DM blends

The USCS and AASHTO soil classifications for CG, DM, and their blends were also determined. In general, the CG classifies as poorly graded (well sorted) sand (SP). The DM classifies as high plasticity organic silt (OH). The raw CG and DM materials defined the limits of the classification for the CG–DM blends. The CG–DM blends containing 50, 60, and 80% CG classified as silty sand (SM); while the blends containing greater than 50% DM meet the OH classification. In terms of the AASHTO soil classifications, 100% CG was an A-1-a material while the 80/20 CG–DM blend was an A-2-7 material. The remaining blends and 100% DM classified as A-7-5 materials. The 100% CG did not classify as either AASHTO Numbers 8 or 10 aggregate gradations (*ASTM D448*, ASTM 2003a), but placed midway between the two ranges.

Compaction Characteristics

Laboratory moisture–density relationships were developed for CG, DM, and CG–DM blends following the standard (*ASTM D698*, ASTM 2000b) and modified (*ASTM D1557*, ASTM 2000a) Proctor methods using five or six moisture–density points. Table 2 summarizes the maximum dry densities ($\gamma_{d,\max}$) in both SI (kN/m^3) and English (lb/ft^3) units and the optimum moisture content (w_{opt}) for both compactive efforts. Figs. 2 and 3 show the compaction curves for the standard and modified Proctor efforts, respectively. Zero air void (ZAV) curves for specific gravities of 2.40 (DM), 2.48 (CG), and 2.65 (typical soil solids) are shown for comparative purposes.

The moisture–density curves for the 100% DM exhibit the characteristic convex shape typical of OH soils. With increased CG content, the w_{opt} decreased and the $\gamma_{d,\max}$ increased, and the shape of the compaction curve trended toward those associated with conventional coarse soils and aggregates. The trends in the line of optimums for the CG–DM blends are summarized in Fig. 4. The impact of CG on the compaction characteristics of 100% DM is clearly evident—the addition of 20% CG results in a 10–20 point reduction in w_{opt} while increasing the dry density by approximately $1-3\ kN/m^3$ ($6-18\ lb/ft^3$) for standard and modified levels of compaction, respectively.

As shown in Fig. 4, the values of $\gamma_{d,\max}$ generally remained within the bounds of the 100% CG and 100% DM materials and increased in a nearly linear fashion. This trend, however, was not observed when CG was blended with kaolinite (K) and quarry fines (QF) (Wartman et al. 2004b), which showed that the CG–K and CG–QF blends were denser than the individual materials, despite their significant difference in the specific gravities [2.48 (CG) versus ~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. Hence, it appears that the organic matter of the DM prevents "tight" packing to unit weights greater than the raw materials, a trend observed when blending mineral solids (CG, K, QF).

A related issue to "packing" is the "bulking" of the amended DM, i.e., the additional volume that results from amending DM with PC/FA/lime, or in this case, cutting the DM with CG. Interestingly, the ratio of $\gamma_{d,\max}$ of the 100% DM to the 20/80 CG–DM blend [$(12.2\ kN/m^3)/(15.1\ kN/m^3)$] was 80.8% versus the DM content of 80% in the 20/80 CG–DM blend, indicating that essentially no bulking of the DM occurred with 20% CG addition. PC/FA/lime bulking can be on the order of 10–20% of the original volume.

Direct Shear and Unconsolidated Undrained Triaxial Strength Testing

Direct (DS) and unconsolidated undrained triaxial (UU) shear tests were performed on CG, DM, and CG–DM blend samples in general accordance with *ASTM D3080* (ASTM 2004b) and *ASTM D2850* (ASTM 1995) standards, respectively. The remolded specimens were placed in thin lifts and were compacted using a

Table 2. Compaction Properties and Select Strength Parameters of CG, DM, and CG–DM Blends

	Standard compaction *D 698*		Modified compaction *D 1557*		Direct shear *D 3080*		UU Triaxial *D 2850*		CIU Triaxial *D 4767*	
Media tested	$\gamma_{d,\max}$ [kN/m^3 (lb/ft^3)]	w_{opt} (%)	$\gamma_{d,\max}$ [kN/m^3 (lb/ft^3)]	w_{opt} (%)	c [kPa (lb/ft^2)]	φ (°)	c [kPa (lb/ft^2)]	φ (°)	c [kPa (lb/ft^2)]	φ (°)
100% CG	17.1 (109)	8	18.7 (119)	8	0	42	11 (225)	40	0	37
Blends										
80/20 CG–DM	17.3 (110)	14	18.2 (116)	10	11 (230)	36	29 (610)	34	1 (15)	39
60/40 CG–DM	15.6 (100)	19	17.3 (110)	10.5	19 (400)	33	28 (590)	26	6 (115)	39
50/50 CG–DM	14.8 (94)	24	16.6 (106)	15	26 (540)	32	48 (1,010)	30	2 (45)	38
40/60 CG–DM	13.7 (88)	25	16.1 (102)	11.5	25 (520)	31	45 (940)	23	2 (45)	37
20/80 CG–DM	11.8 (75)	29	15.1 (96)	11	26 (540)	33	70 (1,470)	16	1 (30)	35
100% dredged material (DM)	10.8 (69)	39	12.2 (78)	29	20 (420)	33	66 (1,380)	20	12 (260)	34

Note: All blends were made using Fort Mifflin DM. ASTM test designations shown where applicable.

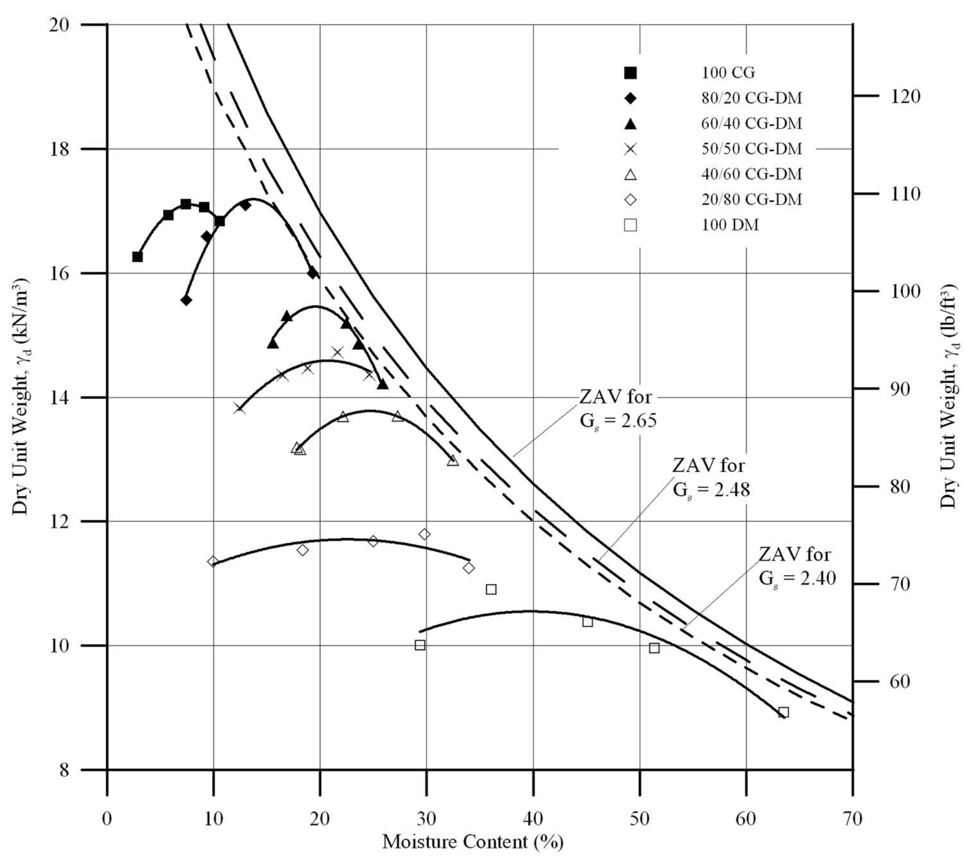

Fig. 2. Standard Proctor compaction results for CG, DM, and CG–DM blends

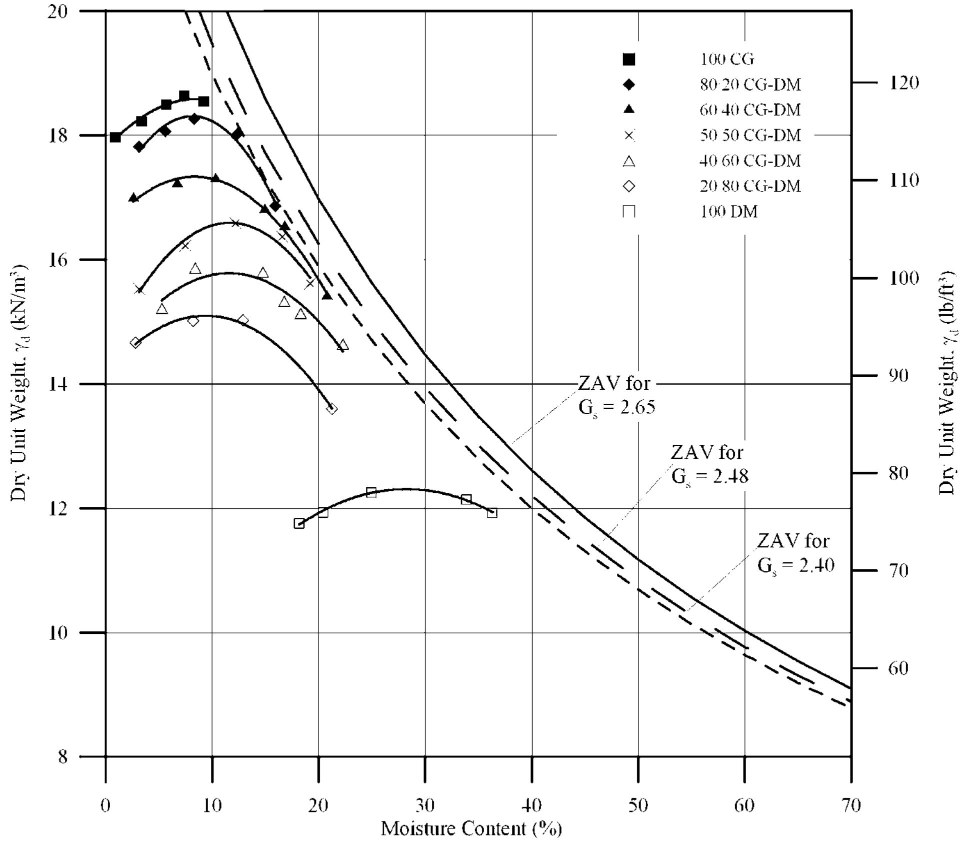

Fig. 3. Modified Proctor compaction results for CG, DM, and CG–DM blends

rubber-tipped pestle to a minimum of 95% of their $\gamma_{d,\max}$ values and within ±2% of w_{opt} based on *ASTM D1557*. For the DS tests, three uniform sample lifts were loosely placed, compacted and scarified prior to the next lift being applied (except top lift). For the UU tests, five uniform sample lifts were compacted in the same manner as the CIU tests. The DS and UU shear test results are summarized in Table 2 and Fig. 5. The selected normal stresses and confining pressures corresponded to shallow to moderate depth overburden conditions (45–160 kPa). The DS and UU tests were performed under as-compacted (partially saturated), total stress conditions. Shear rates were selected as 2 mm/min. and 1%/min. for the DS and UU tests for all samples for consistency, respectively, as testing on regional DM has shown that DS shearing rates between 20%/min. and 0.002%/min. produced results within 5% variation (Mr. Peter Kearney, personal communication, 2005). Hence, that the DS and UU samples were remolded suggests that the strain rates adopted for testing were viewed to be conservative from a drained perspective. In most of the specimens tested, there was strain hardening rather than a definitive peak stress. Therefore, failure was defined as the shear stress corresponding to the largest ratio of peak stress to normal stress.

Fig. 5 shows the variations in friction angle and cohesion as a function of CG for each blend. As expected, the total stress friction angle and cohesion of the blends generally increased and decreased, respectively, with addition of CG. With respect to the DS results, it appears that significant changes in either the ϕ_{DS} or c_{DS} were delayed until about 60% CG. Above 60% CG, ϕ_{DS} increased in a fairly linear fashion from approximately 33 to 42° at 100% CG, while the cohesion decreased to zero. Fig. 5 also shows that the ϕ_{UU} of the DM and CG–DM blends up to 40% CG were significantly lower than the φ_{DS}; however, these correspond to c_{UU} values that were significantly higher than the comparable c_{DS} values. Above 40% CG, the UU and DS results are similar. 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.

CI$\bar{\text{U}}$ Strength Testing

Isotropically consolidated, undrained triaxial (CI$\bar{\text{U}}$) shear tests with pore pressure measurements were performed on CG, DM, and CG–DM blend specimens in general accordance with *ASTM D4757* (ASTM 2004c). Initially, the specimens were placed in thin lifts and compacted using a rubber-tipped pestle, to a minimum of 95% of their $\gamma_{d,\max}$ values and ±2% of w_{opt} based on *ASTM D1557*. However, there were two difficulties associated with sample preparation: (1) the CG tended to puncture the membranes during specimen preparation; and (2) the low hydraulic conductivity of some of the blends made it difficult to adequately saturate the specimens. Therefore, the procedure described below was adopted.

A split mold was assembled and lined with a nonwoven geotextile (weight ~50 g/m^2) instead of a rubber membrane. The amount of dry material necessary to achieve 95% of $\gamma_{d,\max}$ based on *ASTM D1557* was measured. The material was then moistened until it was about 6% wet of optimum. The wet material was placed in the mold in 5–7 lifts using a modified undercompaction

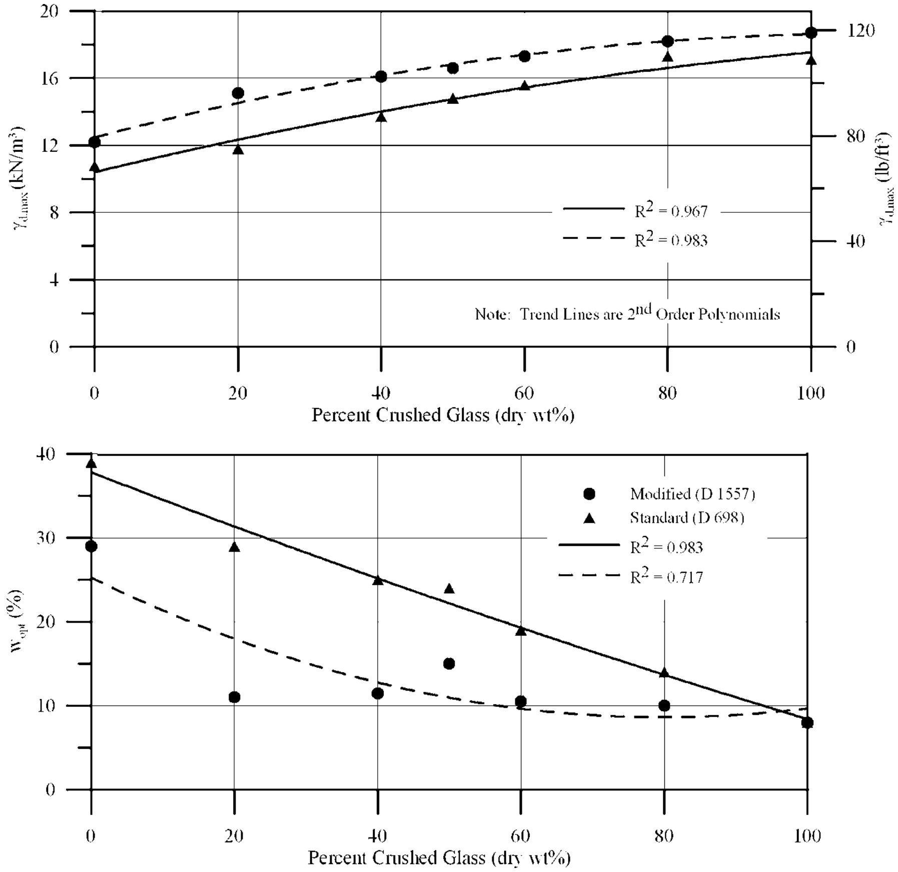

Fig. 4. Line of optimums for CG, DM, and CG–DM blends

procedure (Ladd 1974). Each lift was compacted by placing a rubber stopper on top of the wet soil and tamping the lift with a Harvard miniature compactor to achieve the required dry density based on the volume of the mold and the mass of the dry blend. The number of blows was evenly scaled from 10 to 25 blows/layer between the bottom and top lifts, respectively. The force applied by the Harvard miniature compactor and blows/layer were recorded to determine the preconsolidation pressure of each sample.

After each specimen was compacted to the required density, the split mold was removed and the geotextile was carefully peeled off and replaced with a single rubber membrane. Mounted samples in the triaxial device were flushed with CO_2 for about 20 min and de-aired water for another 60 min. Finally, backpressure saturation was applied to achieve a B value of at least 0.95.

Confining pressures of 70, 210, and 345 kPa were selected because they exceeded the compaction stresses induced during sample preparation, placing the samples in the normally consolidated range. A strain rate of 2.5% was selected based on the t_{50} values which generally were less than 10 min. Time to failure during the tests ranged from 120 to 180 min. There was no definitive peak stress, so failure was defined as the shear stress corresponding to the largest ratio of peak stress to normal stress.

The effective stress strength parameters are summarized in Table 2 and Fig. 6. The 100% DM had a $c'_{CI\overline{U}}$ of about 12 kPa. The addition of CG to the DM caused a gradual increase in $\phi'_{CI\overline{U}}$ from 34° (100% DM) to a high of about 39° for the 80/20 CG–DM blend. The DM results compare well with Weston (2002), who determined the $\phi'_{CI\overline{U}}$ to be on the order of 29–32° for the same failure criteria but using USACE Fort Mifflin Basin A OH samples with approximately 17% organic matter (slightly higher than samples studied here).

The $\phi'_{CI\overline{U}}$ of the 100% CG was determined to be 37° using confining pressures of 70, 210, and 345 kPa. As this was approximately 10° less than reported by Wartman et al. (2004a) for two other sources of CG with a similar gradation but tested at lower confining pressures (30, 80, and 140 kPa), it was originally believed that the discrepancy was potentially related to differences in confining pressures and nonlinearities in the Mohr–Coulomb failure envelope over the evaluated confining stress range. Therefore, both sets of CG samples (this study and Supplier I from Wartman et al. 2004a) were retested using the protocols described above for confining pressures between 70 and 345 kPa. Values of $\phi'_{CI\overline{U}}$ of 37 and 41° were, respectively, measured for the CG samples from this study and that of Wartman et al. (2004a) across the entire range of confining pressures, indicating that there was little or no nonlinearity in the Mohr–Coulomb failure envelope. However, the Supplier I CG sample now exhibited a 7° loss from the previous study. The (minor) differences in the friction angles between the two CG samples was therefore attributed to material characteristics, whereas the difference in friction angles between the two studies was attributed to data interpretation criteria. In this study, a maximum stress obliquity criterion was used to define failure, whereas Wartman et al. (2004a) assigned failure at 10% axial strain. While both failure criteria are acceptable for strain hardening materials, they provided significantly different values of $\varphi'_{CI\overline{U}}$. Reinterpreting the raw data from

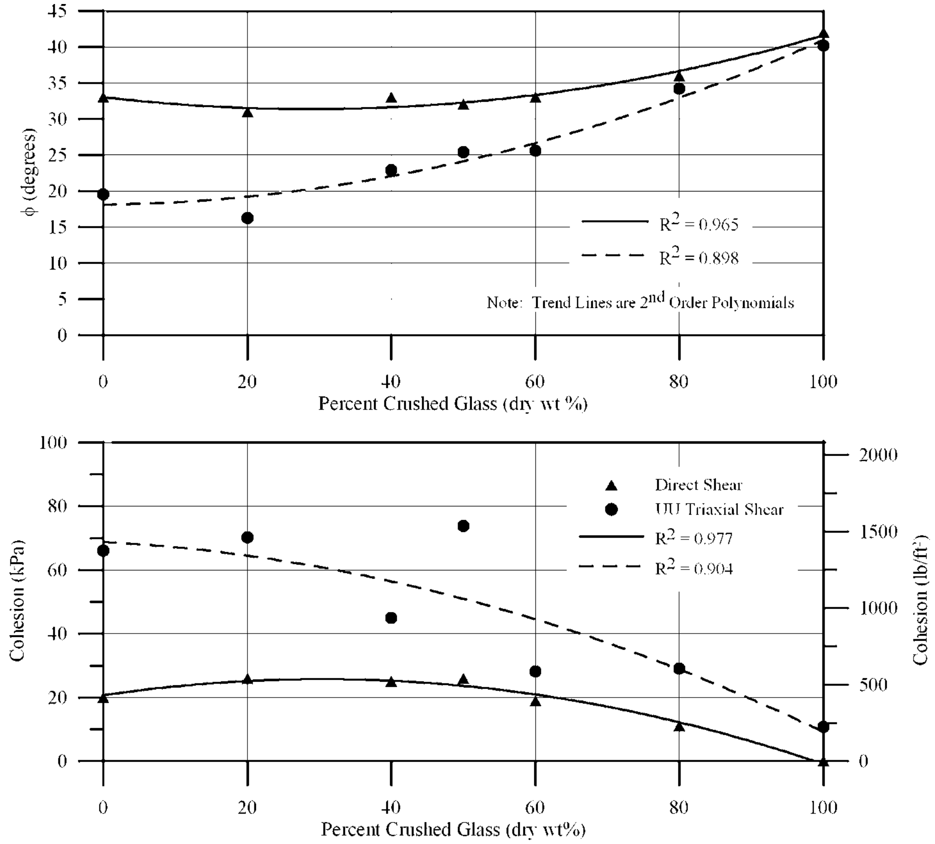

Fig. 5. Strength parameters (ϕ, c) for compacted CG, DM, and CG–DM blends

Wartman et al. (2004a) using maximum stress obliquity approach yielded $\phi'_{\mathrm{CI\overline{U}}}$ values of 41–42°, stressing the importance of data interpretation techniques and their influence on the values assumed for design and analysis.

Fig. 7 shows the initial elastic modulus (E_i) was determined from the stress–strain curves and is plotted as a function of increasing CG content and confining pressure. The E_i for the 100% DM is significantly higher than values reported in Bardet (1997) for unconsolidated silts, demonstrating that simply compacting the 100% DM to a minimum of 95% relative compaction by *ASTM D1557* caused a tremendous increase in E_i. The addition of 80% CG increased E_i approximately 50% more.

Hydraulic Conductivity

The hydraulic conductivities of the 100% DM and CG–DM blends were determined in accordance with *ASTM D5084* (ASTM 2003b), while *ASTM D2434* was used for the 100% CG. Specimens were compacted in three lifts to a minimum of 95% of their $\gamma_{d,\max}$ values and between 0 and plus 2% of w_{opt} based on *ASTM D1557*. All tests were conducted at approximately 20 °C with confining pressures on the order of 35 kPa (5 psi). The results are summarized in Table 3 and Fig. 8. Fig. 8 illustrates that the 20/80 and 40/60 CG–DM blends had lower hydraulic conductivity values than the 100% DM, which is likely due to the increased density that occurred (Table 2) prior to reaching a CG content (~50%) corresponding to a more open and interconnected pore space.

These results are consistent with results reported by Shakoor and Cook (1990) and Shelley and Daniel (1993). Shakoor and Cook (1990) also reported a similar trend in hydraulic conductivity for silty clay (CL) of glacial origin mixed with gravel particles (13–19 mm diameter) in increments of 10–80% gravel by weight. Specimens were compacted to a minimum of 95% of their $\gamma_{d,\max}$ values and between ±2% of w_{opt} based on *ASTM D698*. The hydraulic conductivity decreased about 1/2 order of magnitude as the gravel content increased up to 30% and then increased about half an order of magnitude as the gravel content increased to 50%, but stayed in the range of 8×10^{-6}–1×10^{-7} cm/s. As the gravel content increased from 50 to 60%, the hydraulic conductivity increased about 4 orders of magnitude, from about 8×10^{-6} to 1×10^{-2} cm/s. Likewise, Shelley and Daniel (1993) evaluated the hydraulic conductivity behavior of mine spoil and kaolinite mixed separately with gravel. The mine spoil had plasticity indices similar to the DM used in this study. Shelley and Daniel (1993) used specimens compacted to the $\gamma_{d,\max}$ at 2–4% above w_{opt} based on *ASTM D698*, and 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 1 order of magnitude increase for the mine spoil–gravel and kaolinite–gravel blends.

Consolidation Properties

One-dimensional consolidation properties of the CG and DM materials were determined in accordance with *ASTM D2435* (ASTM 2004a), as summarized in Table 3. Specimens were compacted in three lifts to a minimum of 95% of their $\gamma_{d,\max}$ values and between 0 and +2% of w_{opt} based on *ASTM D1557*. The $e \log P$ curves for the CG–DM blends are shown in Fig. 9, using weight-averaged specific gravities for the blends. The response of the

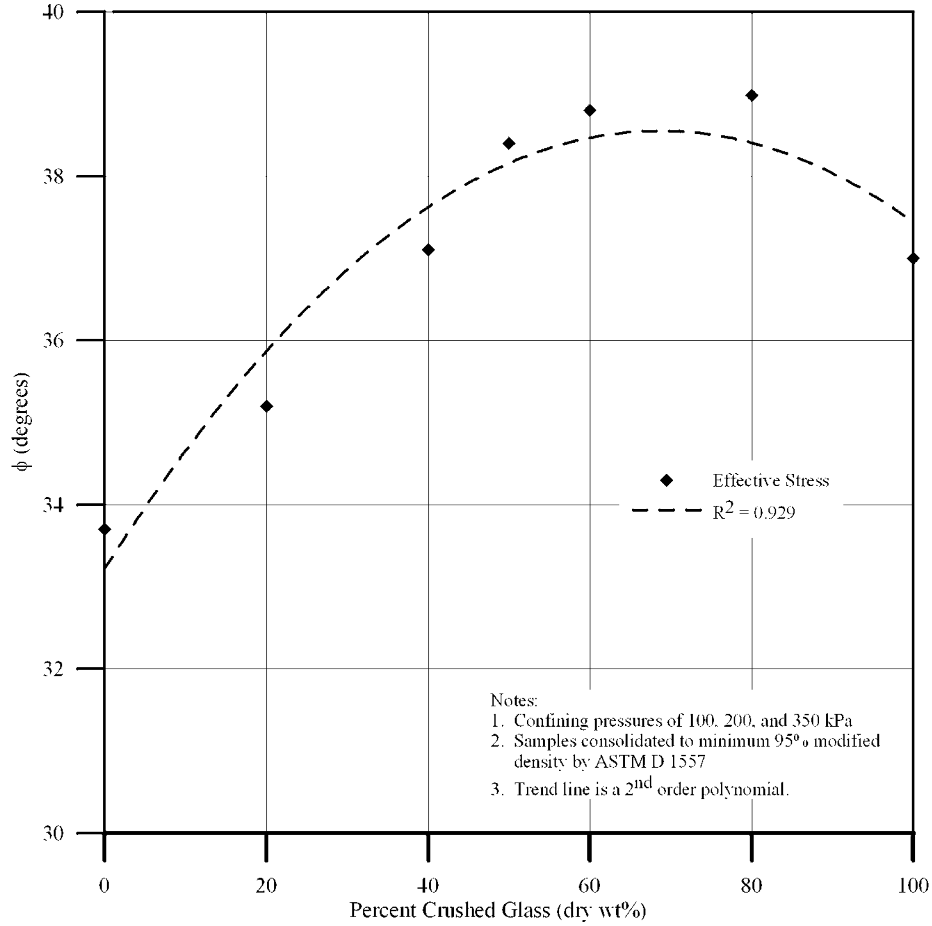

Fig. 6. Isotropically consolidated undrained (CIŪ) triaxial results for compacted CG, DM, and CG–DM blends

100% DM to loading conditions is consistent with that of OH soils. Fig. 9 illustrates a substantial reduction in settlement with only 20% CG with the addition of glass particles potentially corresponding to the emergence of a skeleton or network of relatively incompressible particles that significantly decreased the potential for settlement. After 40% CG, the $e \log P$ curves begin to plot on top of each other, indicating a diminishing return on CG addition for settlement reduction.

As expected, the compression index (C_c) of DM decreased significantly as the percentage of CG increased, (see Fig. 10). The largest drop, approximately 50%, occurred with the addition of 20% CG. C_c continued to decrease as the percentage of CG increased to a low of 0.08, but the most dramatic decrease occurred for the increment between the 100% DM and the 20/80 CG–DM blend. There is a general decrease in C_r with increasing percentage of CG. For most data points, $C_c/C_r \sim 7$, in general agreement with the critical state model that predicts $C_c/C_r \sim 5$ (Wroth and Wood 1978).

The values of the coefficients of consolidation and secondary compression, c_v and C_α, respectively, were obtained from the consolidation curves from the CIŪ tests. Table 3 and Fig. 11 show c_v for two confining pressures. As expected, c_v generally increased with increasing CG, the scatter in the data reflecting that c_v is a complex function of hydraulic conductivity, unit weight, and compressibility. The trend line for the 200 kPa confining pressure mimicked the shape of the hydraulic conductivity curve, i.e., a slight decrease in c_v was followed by large increases above 60% CG. The CG–DM results fall within the range of c_v values reported for silt ($0.01-1.0\ \mathrm{cm}^2/\mathrm{s}$) in Bardet (1997). The c_v was fairly consistent, indicating that the consolidation properties should remain fairly constant for the loading conditions anticipated for construction. Table 3 indicates a significant decrease in C_α in the vicinity of 40–50% CG, which plateaus thereafter.

Discussion

The results of the laboratory testing program indicate that the workability and construction characteristics of DM can be improved by the addition of CG beginning with as little as 20% CG. The addition of CG caused significant improvements in the physical properties of DM, including reductions in moisture content, organic content, and plasticity index, as well as coarsening of the grain size distribution. These changes increased the workability of DM for construction. There are significant increases in $\gamma_{d,\max}$ and corresponding decreases in w_{opt} for all of the CG–DM blends. For example, the addition of 20% CG produced a decrease in w_{opt} of 20 points (67%) and increased $\gamma_{d,\max}$ by 23% at modified levels of compaction. The improved workability of the blends was also indicated by the simple observation that it was significantly easier to achieve the target compacted density in the laboratory specimens of blends over the 100% materials. The practical significance of these observations are consistent with the results of the field study (Grubb et al. 2006) which indicated that unworkable and wet DM ($w \sim 40-50\%$) blended with as little as 20% CG

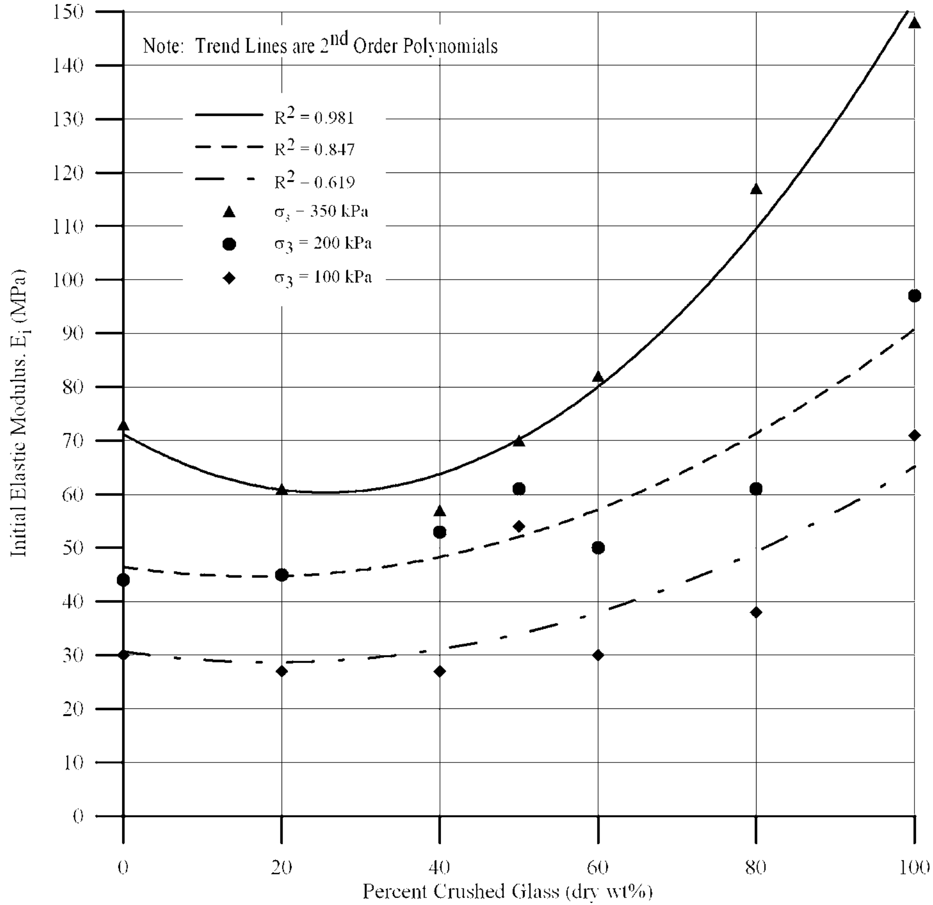

Fig. 7. Initial elastic modulus for compacted CG, DM, and CG–DM blends

produced material that was suitable for construction immediately after blending.

What is misleading about the CG–DM blends is that triaxial friction angle results suggest that CG addition to DM does not significantly improve the overall strength of the 100% DM. Fig. 6 shows a maximum increase only on the order of 6° (based on maximum stress obliquity), whereas Wartman et al. (2004b) showed substantial increases (~12°) in the friction angles of the CG−*K* blend when blending 50% CG with kaolinite (based on 10% axial strain). While part of this difference is attributable to the difference in the failure criteria, a more complete picture of the improvements offered by CG addition to DM becomes evident when the shear strength of the CG–DM blend is evaluated considering the influence of cohesion, density, and the friction angle. The shear strength of soil is defined as

$$\tau_i = c_i + (\gamma_i H_{\text{fill}})\tan \phi_i \quad (1)$$

where τ_i=soil shear strength; c_i=cohesion; γ_i=soil unit weight; H_{fill}=thickness/height of a simulated fill; ϕ_i=internal friction

Table 3. Hydraulic Conductivity and Consolidation Properties of CG, DM, and CG–DM Blends

	Hydraulic conductivity *D5084*			1D consolidation *D2435*		
Media tested	K (cm/s)	C_c	C_r	c_v @ 400 kPa (cm^2/s)	c_v @ 800 kPa (cm^2/s)	C_α
100% CG	6.20E−02	0.042	0.005	0.1451	0.0896	0.0016
Blends						
80/20 CG–DM	7.40E−03	0.0820	0.011	0.0731	0.0700	0.0009
60/40 CG–DM	2.90E−05	0.1380	0.006	0.0755	0.0341	0.0038
50/50 CG–DM	4.20E−06	0.1050	0.014	0.0275	0.0418	0.0065
40/60 CG–DM	1.70E−06	0.1650	0.022	0.0601	0.0105	0.0179
20/80 CG–DM	1.20E−06	0.1450	0.019	0.0270	0.0136	0.0191
100% DM	3.60E−06	0.2600	0.017	0.0611	0.0010	0.024

Note: All blends were made using Fort Mifflin DM. ASTM test designations shown where applicable. *K* for 100% CG by *ASTM D2435*.

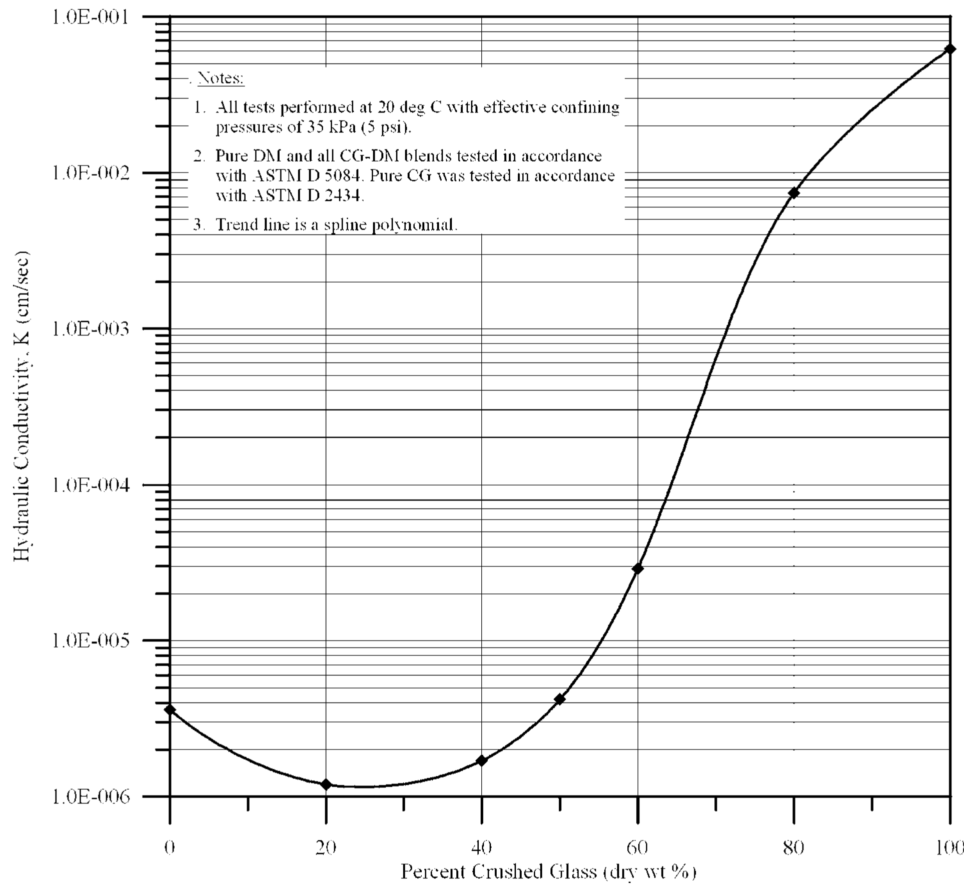

Fig. 8. Hydraulic conductivity versus percent crushed glass (dry % by weight)

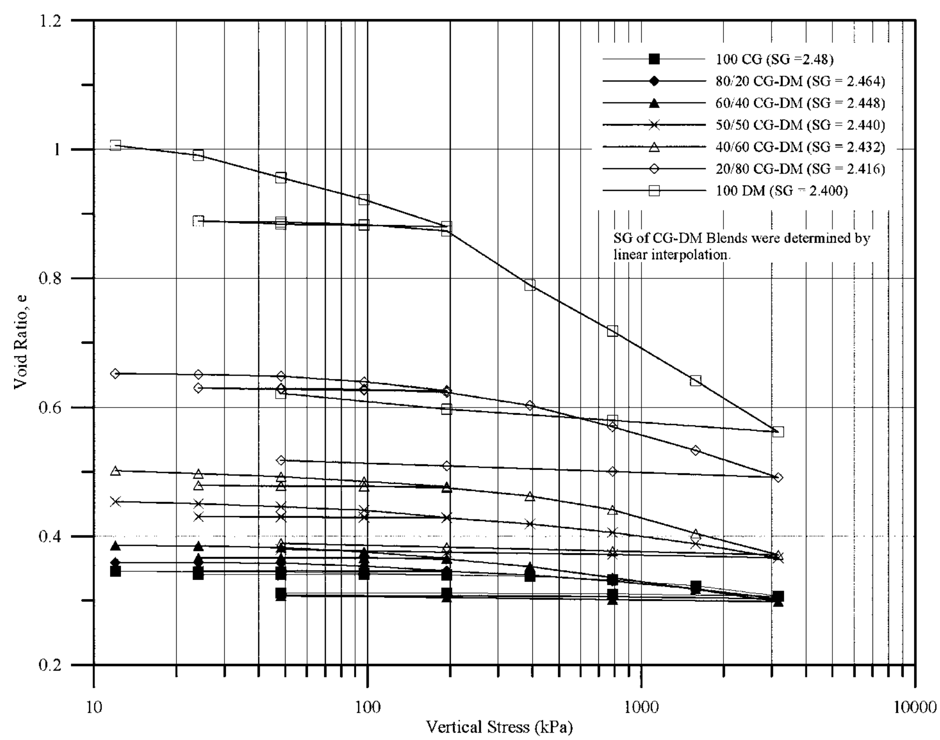

Fig. 9. Void ratio (e) versus vertical stress for compacted CG–DM blends

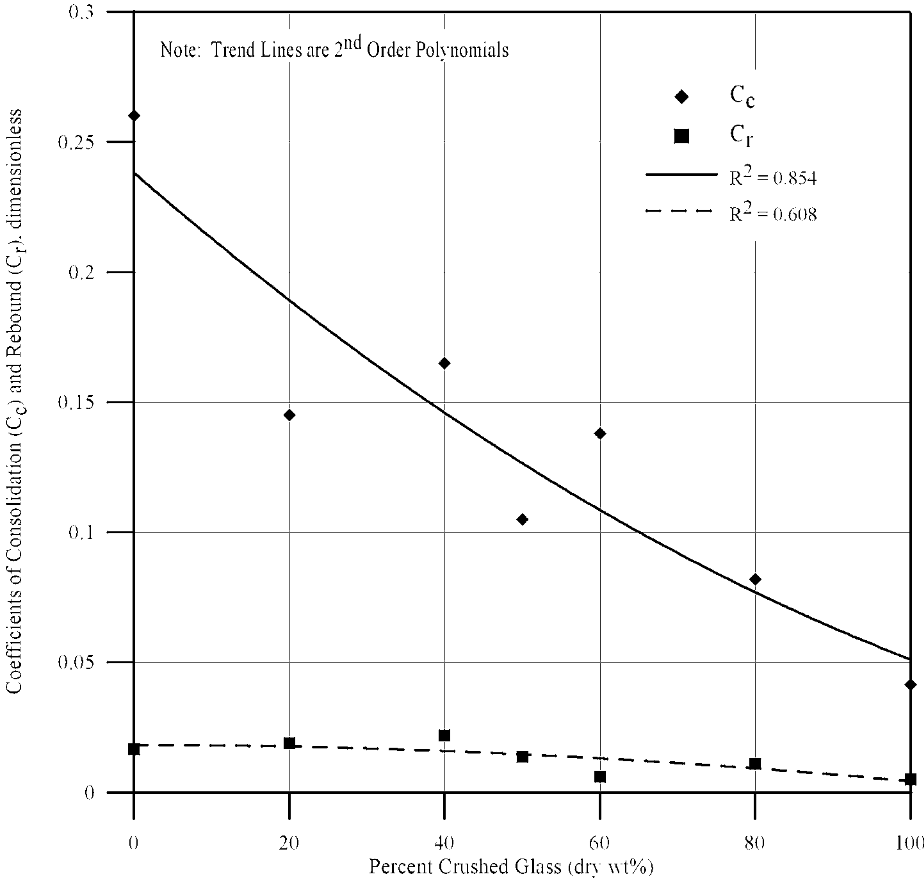

Fig. 10. Coefficients of consolidation (C_c) and rebound (C_r) for CG–DM blends as function of CG content

angle; and i=blend. Fig. 12 presents a contour plot of the relative (normalized; $\tau_{\text{blend}}/\tau_{\text{DM}}$) shear strength increase achieved through CG–DM blending over 100% DM for simulated fill depths ($0 \leqslant H_{\text{fill}} \leqslant 15$ m). Thus, for any fill depth, the normalized shear strength of DM is unity, and therefore provides a reference plane to show the benefits of CG addition. The plot is based on the $\text{CI}\bar{\text{U}}$ triaxial effective strength values and material properties (Tables 1–3) corresponding to a minimum of 90% modified Proctor compaction for the 100% DM and 20% CG–DM blend, and a minimum of 95% modified Proctor compaction for blends containing greater than 20% CG. The difference in minimum densities for this simulation arose from the observation that it was extremely difficult to achieve greater than 95% modified Proctor compaction of the 20/80 CG–DM blend in the field (Grubb et al. 2006), and by extension, the 100% DM.

The left front portion of Fig. 12 clearly shows that 100% DM is stronger than most CG–DM blends because Eq. (1) indicates that c_i dominates the other parameters at shallow depths (0–2.5 m, depending on blend). However, the situation changes rapidly with depth thereafter, as greater than 50% CG addition results in shear strength increases up to 1.7 times greater than 100% DM ($H_{\text{fill}} \sim 15$ m). In contrast, the 20/80 CG–DM blend appears only to achieve a strength increase on the order of 20% above 100% DM, even though the material was significantly more workable than 100% DM. Accordingly, as long as the workablility issue is satisfied (>20% CG) and the strength requirements are met for an actual field application (also >20% CG in all likelihood), CG–DM blending offers a versatility that allows for the design of fills potentially optimizing on several parameters (e.g., less settlement, improved drainage, higher CG or DM content, or satisfying environmental parameters such as pH, leaching criteria of constituent compounds, etc.).

There are several design considerations that can be evaluated or balanced for construction, the first of which is the ratio of available CG:DM. This may drive many choices, but it appears the major changes in DM behavior begin at 20% CG. For example, decreased compressibility occurs with the addition of just 20% CG, which reduces the compression index by 50%. Twenty to 40% CG content decreases the hydraulic conductivity value below that of 100% DM, whereas a 60–80% CG content increased the hydraulic conductivity by 1–3 orders of magnitude, respectively. Related increases in c_v would result in decreased times required for consolidation. In blends containing more DM, the time for consolidation may be reduced from months to weeks. In blends containing more CG, the time for consolidation may be reduced from weeks to days. With respect to elastic compression, simply compacting DM to 95% $\gamma_{d,\max}$ caused an appreciable increase in the modulus above reported values for silts (Bardet 1997). CG addition thereafter produced continued but smaller increases in modulus.

Concluding Remarks

The results of this laboratory evaluation of blending crushed glass and dredged material indicate that blending CG with DM can significantly improve the properties of the DM with the addition of as little as 20% CG. The significant findings are summarized below:

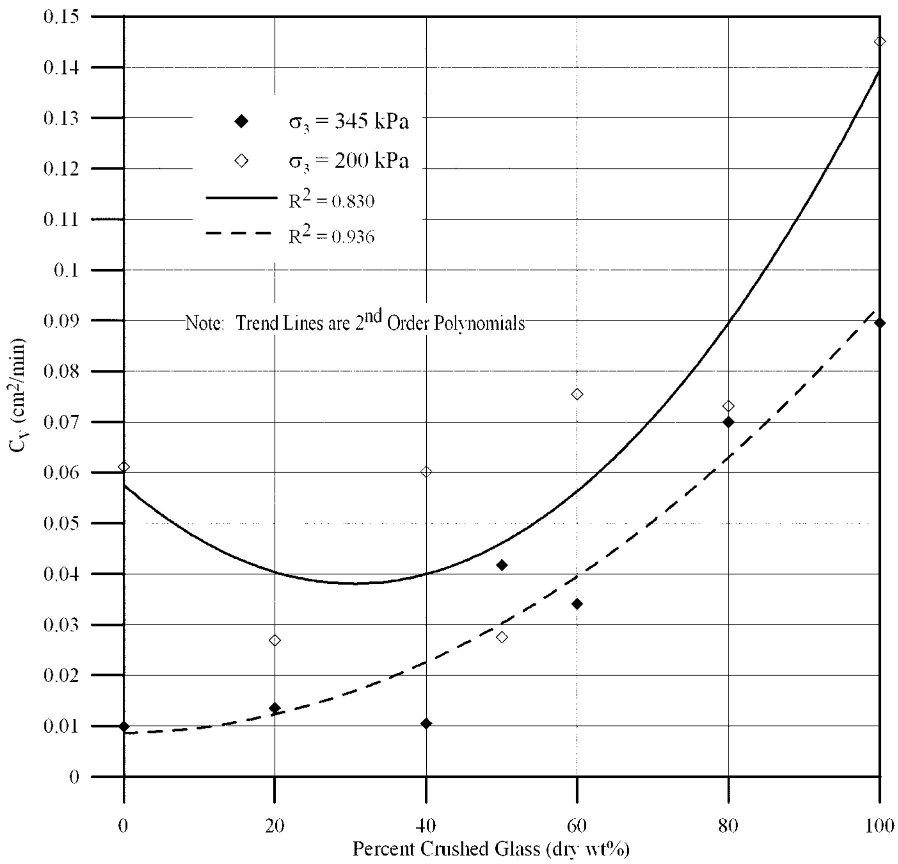

Fig. 11. C_v for compacted CG, DM, and CG–DM blends

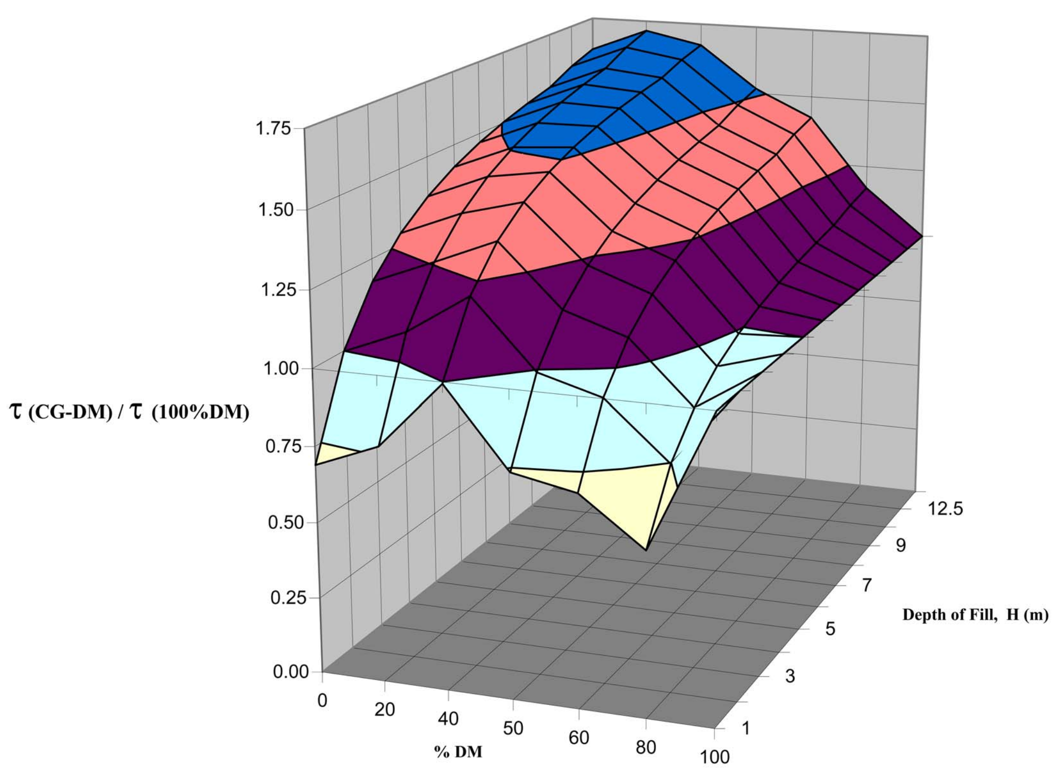

Fig. 12. Normalized strength of CG–DM blends as function of DM content and simulated fill depth

1. The addition of 20% CG resulted in a 10–20 point (33–67%) reduction in w_{opt} and increased the dry density of the DM by approximately 1–3 kN/m^3 (6–18 lb/ft^3) for standard and modified levels of compaction, respectively. The loss in moisture sensitivity at 20% CG significantly improved the workability of the 100% DM.
2. The addition of 20% CG reduced the compressibility of the DM by approximately 50%.
3. The addition of 20–40% CG reduced the hydraulic conductivity of the blends below the values for 100% DM. However, the addition of 60 and 80% CG increased the hydraulic conductivity by 1–3 orders of magnitude, respectively, compared to 100% DM. Associated increases in c_v corresponds to decreased times required for consolidation.
4. CI$\bar{\text{U}}$ triaxial strength testing indicated effective friction angles of 34 and 37° when the 100% DM and CG were compacted to a minimum of 95% relative compaction by *ASTM D1557*, respectively. A peak effective friction angle of 39° occurred for the 60/40 and 80/20 CG–DM blends. Effective shear strength estimates indicated that CG addition can increase the strength of 100% DM by a factor up to 1.7 depending on the CG–DM blending ratio for fills having depths up to 15 m. Eq. (1) illustrates that this increase is the net effect of simultaneous changes in the cohesion, unit weight, and friction angle of the blends (whereas lime addition to DM cannot significantly increase the unit weight).

In conclusion, the range of properties obtainable by CG–DM blends offers the designer a versatility to utilize different proportions of CG and DM to potentially optimize on several design parameters, or even in different fill areas of the same site. This versatility can increase the beneficial use of CG and DM as fill materials for urban applications.

Acknowledgments

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Notation

The following symbols are used in this paper:

C_c = compression index (dimensionless);
C_r = recompression index (dimensionless);
C_α = coefficient of secondary compression (dimensionless);
c = cohesion (kPa);
c_v = coefficient of consolidation (cm^2/s);
G_s = specific gravity (dimensionless);
K = hydraulic conductivity (cm/s);
w_{opt} = optimum water content (%);
$\gamma_{d,\max}$ = maximum dry density (kN/m^3);
ε_a = axial strain (%);
σ_c = effective normal stress during triaxial shear testing (kPa);
σ_n = applied effective normal stress during direct shear testing (kPa);
σ_1 = maximum principle effective stresses (kPa);
σ_3 = minimum principle effective stresses (kPa);
σ_1-σ_3 = deviator stress (kPa);
τ_i = soil shear strength (kPa);
ϕ = friction angle (degrees); and
% by weight = percent by weight.

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