Field Evaluation of Crushed Glass–Dredged Material Blends

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Abstract: Based on the laboratory results reported in a companion paper, three crushed glass–dredged material (CG–DM) blends were prepared and evaluated in the field to explore the feasibility of using CG–DM blends in general, embankment and structural fill applications. A trailer-mounted pugmill successfully prepared 20/80, 50/50, and 80/20 CG–DM blends (dry weight percent CG content reported first) within a tolerance of ±5 dry % by weight of the targeted percentages. Blending criteria were routinely met at pugmill throughputs up to 1,500 m^3/day. The constructed 20/80 CG–DM embankment was compacted to a minimum of 90% modified Proctor compaction, whereas the 50/50 and 80/20 CG–DM embankments were constructed to a minimum of 95% modified Proctor compaction. Twenty to 80% CG addition to DM resulted in 1.5–5.5 kN/m^3 increases in field dry densities above 100% DM, densities not achievable with other DM stabilization techniques such as Portland cement, fly ash, and/or lime (PC/FA/lime) addition. CG substantially improved the workability of DM allowing construction with conventional equipment and three person crew while achieving very consistent and reproducible results during a timeline of frequent and heavy precipitation events. The 20/80, 50/50, and 80/20 CG–DM embankments were characterized by average cone tip resistances on the order of 1.0, 1.5, and 2.0 MPa, respectively. An environmental evaluation of 100% CG, DM and 50/50 CG–DM blend samples coupled with an economic analysis of a scaled-up commercial application illustrated that the CG–DM blending approach is potentially more cost effective than PC/FA/lime stabilization approaches. These features of CG–DM blending make the process attractive for use in urban and industrial settings.

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Introduction

This paper reports on the field testing trials associated with a laboratory evaluation of crushed glass-dredged material (CG–DM) blends described in a companion paper (Grubb et al. 2006). Three CG–DM blends were prepared (20/80, 50/50, and 80/20 CG–DM; dry weight percent CG reported first) to explore the suitability of these materials as general, embankment and structural fill materials for Department of Transportation (DOT), airport, building and maritime construction, land reclamation, and brownfields and portfields applications. The overall objective was to identify applications to increase the recycling of both CG and DM in urban construction, as both are generated in large volumes in or near coastal cities, thus reducing fill transportation costs. The blending and trial embankment construction operations were conducted at the United States Army Corps of Engineers (USACE) Fort Mifflin site located in Philadelphia, which maintains three active containment and disposal facilities (CDFs) for the dredging of the lower Schuylkill and Delaware Rivers.

This paper will report on the blending and compaction compliance, workability, cone penetration testing (CPT) results, and economic issues associated with trial embankment construction using the 20/80, 50/50, and 80/20 CG–DM blends. Additionally, the 100% CG, DM and 50/50 CG–DM blends were also tested for a large suite of environmental indicators that are associated with drinking water impact evaluation and beneficial use. Cost estimates for commercial-scale operations are presented.

Experimental Study

Materials

City of Philadelphia curbside-collected glass was the source of glass materials for this study. The glass was crushed and sieved through a 9.5 mm (3/8 in.) sieve, a size that does not represent a physical handling hazard. The dredged material (DM) was excavated from Basin A at USACE Fort Mifflin in the same area that materials were collected for the laboratory study (Grubb et al. 2006). Ten random samples ($n=10$) each were obtained from the

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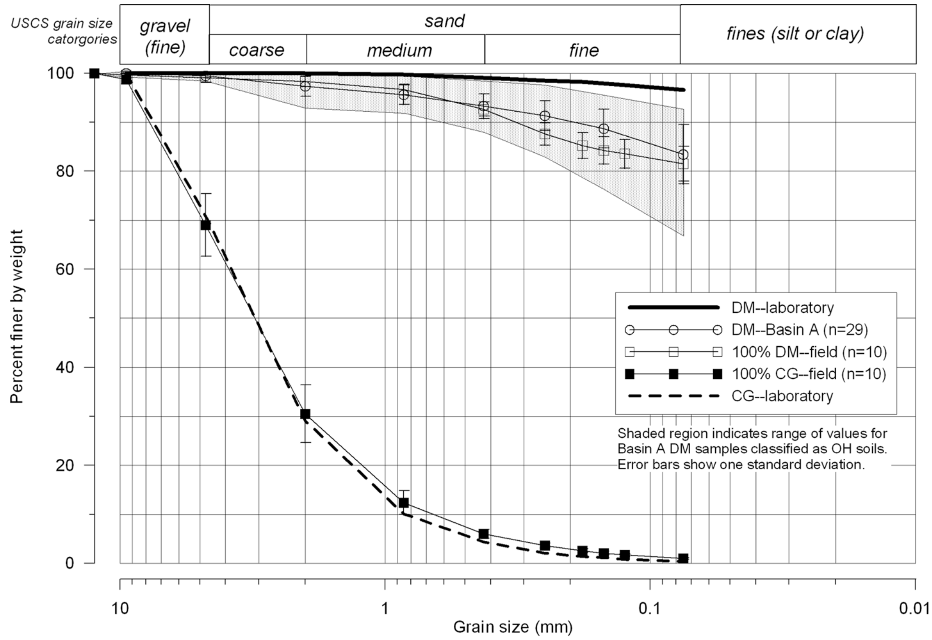

Fig. 1. Grain size distributions for CG and DM field samples, USACE-Fort Mifflin

CG and DM stockpiles to evaluate if the grain size distributions generated in the laboratory were representative of the materials stockpiled in the field. Samples from the CG and DM stockpiles were collected by excavating to a minimum depth of 0.3 m (1 ft) into the stockpiles to ensure consistency from the perspective of both gradation (potential loss of fines due to rainfall) and moisture content (evaporation). The grain size distributions of all field samples were determined according to *ASTM D422-63*.

Fig. 1 includes the laboratory-determined gradation curves for 100% CG and DM materials used to develop the compaction criteria for contracting purposes. Plotted for comparison are the average grain size distributions of the CG and DM stockpile samples with error bars representing 1 standard deviation. While the gradation characteristics of the laboratory and field samples of CG are virtually identical, the field DM sample contained significantly more coarse fraction [CF; >75 μm (Number 200) sieve] than the laboratory-based DM. Specifically, the laboratory DM sample had approximately 97% fines whereas the DM stockpile had only 81.5% fines with a standard deviation of 3.54. More globally, the stippled region in Fig. 1 shows the maximum and minimum percents finer by weight of 29 DM samples classifying as organic silts (OH) soils collected from Basin A (Weston 2002), which were found to have between 67 and 93% fines with an average of 83.4% fines and a standard deviation of 6.06 and approximately 14.2% organic matter content. Fifteen samples of OH soils collected from Basin B had 58–94.9% fines (SAIC 2002). The discrepancy between the laboratory-based and field values had ramifications for the quality assurance testing and compliance protocols established for the contract in terms of blending and compaction criteria. Reliance was ultimately placed on the results of the DM stockpile testing as they were consistent with the Basin A results, but were specific to the material excavated for the field testing program.

As summarized in Table 1, the moisture content of the CG stockpile ranged from 2.05 to 8.14% with an average on the order of 6.3% and a standard deviation of 1.7%. The moisture content of the DM stockpile ranged from 23.9 to 50.2% with an average of 39.3% and a standard deviation of 10.1%. The DM stockpile sample had less moisture than the 29 samples of DM classifying as OH soils randomly collected from Basin A up to depths of approximately 2 m (47.9% average moisture; standard deviation 13.3%), reflecting the effects of drying upon removal from the basin.

Field Operations and Equipment

All blending operations and embankment construction were conducted at USACE Fort Mifflin by three operators working four 10 h shifts/week. Mechanical pre-blending of the CG and DM stockpile materials was completed using an excavator (Hitachi EX300 LE) and loader (Kawasaki 85Z). The excavator was used to feed the hopper of the pugmill as shown in Fig. 2. CG–DM

Table 1. Field CG and DM Characteristics

Source materials	Units	CG	DM	Basin A DM (OH soils)
% Coarse fraction (>75 μm sieve)	%	99.00	18.46	16.60
% Fines (<75 μm sieve)	%	1.00	81.54	83.40
Standard deviation, % Fines	% by weight	0.22	3.54	6.06
Samples collected	*n*	10	10	29
Range, H_2O content	% by weight	2.05–8.14	23.88–50.20	—
Mean H_2O content	% by weight	6.31	39.28	47.88
Standard deviation, H_2O	% by weight	1.73	10.14	13.30

Fig. 2. Overview of pugmilling operation and CG–DM blend stockpile generation using a radial stacker

blending was accomplished with a trailer-mounted custom-designed Tradewinds 37 kW (50 hp) twin-shaft pugmill with counter-rotating paddle augers that had a 1.815×10^5 kg/h (200 t/h) throughput. The pugmill was operated in a batch mode to produce lot sizes on the order of 200–400 ts. A 1 m wide (3 ft), 13 m (40 ft) long radial stacking conveyor (Powerscreen) was utilized to move the blended material from the pugmill discharge to individual stockpiles. After a blended stockpile was approved, the loader and an articulated off-road dump truck (Volvo BM A30) with a 30 t capacity were used to convey the CG–DM blends to the areas designated for embankment construction.

The embankments were constructed on the natural ground surface adjacent to the blending operations, and in the general vicinity of warehouses at USACE Fort Mifflin. Historically, these areas have been heavy trafficked and used as storage areas for military supplies and vehicles making them quite firm. Geologically, the area is underlain at shallow depths ($\sim$8 m) by firm compacted silty and sandy soils. These shallow materials overlie deeper silty soils of fluvial origin. Embankment construction featured the leveling and blading of each CG–DM blend using a bulldozer (Komatsu D41E). Lifts of CG–DM blends were compacted using a smooth 6 t static, 12 t vibratory roller (Caterpillar CS563C) operated in both modes.

Construction Specifications

The contractor was tasked with blending approximately 2,750 m^3 (3,600 yd^3) of CG and DM, followed by the construction of three embankments. The targeted ratios (dry % by weight) for the three embankments were 20/80, 50/50, and 80/20 CG–DM with a blend tolerance of ±5 %. The tolerance limit was based on two competing factors. First, since the compaction curves for the CG–DM blends changed significantly in terms of $\gamma_{d,\max}$, w_{opt}, and shape at every 20% increment (see Fig. 3; Grubb et al. 2006), greater tolerance limits translated into potential difficulties obtaining the specified compaction for each blend. Second, the tolerance limit had to allow for a cost-effective and realistically attainable compliance window for blending operations at high throughputs. Each trial embankment was constructed with the rectangular core dimensions of approximately 3.6 m (12 ft) high $\times$ 3.6 m (12 ft)

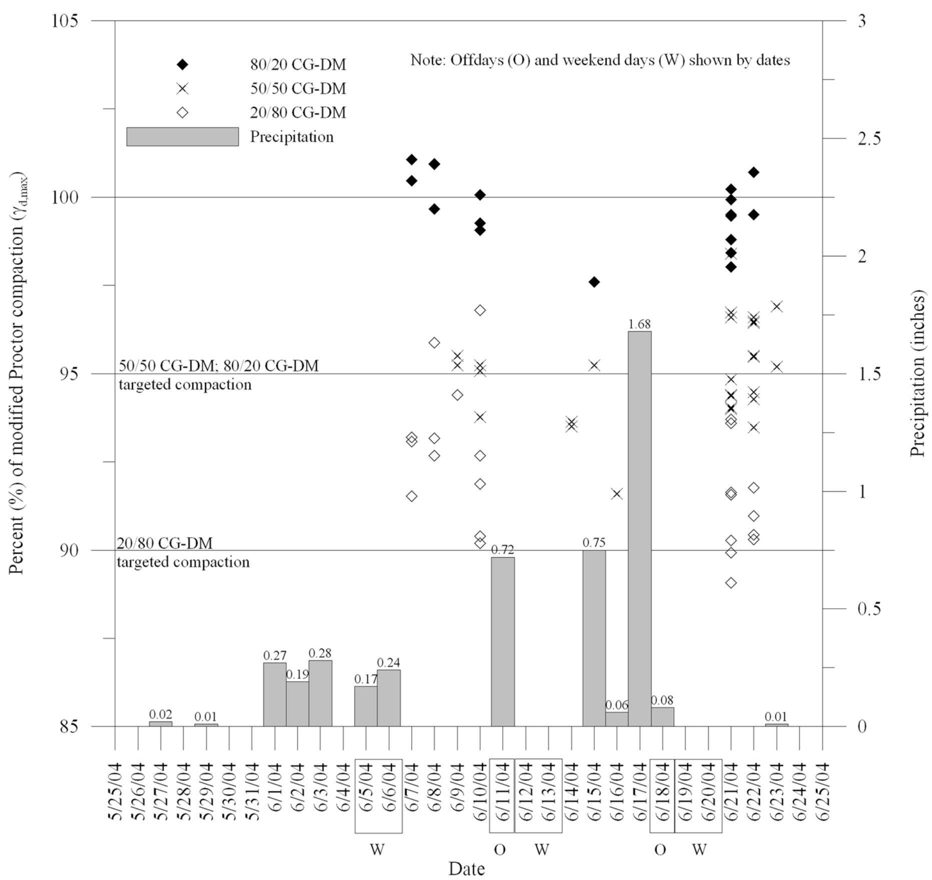

Fig. 3. CG–DM embankment compaction results versus precipitation

wide × 15.2 m (50 ft) long with 3:1 ramps and 2:1 side slopes (side slopes were often 1.5:1 at the contractor's own risk). Embankment construction adhered to the procedures outlined in PennDOT Publication 408, Section 206 (PennDOT 2004), except for (higher) minimum compaction requirements and a tolerance of ±3% on the optimum water content (w_{opt}).

Quality Assurance Testing

The key challenge was to identify a rapid field testing approach to ensure that the CG–DM blends generated by the pugmilling operations were within the prescribed tolerance (±5%). The implemented approach involved collecting random samples of the CG–DM blend from the exit conveyor of the pugmill within every 30 min. production window according to Pennsylvania Test Method (PTM) No. 1 (which identifies randomized road station and offset testing locations, but can be similarly applied to sample lots, time intervals, etc.; PennDOT 1995).

The CG content of the blends was derived from the coarse fraction of the CG–DM blend sample (CF_{blend}) versus a weight averaging of the coarse fraction contents of the 100% CG (CF_{CG}) and DM (CF_{DM}) based on their gradation (Fig. 1). This strategy was adopted owing to the very low fines content of the 100% CG (~1%) and because the standard deviations of the stockpiled CG (0.22%) and DM (3.54%) materials were within the specified blending tolerance.

Procedurally, each collected CG–DM sample was pushed through a 9.5 mm sieve, weighed, and oven dried for 1–3 min./cycle using a microwave oven until the sample mass did not change more than 0.1 g after three sequential readings. After the dry weight of the sample was determined, the CG–DM sample was wet sieved over a (Number 200) 75 μm sieve. The material retained on the 75 μm sieve, i.e., the CF_{blend}, was then re-dried using the aforementioned microwave process. The CG content of the CG–DM blend (CG_{blend}) was subsequently calculated as

$$CG_{Blend} = CF_{Blend} - (\%DM)(CF_{DM}) + (1 - \%DM)(CF_{CG}) \quad (1)$$

The calculated CG content was then compared to the targeted blending ratio to determine compliance.

In situ density testing of the CG–DM blends was confirmed for each 20 cm (8 in.) lift in triplicate according to *ASTM D2922-96*, at the randomized locations identified by PennDOT PTM No. 1 in the central footprint of the embankment (3.6 m × 15.2 m, or 12 ft × 50 ft). Compliance for each lift was based on the average of the triplicate results versus the prescribed compaction criteria.

Field Testing Results

Blending Operations

The contractor developed an approach to pre-blending and pugmilling of CG and DM materials based on the (daily) measured moisture contents of the CG and DM stockpiles and estimated loader bucket densities. After manual mixing with a loader and excavator, the pre-blended materials were pugmilled and placed into three separate 20/80, 50/50, and 80/20 CG–DM blend stockpiles of 200–400 t each, resulting in the creation of a total of 5–6 stockpiles per blend for trial embankment construction purposes. The pre-blending and pugmilling successfully produced a material whose composition was visually uniform. Blended CG–DM materials exiting the radial stacker (conveyor) feeding individual blend stockpiles were sampled (4–8 times depending on the volume) to determine compliance with the blending criteria. No individual stockpile was approved for construction if it fell outside of the targeted blend and tolerance criteria. For the single stockpile that did not initially meet the criteria, blending with another blended stockpile of a similar size was allowed so that the combined composition enabled both stockpiles to satisfy the blending criteria. This entailed mining material from both stockpiles in an alternating fashion recognizing that the embankment placement, blading, and grading process involved additional mixing prior to proofrolling and compaction.

Table 2. CG–DM Blend Stockpile Characteristics

CG–DM blends	Units	20/80	50/50	80/20
Targeted CG content	% by weight	20.00	50.00	80.00
Mean CG content	% by weight	21.96	50.04	77.39
CG standard deviation	% by weight	5.30	5.35	2.90
Mean fines content	% by weight	63.45	41.23	19.71
Samples collected	*n*	25	24	23
Samples outside of ±5 % by weight	*n*	11	8	8
Stockpiles outside of ±5 % by weight	*n*	1	0	0
Mean H_2O content	% by weight	31.55	20.01	12.60
Standard deviation, H_2O	% by weight	1.58	2.67	1.29

The overall blending quality assurance testing results are summarized in Table 2. Compliance with the blending objectives was routinely met even though individual samples often fell outside of the blending criteria. Individual sample values averaged out across multiple samples per stockpile, with only one 20/80 CG–DM stockpile failing the blending criteria. These results are considered excellent given the natural variability of DM materials, the variable bucket densities and moisture contents of the CG and DM stockpiles, the high throughputs of the pugmill, lack of metering/automation for feedstock materials (such as in weight conveyors used for mineral processing), and the frequency of precipitation.

Compaction Tests

A summary of the field density testing results is presented in Table 3. A nuclear density gauge (Troxler Model 3411) was used to determine the degree of compaction of the embankments in accordance with *ASTM D2922-96*. There were two factors that may have impacted the field compaction results. First, the higher coarse fraction of the stockpiled DM (CF_{DM}=18.5) may have contributed to slightly denser samples relative to the laboratory samples (CF_{DM}=3), making it somewhat easier to attain specification, and even possibly achieving 100% relative compaction. The modified compaction curves from the companion paper (Fig. 3) were nevertheless used to enforce the compaction specification because of the role of the additional coarse material (15.5%) in the DM was not viewed as critical at high CG contents (small gap between 80/20 CG–DM and 100% CG compaction curves represents 20% CF), and at lower CG contents, the role of organic matter and fines on lowering density was viewed to dominate the limited but positive impacts of the additional coarse fraction in the DM. Second, the moisture content estimated by the nuclear density gauge were likely impacted by the hydrogen atoms present in the natural organic matter of the DM

Table 3. Summary of Field Density Testing Results

Blend criteria/units	20/80 CG–DM embankment $\gamma_{d,\max}$ [kN/m^3 (lb/ft^3)]	20/80 Moisture (% by weight)	20/80 $\gamma_{d,\min}$ [kN/m^3 (lb/ft^3)] [%$\gamma_{d,\max}$]	50/50 CG–DM embankment $\gamma_{d,\max}$ [kN/m^3 (lb/ft^3)]	50/50 Moisture (% by weight)	50/50 $\gamma_{d,\min}$ [kN/m^3 (lb/ft^3)] [%$\gamma_{d,\max}$]	80/20 CG–DM embankment $\gamma_{d,\max}$ [kN/m^3 (lb/ft^3)]	80/20 Moisture (% by weight)	80/20 $\gamma_{d,\min}$ [kN/m^3 (lb/ft^3)] [%$\gamma_{d,\max}$]
Specification	15.1 (96.0)	8–14	13.59 (86.4) [90 min.]	16.6 (106.0)	12–18	15.77 (100.70) [95 min.]	18.2 (116.0)	7–13	17.29 (110.2) [95 min.]
Average of all readings	—	—	13.83 (88.7) [92.3]	—	—	15.79 (100.9) [95.1]	—	—	18.15 (115.7) [99.7]
Number of reworked lifts	—	—	2 (5)[a]	—	—	12	—	—	2
Moisture range (%)	—	21.6–32.4	—	—	16.0–23.7	—	—	8.1–13.7	—
Ave. moisture (%)	—	28.32	—	—	19.8	—	—	10.74	—
Standard deviation moisture (%)	—	2.66	—	—	1.60	—	—	1.25	—

Notes: Field moisture contents uncorrected for organic matter content.

[a]Number of reworked lifts prior to reducing compaction criteria from 95 to 90% modified Proctor. All five failures passed 90% *ASTM D1557*.

(Troxler 2001) which misattributes the hydrogen atoms in organic matter to water. Hence, nuclear density gauges may therefore overestimate the soil moisture content and underestimate the dry density of organic soils, the magnitude of which increases with increasing soil organic matter content. Moisture/organic content calibrations for the nuclear density gauge require the collection and analysis of core samples immediately adjacent to the density testing locations, usually with a minimum 24 h turnaround time for results. Due to cost and to avoid construction delays, the need for calibrations was thus evaluated.

Randrup and Lichter (2001) reported that soils having less than 5% organic matter usually produce water content results within 1% of the standardized (oven dried) content when tested by nuclear density methods. While the organic matter content of 29 OH soils from Basin A at Fort Miffin was estimated to be on the order of 14% (Weston 2002), the 50/50 and 80/20 CG–DM blends had organic matter contents (loss on ignition; LOIs) on the order of 5.7 and 2.9%, respectively (Table 4). As such, the nuclear density gauge results were taken to be both accurate and slightly conservative for these two embankments. The 20/80 CG–DM

Table 4. Comparison of Field Density Testing Results to Regional DOT Standards and Other Stabilization Methods

	LOI *D 2974* (% by weight)	Standard compaction *D 698* $\gamma_{d,\max}$ [kN/m^3 (lb/ft^3)]	Standard compaction *D 698* w_{opt} (% by weight)	Modified compaction *D 1557* $\gamma_{d,\max}$ [kN/m^3 (lb/ft^3)]	Modified compaction *D 1557* w_{opt} (% by weight)	This study 90% mod. [kN/m^3 (lb/ft^3)]	This study 95% mod. [kN/m^3 (lb/ft^3)]	PennDOT 97% stan. [kN/m^3 (lb/ft^3)]	NJDOT DelDOT 95% stan. [kN/m^3 (lb/ft^3)]
CG	3.1	17.1 (109.0)	8	18.7 (119.0)	8	—	—	—	—
Blends									
80/20 CG-DM	2.9	17.3 (110.0)	14	18.2 (116.0)	10	16.4 (104.4)	17.3 (110.2)	16.78 (106.70)	16.44 (104.50)
50/50 CG-DM	5.7	14.8 (94.0)	24	16.6 (106.0)	15	14.9 (95.4)	15.8 (100.7)	14.36 (91.18)	14.06 (89.3)
20/80 CG-DM	8.7	11.8 (75.0)	29	15.1 (96.0)	11	13.6 (86.4)	14.3 (91.2)	11.45 (72.75)	11.21 (71.25)
DM	11.0	10.8 (69.0)	39	12.2 (78.0)	29	—	—	10.5 (66.9)	10.3 (65.6)
DM basin A (OH soils)[a]	14.2	11.68 (74.6)	35	12.32 (78.7)	33.4	—	—	11.33 (72.36)	11.10 (70.87)
DM NP CDF (OH soils)[b]	9.7	11.58 (74.0)	36.5	12.83 (82.0)	31	—	—	11.23 (71.78)	11.00 (70.30)
DM (MH soil)+8%PC[c]	8	—	—	11.99 (76.6)	31.5	—	—	—	—

Notes: ASTM test designations shown when relevant. Mod. and stand. denote D1557 and D698 compaction.

[a]Weston (2002); USACE Fort Mifflin.

[b]USACE North Pedricktown CDF, Salem Co., N.J.

[c]Maher (2001); DM classifying as MH soil cured for 6 months with 8% Portland cement (wet basis).

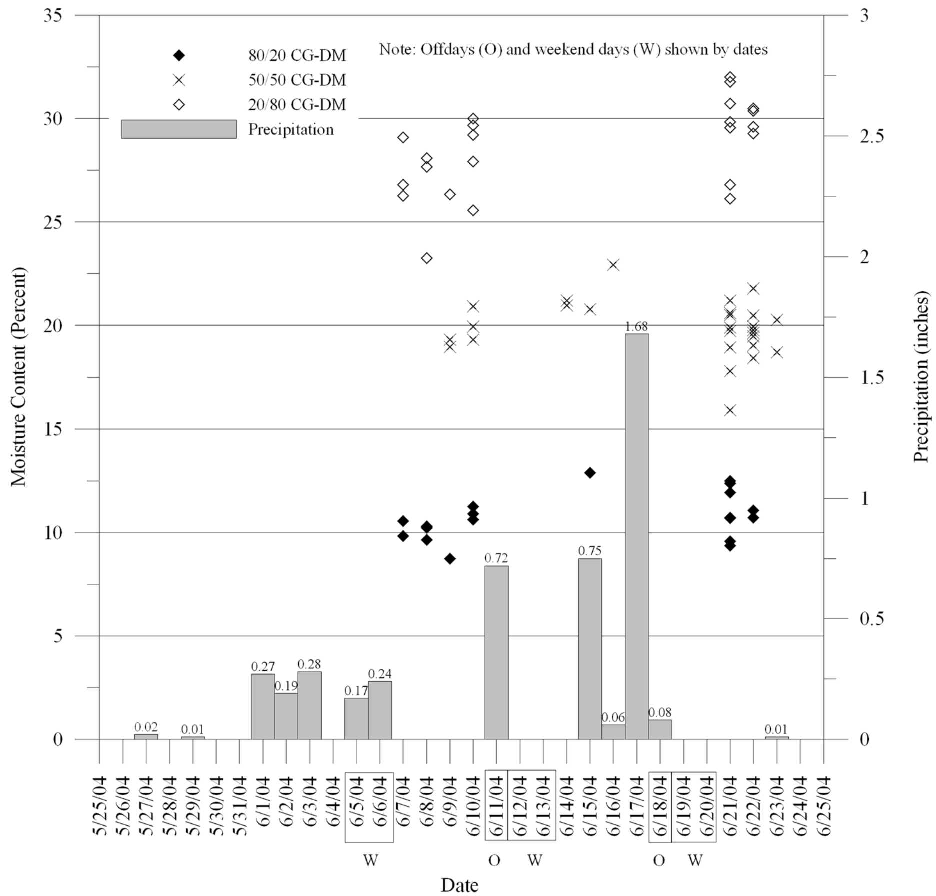

Fig. 4. CG–DM embankment moisture content results versus precipitation

blend contained on the order of 8.7% organic matter, so the corresponding moisture contents and dry density may have been overestimated and underestimated by a few percent, respectively. Calibrations were therefore not pursued. Consequently, the moisture content criteria in the contract specifications could only be used as general guidelines.

The field compaction results are shown in Fig. 3 versus the workday and precipitation data from the Philadelphia International Airport (PA Climatologist 2004), located immediately adjacent to the project site. Fig. 4 presents a similar comparison using the moisture content, wherein the boxed dates in Figs. 3 and 4 denote the off (*O*) and weekend (*W*) days. Fig. 3 indicates that the 80/20 CG–DM embankment routinely exceeded approximately 97.5% modified Proctor compaction with several values in excess of 100% (see qualifying discussion on compaction criteria above). Figs. 3 and 4 also suggest that the 80/20 CG–DM blend is relatively insensitive to moisture conditions and can be easily worked to greater than 95% modified Proctor compaction even during periods of intense rainfall. While it may appear that the concentrated rainfall beginning the week of June 14, 2004 resulted in less percent relative compaction thereafter (Fig. 3), the moisture content of the 80/20 CG–DM blend is relatively consistent (Fig. 4). Therefore, the slight decrease in compacted density is attributed to the lower CG content of the upper lifts of the embankment. By tracking the CG–DM blend stockpile CG contents during the blending operation and matching them which the actual lifts they were used to construct, it was possible to correlate the CG content of each lift to the compaction results, as shown in Fig. 5. Fig. 5 illustrates that there is a minor reduction in the dry density of the upper lifts of the 20/80 and 80/20 CG–DM blend embankments, presumably due to their slightly lower CG contents (close to lower tolerance limit).

The results for the 50/50 CG–DM embankment appeared to scatter around 95% modified Proctor compaction (Fig. 3), requiring a total of 12 lifts (Table 3) to be reworked. This suggests perhaps that a limitation of the compaction equipment (i.e., too light) and/or materials (role of wetness, organic matter) was approached given the: (1) relatively constant CG content of the 50/50 CG–DM blend (Fig. 5), and; (2) relatively stable moisture content despite the quantity of precipitation (Fig. 4). Accordingly, to promote continuous construction, it therefore may be prudent in future applications to slightly reduce the required compaction limit of the 50/50 CG–DM blend to 92.5% of *ASTM D1557*.

The minimum compaction of 95% by *ASTM D1557* initially established for the 20/80 CG–DM embankment was relaxed to 90% after the first two lifts had to be reworked a total of 5 times (Table 3). This suggested that the 20/80 CG–DM blend could not be cost effectively compacted to achieve typical structural fill compaction criteria, i.e., 95% minimum compaction by *ASTM D1557*. Thereafter, two failed lifts occurred relative to the 90% modified compaction criteria, but in every case, the attained densities far exceeded the DOT compaction criteria (95–97% compaction by *ASTM D698*), often taken to be synonymous with general and embankment fill applications. The failures and generally lower compaction results of the 20/80 CG–DM blend occurring after the large rainfall events during the week of June 14, 2004 (Fig. 3) cannot be entirely attributed to moisture conditions

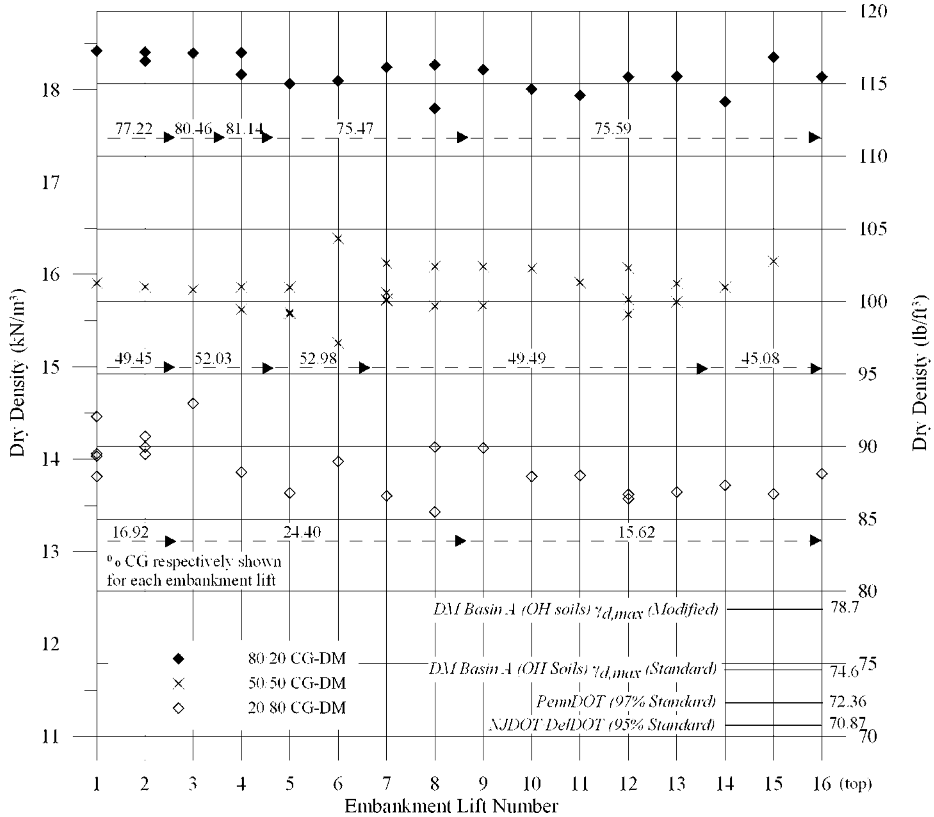

Fig. 5. CG–DM embankment dry density versus embankment lift number

alone, as the top eight lifts of the embankment were lean in CG content.

Plotted for comparison in Fig. 5 are the $\gamma_{d,\max}$ values of DM from Basin A (OH soils only) along with local DOT minimum compaction criteria (DelDOT 2001; NJDOT 2001; PennDOT 2004) for embankment construction based on the use of 100% DM. Fig. 5 illustrates that 20–80% addition of CG to DM resulted in 1.5–5.5 kN/m^3 (10–35 lb/ft^3) increases in the field dry densities above 100% DM. Compared to the CG–DM blend data itself (and not 100% DM), Table 3 indicates that the 20/80 CG–DM blend was compacted to 13.83 kN/m^3 (88.7 lb/ft^3) in the field which exceeded the 11.45 kN/m^3 (72.75 lb/ft^3) required by 97% standard compaction (PennDOT, Table 4). Likewise, the 50/50 CG–DM blend was compacted to 15.79 kN/m^3 (100.9 lb/ft^3) versus the 14.36 kN/m^3 (91.18 lb/ft^3) required by 97% standard compaction (PennDOT, Table 4). And finally, Table 3 shows the 80/20 CG–DM blend was compacted to 18.15 kN/m^3 (115.7 lb/ft^3) versus the 16.78 kN/m^3 (106.70 lb/ft^3) required by 97% standard compaction (Table 4). Hence, whether the comparison is to show improvements by CG addition to 100% DM, or the ability to exceed local DOT specifications based on the actual blend characteristics, the ability to exceed embankment fill criteria (i.e., 95–97% standard compaction) was on the order of 1–3 kN/m^3 (or 6–20 lb/ft^3).

When the blending and compaction results are jointly considered, the enormous impact of the CG on the workability of DM emerges. While the compaction curves (Figs. 2 and 3; Grubb et al. 2006) for the CG–DM blends clearly show substantial reductions in the w_{opt} versus 100% DM, this is of less interest to contractors who are confronted with the stabilization of wet and/or saturated soils in the field, i.e., the drying of soils in the field to obtain the required compaction is the main challenge. Here, again, the benefits of CG addition to DM are clear. The moisture contents of the CG and DM stockpiles are shown in Table 1 with the moisture content of the DM ranging from 23 to 50%. Moreover, the DM stockpiles remained very wet from the frequent precipitation (Fig. 4). Table 2 presents the moisture contents of the CG–DM blends immediately after blending and prior to construction, the only delay being the time required to approve the stockpile. Hence, the moisture content reduction of the 100% DM (39%) was 7.7, 19.28, and 26.6 moisture points for 20, 50, and 80% addition of CG, respectively. As shown in Table 3, the average moisture of the 50/50 and 80/20 CG–DM blends fell within or close to the compaction criteria, whereas the 20/80 CG–DM blend remained on the wet side of optimum but was nevertheless compacted to over 90% modified compaction. In short, essentially dry CG blends out the moisture in wet DM enabling minimum compaction limits to be satisfied without delays or the need for Portland cement/fly ash/lime (PC/FA/lime) addition to eliminate moisture.

Cone Penetrometer Tests

Three locations along the long axis of each embankment were tested according to *ASTM D5778-95* for their CPT resistance. The two outer locations were situated 2 m from the top edge of the embankment while the third location was taken at the center (locations were 7 m apart). Tip resistance (q_t), sleeve friction (F_s), and dynamic pore pressure (U_t) were measured continuously from the top of each embankment to depths of 3.5 m (~12 ft), depending on the undulating but firm ground surface beneath the embankment (denoted by the sudden increases in q_t at depths of 3–3.5 m).

Figs. 6–8 respectively show the tip and frictional resistance

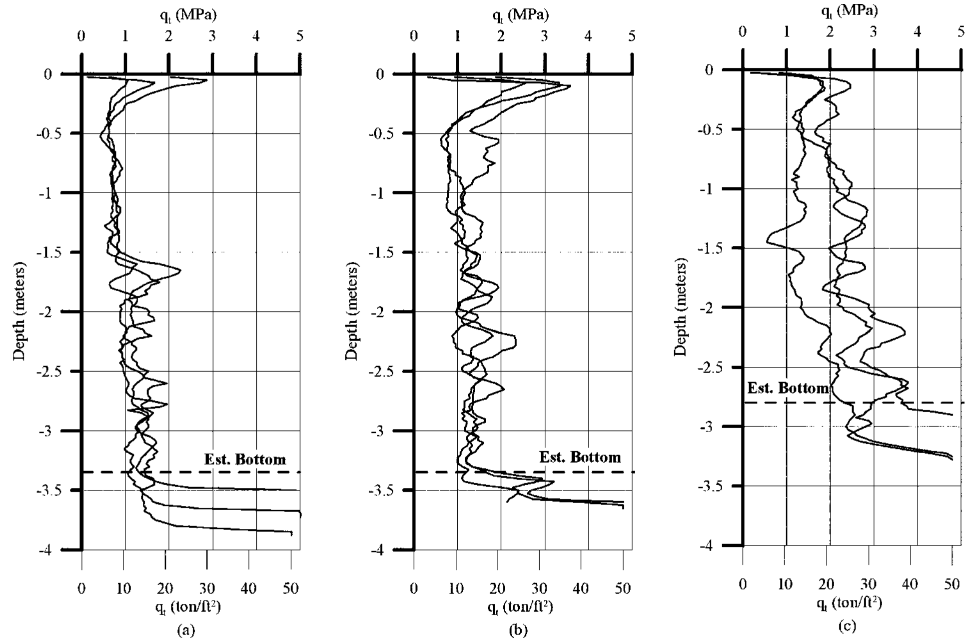

Fig. 6. CPT tip resistance results for (a) 20/80; (b) 50/50, and (c) 80/20 CG–DM embankments

and pore-water pressure results for each embankment. Fig. 6 indicates that a surface crust formed on the 20/80 and 50/50 CG–DM embankments as indicated by the very high tip pressures for the first 0.25 m of depth. The low tip resistance values shown in Fig. 6(a) to a depth of 1.5 m (ignoring the surface crust) are attributed to the low CG content (15.6%) of the top eight lifts (0–1.6 m) of the 20/80 CG–DM embankment (see Fig.5). Aside from these phenomena, the profiles for the 20/80, 50/50, and 80/20 CG–DM embankments are generally characterized by average tip resistances on the order of 1.0, 1.5, and 2.0 MPa for their entire depths, respectively. These q_t values correlate to friction angles of 37–39° based on an empirical relationship that was developed for clean sands, although it is not directly applicable to silty soils (Robertson and Campanella 1983). Nevertheless, the correlated friction values are similar to those measured in the laboratory investigation (Grubb et al. 2006).

Fig. 7 provides a record of the sleeve friction, which is largely related to the cohesive strength of the embankment materials. As expected, the sleeve friction values are proportional to DM content. As shown in Fig. 8, the increasing CG content significantly reduces the pore-water pressure development in the embankments, having by far its largest impact on the 80/20 CG–DM embankment which reflects essentially no pore-water pressure development during testing (except for the lower half of the em-

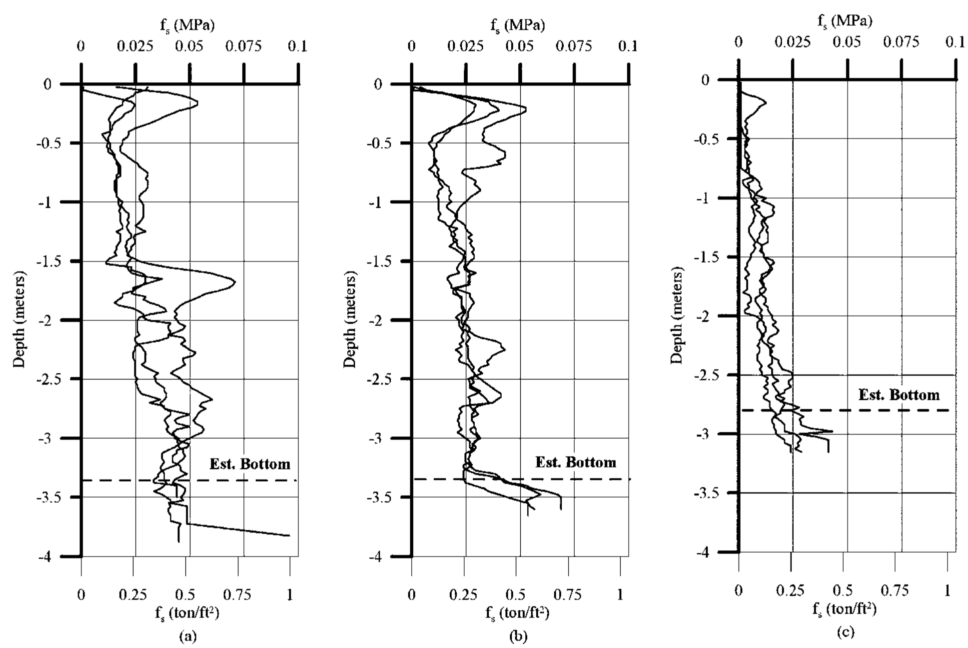

Fig. 7. CPT sleeve friction results for (a) 20/80; (b) 50/50, and (c) 80/20 CG–DM embankments

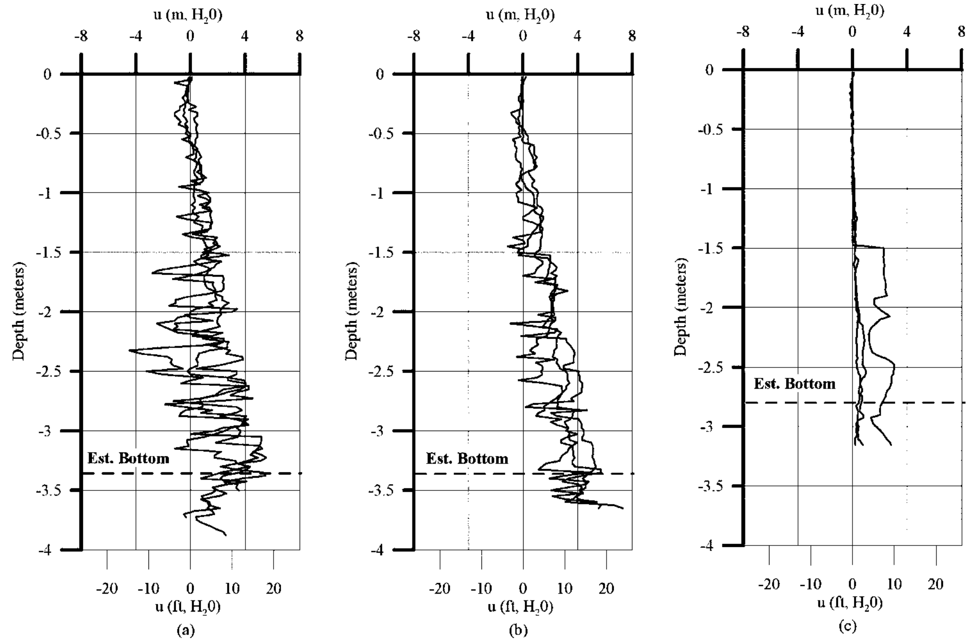

Fig. 8. CPT pore pressure results for (a) 20/80; (b) 50/50, and (c) 80/20 CG–DM embankments

bankment at one location). The CPT pore-water pressure results are consistent with the trends in the hydraulic conductivity of the CG–DM blends (Fig. 8; Grubb et al. 2006).

While no CPT soundings were available on the compacted 100% DM or the DM Basins at USACE Fort Mifflin, several soundings have been performed in the Wilmington Harbor North CDF in areas just inside the dikes. At Wilmington Harbor North (Delaware), the DM classified as MH but its plasticity indices were very similar to the OH DM soils from Basin A at Fort Mifflin. CPT soundings completed to depths of 15 m were characterized by q_t values on the order of 0.3–0.7 MPa (Duffield 2001).

To put the CPT results for the CG–DM blends into perspective with other DM stabilization approaches, Maher (2001) used 8% Type II Portland cement (PC) on a wet basis to stabilize an MH DM from northern New Jersey that had similar physical properties to the DM from Basin A at USACE Fort Mifflin (see Table 4). The repeated disking and aeration of the PC stabilized DM prior to final placement and compaction meant that the PC had essentially no improvement on the density and strength parameters even though the PI was reduced. The stabilized DM was compacted to a minimum 85% modified Proctor compaction with the moisture content limited to a maximum of 50% (moisture values well above the present study). The results of 16 CPT soundings taken at 1 and 12 months after construction of the PC stabilized DM embankments indicated q_t values on the order of 2–3 MPa. These results are comparable to the 80/20 CG–DM embankment. However, the sleeve friction was generally on the order of 0.5–1.0 MPa (Maher 2001), approximately 2–3 times greater than the CG–DM embankments.

Environmental Quality Tests

Dredged materials are regulated (often as residual wastes) by federal and state environmental programs which include the dredging operations, handling, and beneficial use to ensure that DM management approaches are protective of human health and the environment. The toxicity characteristic leaching procedure (TCLP) is used to determine whether wastes must be classified as characteristic hazardous wastes (USEPA 1998), whereas the synthetic precipitation leaching procedure (SPLP; USEPA, 1991) is commonly used to evaluate the waste leaching potential impacts to groundwater.

In Pennsylvania, DM is regulated as a residual waste pursuant to the PA Solid Waste Management Act (SWMA) and various beneficial use permits (BUPs) for industrial byproducts and residual waste have been issued under its authority. For example, PADEP BUP WMGR083 (PADEP 2003) governs the use of DM as a fill material in commercial/industrial settings. In preparing these BUPs, PADEP has often relied on standards that utilize both leaching tests and totals analyses, and other states have taken similar approaches, so the PA approach will be used here for illustrative purposes. In addition, under the PA Land Recycling and Environmental Remediation Standards Act (Act 2; PADEP 1995), PADEP developed cleanup levels for soils at residential and nonresidential properties, the latter of which may include brownfields and portfields sites. In certain instances, PADEP has used such cleanup levels as reference points in setting standards to determine whether materials are subject to regulation as wastes and their potential beneficial use. Also of relevance for the beneficial use of DM is the recently issued "Management of fill" policy or "Clean fill standards" (PADEP 2004), which if DM can meet, it can be used as fill in any application.

Three samples were evaluated as part of this study: 100% CG and DM collected from the active stockpiles; and the 50/50 CG–DM blend collected from the exit conveyor of the pugmill. SPLP and total concentration analyses were performed on the grab samples utilizing USEPA test procedures (USEPA 1983, 1998) for priority pollutant metals, volatile organics, semivolatile organics, pesticides, PCBs (total concentration only), and herbicides (SPLP only). Total concentration analyses for chloride, cyanide, sulfate, and pH were also determined. The relevant test methods are summarized in Tables 5–7 for compounds having detections above the reporting limit and "estimates" for those

Table 5. SPLP Test Results

	USEPA drinking water standard[a]	Hazardous waste designation[b]	PADEP WMGR083 BUP standard[c]	Crushed glass	50/50 CG–DM blend	Dredged material	EPA test method
Metals							
Barium	2.0	100	50.0	0.14	0.11	0.098	200.7
Lead	0.015	5.0	1.25	<0.005	0.009	<0.005	7421
Volatiles							
Acetone	—	—	—	<0.050	0.18	<0.050	1312/8260B
Ethylbenzene	0.7	—	—	0.0074	<0.002	<0.002	1312/8260B
Trichloroethene	0.005	0.5	0.005	0.0027	0.0013	0.0069	1312/8260B
Xylenes (total)	10.0	—	—	0.054	<0.006	<0.006	1312/8260B

Note: All data in milligrams per liter (mg/L), no other SPLP analytes detected. Other EPA test methods included, As (7060), Hg (7470), semivolatile organics (1312/8270C), pesticides (8081A), and herbicides (8151A).

[a]USEPA (1999a).

[b]USEPA (1999b).

[c]PADEP (2003).

quantified but below the detection limits. Nondetects were not included in Tables 5–7 for brevity and clarity of presentation.

For comparative purposes, the SPLP leaching results were compared to: (1) USEPA drinking water standards (USEPA 1999a,b); (2) the USEPA RCRA characteristics for hazardous waste based on TCLP (USEPA 1998); and (3) the PADEP BUP WMGR083 standards. Total concentration "as is" analyses and secondary water quality parameters of the 100% CG, DM and 50/50 CG–DM blend were compared to: (1,2) PADEP Act 2 residential/nonresidential cleanup levels; (3) the PADEP clean fill standards; and (4) the PADEP BUP WMGR083 standards.

The only SPLP analytical result (Table 5) to exceed any regulatory criteria was trichloroethene (TCE). TCE in the SPLP extract from the 100% DM (0.0069 mg/L) exceeded the USEPA drinking water standard and the PADEP BUP standard (both at 0.005 mg/L). However, blending with 50% CG dropped the TCE concentration well below the applicable limits. Trace level concentrations of other constituents were detected at or several orders of magnitude below the applicable regulatory criteria. The metals detected by SPLP were identified previously as constituents in CG (Wartman et al. 2004) and DM (Weston 2002). CG addition to the DM generally resulted in mass reductions in the reported constituent concentrations (for 100% DM), though there are some exceptions.

As expected, a larger number of compounds was detected using total concentration analyses than the SPLP results, as shown in Table 6. There were only two results that were at or exceeded the regulatory criteria, both in the 100% DM sample. Arsenic (16 mg/kg) exceeded the PADEP Act 2 statewide health standard residential criteria and the clean fill standards (both 12 mg/kg), while silver was detected at the PADEP BUP criteria (5.0 mg/kg). The mass reduction effect of the CG addition on the constituents found in 100% DM was more pronounced by the total analyses. The concentrations of metals detected in the 50/50 CG–DM blend were generally found to be approximately half the concentrations of metals in the 100% DM, demonstrating that the DM is the primary source of metals.

Trace levels of volatiles, semivolatiles, pesticides, and PCBs detected in the total concentration analyses were several orders of magnitude below the applicable regulatory criteria (Table 6). Most of the detected substances are commonly associated with urban/industrial environments, and have been historically detected in the CDFs at USACE-Fort Mifflin (Weston 2002). The only unexpected result was bis(2-ethylhexyl)phthalate, a common plasticizer, which was detected at a trace concentration in the 100% CG. The occurrence of this constituent attributed to: (1) plastic fragments from bottle lids/coatings in the recycling stream; or (2) common laboratory/field contamination resulting from sampling (gloves) and sample processing. The impacts of CG blending on the secondary parameters that were evaluated were also apparent (Table 7), including the pH buffering of the slightly acidic DM. Overall, while the environmental data sets here are obviously small, they do suggest that CG will have positive impacts on the furnished properties of CG–DM blends.

Economics

All discussion of economics in this section has been normalized to the unit cost per in situ cubic meter (yd^3) of DM [i.e., the excavated volume of DM from the CDF (Table 8, Columns 1 and 2) or the waterway (Table 8, Column 3)]. Processing costs are normalized for CG–DM blends similar to a "quarrylike" operation since the key difference between Columns 2 and 3 relates to how the DM is ultimately acquired (mining from a CDF or unloading from a barge) and processed. Postblending transportation and site embankment/fill construction costs are explicitly excluded, as these are regional and project specific. All data are presented in United States dollars.

The first column in Table 8 summarizes the costs associated with the pugmilling of CG–DM blends based on the Fort Mifflin demonstration project quantity of approximately 3,058 m^3 (4,000 yd^3). These economics are based on using a trailer-mounted pugmill rated at approximately 1,500 m^3/day (200 t/h, when operated) excluding the excavation of the DM from the CDF and the CG supplies, as both were provided by the project sponsors. The high unit price for the field demonstration is skewed by the high mobilization cost.

To compare the CG–DM approach with the conventional solidification/stabilization (S/S) processes employing PC, FA, and quicklime to enhance the geo-environmental characteristics of DM, it is important to factor in the differences of the DM at the time of processing. The CG–DM blending approach described herein indirectly benefits from existing CDF dewatering operations and crust management activities that are bypassed by "wet" S/S processes. For proper economic comparison of stabilization techniques, the cost of full-scale CDF crust management and re-excavation operations must be added to the CG–DM blending operations at an estimated \$5.23/m^3 (\$4.00/yd^3) as shown in

Table 6. Total Analyte Concentration Testing Results

	PADEP ACT 2 residential[a]	PADEP ACT 2 nonresidential[a]	PADEP clean fill[b]	PADEP WMGR083 BUP standard[c]	Crushed glass	50/50 CG–DM blend	Dredged material	EPA test method
Metals								
Arsenic	12	53	12	41	<8.0	11	16	6010B
Beryllium	440	5,600	320	2	<0.2	0.61	1.3	6010B
Cadmium	47	210	38	20	<1.0	2.2	4.8	6010B
Chromium	190,000	190,000	190,000	1,000	<2.5	57	99	6010B
Copper	8,200	100,000	8,200	700	3.2	82	110	6010B
Lead	500	1,000	450	200	5.9	89	150	6010B
Mercury	66	840	10	20	<0.1	0.389	0.541	7471A
Nickel	4,400	56,000	650	200	<2.5	21	36	6010B
Silver	1,100	14,000	84	5	<2.5	<2.5	5.0	6010B
Zinc	66,000	190,000	12,000	1,000	71	320	540	6010B
Volatiles								
Toluene	7,600	10,000	44	—	<0.002	0.0057	<0.0027	8260B
Semivolatiles								
Benzo(a)anthracene	25	110	25	6	<1.3	0.12	<1.3	8270C
Benzo(a)pyrene	2.5	11	2.5	1.8	<1.3	0.12	<1.3	8270C
Benzo(a)flouranthene	25	110	25	6	<1.3	0.16	<1.3	8270C
Bis(2)ethylhexylphthalate	1,300	5,700	130	300	9.2	<0.33	<4.4	8270C
Chrysene	2,500	11,000	230	500	<1.3	0.12	<1.3	8270C
Flouranthene	8,800	110,000	3,200	400	<1.3	0.21	<1.3	8270C
Pyrene	6,600	84,000	2,200	300	<1.3	0.14	<1.3	8270C
Pesticides/PCBs								
Aldrin	1.1	4.7	0.10	0.3	<0.002	0.0022	<0.0027	8081A
Alpha-BHC	2.8	13	0.046	0.71	<0.002	0.002	<0.0027	8081A
Chlordane (technical)	51	230	49	—	<0.04	0.028	<0.054	8081A
Chlordane (gamma)	51	230	49	—	<0.004	0.0053	<0.0054	8081A
4,4′-DDE	53	230	41	10	<0.004	0.0035	<0.0054	8081A
4,4′-DDT	53	230	53	10	<0.012	<0.006	0.03	8081A
PCB-1260	30	130	30	4	<0.1	0.1	0.17	8082

Note: All data in milligrams per kilogram (mg/kg) dry weight, no other analytes detected. Other EPA test methods included, T1 (7841).
[a]PADEP (1995).
[b]PADEP (2004).
[c]PADEP (2003).

Table 8 (Column 2). Alternatively, traditional *S/S* processes utilized for full-scale processing of DM generated from mechanical dredging operations in harbors such as the New York/New Jersey Harbor use PC/FA/lime at \$12.43/m^3 (\$9.50/yd^3) to stabilize slurried and/or wet DM directly off-loaded from barges fresh from the actual dredging site (Table 8, Column 3).

The amortization (mobilization) of setup costs for a fixed-base processing (pugmill) plant located adjacent to an existing CDF facility in the New Jersey/New York Harbor area (New York City metro area) with a minimum throughput of approximately 382,222 m^3/year (500,000 yd^3/year) corresponds to a mobilization far less than the pilot study as shown in Table 8. The fixed plant would have significantly increased efficiencies and economies of scale over the mobile operation, corresponding to considerable reductions in labor and equipment costs, while the indirect and miscellaneous costs would be roughly cut by 50% based on

Table 7. Secondary Environmental Parameter Testing Results (Total Concentrations)

	PADEP ACT 2 residential[a]	PADEP ACT 2 nonresidential[a]	PADEP clean fill[b]	PADEP WMGR083 BUP standard[c]	Crushed glass	50/50 CG–DM blend	Dredged material	EPA test method
Parameter								
Chloride	—	—	—	—	134	<50	<50	325.3
Sulfate (SO4)	—	—	—	—	<56.2	1,010	1,050	375.4
Cyanide (total)	4,400	56,000	200 (free)	20 (reactive)	0.364	0.57	5.03	9012A
pH (pH units)	—	—	—	5.5–9.5	8.66	6.66	6.18	9045B

Note: All data in milligrams per kilogram (mg/kg) dry weight, except pH.
[a]PADEP (1995).
[b]PADEP (2004).
[c]PADEP (2003).

the industry experience of the writers. It is also anticipated that long-term agreements with CG suppliers could yield the equivalent of a small "processing" or "tipping" fee, much less than potential landfill disposal costs (\$30–\$50/t). Therefore, the projected costs of a full-scale CG–DM blending operation, including the cost of CDF operations are anticipated to be on the order of \$11.11–\$13.73/m^3 (\$8.50–\$10.50/yd^3).

Compared to the CG–DM approach, essentially the same processing plant could be used for traditional *S/S* processes employing PC/FA/lime, the main difference being that additional feed silos, processing, and feedstock/conveyor metering equipment may be required. The plant could be sited in the same location or within a reasonable distance from where dredging is performed, as long as sufficient areas exist to allow for curing of the stabilized DM. The most significant cost of the *S/S* process is associated with the PC/FA/lime materials themselves (\$12.43/m^3 or \$9.50/yd^3), their principal functions being dewatering and immobilization of hazardous constituents. Hence, PC/FA/lime stabilization approaches average on the order of \$26.16–\$34.01/m^3 (\$20.00–\$26.00/yd^3) of processed DM material for full-scale operations in a major metropolitan region where upland disposal is required.

To put the CG–DM blend production costs into their proper perspective, two market segments need to be considered—the DM management (dredging and disposal) and urban fill markets.

The nationwide dredging costs for USACE for FY 2004 averaged \$4.30/m^3 (\$3.29/yd^3) (USACE 2005). This average includes all forms of dredging in federal navigation channels and is obviously skewed downwards from the extensive sidecasting and near channel disposal maintenance dredging activities which can be on the order of \$0.60/yd^3 (USACE 2005). However, regionally in Boston, New York City, and Los Angeles, the prices to maintain federal navigation channels can be much higher than the national average. Dredging activities in the New York City metro area, for example, are on the order of \$40–55/yd^3 due to the requirements for upland disposal, which can be more than half of the total cost (Mr. Scott Douglas, Personal Communication 2005) and as shown in Table 8 (Column 3). Private berth dredging from the main navigation channel to individual berths may be on the order of 5–10 times the USACE national average, or as high as the New York City metro prices. Accordingly, CG–DM blending has the potential to reduce total dredging costs in a region like the New York City metro area by 25%. Here, CG can be readily available, as New York City generates on the order of 800 t/day of curbside collected glass (Mr. Steve Sands, personal communication, 2005). For additional perspective, the contractor for the City of Philadelphia processes on the order of 2,300 t CG/month from curbside collection only. However, this excludes glass generated by bars and restaurants, which if captured and long-term beneficial use markets were established, the CG recycling rates for Philadelphia could approach 10,000 t/month (Mr. Herbert Northrop, personal communication, 2005).

On the other side of the equation is the cost of conventional fill in the urban market, which in metropolitan coastal cities can be on the order of \$13.06–\$26.16/m^3 (\$10–\$20/yd^3), a major cost component being the transportation of fill imported from outlying areas. Hence, the purchase cost of CG–DM blends (Table 8) is on the lower end of this scale, which allows local use of CG–DM blends to be attractive (i.e., within the city) when nominal transportation costs are considered. The joint economics of the dredging challenge, landfill disposal prices of CG if not beneficially used, and the urban fill market prices therefore suggest that CG–DM blending operations in coastal cities have the potential to lead to significant overall savings across several industry segments even when modest profits for blending operations are accounted for.

Discussion

Tables 5–7 illustrate that the 50/50 CG-DM blend satisfies the most stringent criteria for beneficial use in Pennsylvania (residential limits, BUP levels, and clean fill standards) by several orders of magnitude in many cases (comparison to other state criteria may provide similar results). Moreover, additional protection is often provided by guidelines for DM beneficial reuse in earth construction. For example, these guidelines also typically require the use of a 1 m (3 ft) thick clean cover soil to isolate the DM from direct contact exposure. This requirement is easily accounted for by the landscaping and design requirements of most roadway subgrades, engineered fills, and embankments. DM materials, including the CG–DM blends themselves, tend to slightly pump, and while strong enough, this characteristic does not make them attractive for use immediately below concrete slabs or asphalt paving without an overlying veneer of competent (stiffer) soils. This enables CG–DM blends to serve as the bulk fill in most (and deep) areas, and limits the use of more expensive quarried

Table 8. CG-DM Blending Economics

	Field scale CG-DM[a]		Full scale CG-DM[b]		Full scale PC/FA/lime[b]	
	(\$/m^3)	(\$/yd^3)	(\$/m^3)	(\$/yd^3)	(\$/m^3)	(\$/yd^3)
CDF operations	—	—	5.23	4.00	—	—
Mobilization	9.81	7.50	0.65	0.50	1.31	1.00
Equipment	10.46	8.00	3.92	3.00	5.89	4.50
Labor	10.46	8.00	6.54	5.00	7.85	6.00
Indirect/Misc.	2.61	2.00	1.31	1.00	1.31	1.00
Crushed glass	—	—	⟨3.92–6.54⟩	⟨3.00–5.00⟩	—	—
10% PC/FA/lime	—	—	—	—	12.43	9.50
Total	33.24	25.5	11.11–13.73	8.5–10.50	28.79	22.00

[a]Portable pugmill rated at ~1,500 m^3/day (200 t/h) throughput (not operated continuously). Basis: total blending production of ~3,050 m^3 (4,000 yd^3).
[b]Fixed pugmill rated at ~6,000 m^3/day (800 t/h) throughput. Basis: minimum throughput of 382,222 m^3/year (500,000 yd^3/year) in New York City metro area.

aggregates and select fills to high resilient modulus areas only, and virgin fill/topsoil to landscaping.

While the geotechnical improvements in DM by CG addition are significant, it could be argued that CG merely dilutes the contamination of DM and no real benefit exists in terms of environmental protection. The key focus of CG addition is to improve the structural performance of DM, not environmental dilution. The commercial use of CG–DM blends as viable geotechnical products deserves attention because the approach addresses several pragmatic realities that currently hold sway: (1) the contingent liability (landfill disposal) associated with CG and DM that cannot be beneficially used is on the order of \$50–\$70/t; (2) fills using CG–DM blends stand to solve the beneficial use challenges associated with both materials, allowing the possibility to undertake urban fill construction with a 100% recycled material (CG and DM) that is actually cheaper than virgin fill materials; (3) CG–DM blends are likely to be cleaner than most soils in urban environments and BUPs provide additional controls to limit use primarily to industrial and commercial settings; (4) the use of CG–DM blends for construction has several advantages over other DM stabilization techniques for earthwork in terms of strategy, workability, permitting and cost; and (5) these features of the CG–DM blends and their characteristics have the potential to foster renewable capacity approaches to be practiced at CDFs on a large scale, thus avoiding the enormous costs required to site, permit, and construct new CDFs (tens to hundreds of millions of dollars).

The mining of DM from existing CDFs takes advantage of the natural particle distribution and dewatering processes, allowing the excavation and hauling of DM from CDFs to a pugmilling operation to be both reliable and predictable. As many of these CDFs are characterized both geotechnically and environmentally by their operators (i.e., USACE, port authorities, dredging companies, etc.), there are likely to be few surprises during CG–DM blending operations unlike the wet-phase blending processes of fresh DM. That the CDFs have been characterized also improves the level of comfort of regulators when approving the necessary BUPs, and the acceptance of the CG–DM blend by the site owner or end user (DOT, developer, etc.). Also, wet-based blending operations require both specialized blending and additional placement equipment to facilitate disking and drying of the DM prior to any type of compaction or construction. The influence of the CG on the workability of the DM is immediate, allowing it to be placed and compacted without predrying, curing, or stockpiling.

The overall framework and its potential cost effectiveness lends itself to the possibility that the USEPA, state environmental regulatory agencies, and USACE can reasonably justify and thereby establish a streamlined beneficial use process for the use of CG–DM blends in urban construction, the details of which could be no more sophisticated than requiring that the BUP terms and conditions accompany the bill of lading for the CG–DM blend (similar to the documentation provided with the purchase of DOT-approved aggregates). The remaining obstacle to such beneficial use that will need to be addressed is the federal definition of "real estate" of DM which currently prevents it from being transferred at zero cost to private entities despite the contingent liability that long-term DM disposal and management poses to USACE. This, coupled with the fact that developers, engineers, and constructors perceive DM classifying as ML, MH, OH, and CH soils as "negatively valued" from a geotechnical, environmental, and regulatory perspective, is a major impediment to DM recycling.

Conclusions

Three crushed glass–dredged material (CG–DM) blends were prepared and evaluated in the field to explore the feasibility of using CG–DM blends in general, embankment, and structural fill applications. Using standard construction equipment, the field densification achieved by blending as little as 20% CG with DM, was to a degree, unprecedented compared to conventional geoenvironmental stabilization techniques for DM. In short, no bulking of DM resulted with 20% CG as the mass blending directly corresponds to the unit weight increase (18 $\mathrm{lb/ft^3}$). The significant geotechnical improvements of DM from CG addition coupled with the corresponding reduction in environmental constituent leaching provide realistic opportunities for the large scale beneficial use of both CG and DM in the urban environment where the reliance on groundwater as a drinking water supply is not a primary concern. CG–DM blending offers substantial beneficial use opportunities and savings over conventional disposal while also remaining within the current pricing constraints of the urban fill market for coastal metropolitan cities. It is hoped that this recognition will serve as the catalyst for the USEPA, state Departments of the Environment, USACE, the geotechnical and construction communities, and developers to jointly and realistically forge a new paradigm for enabling recycled materials reuse of this kind.

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Notation

The following symbols are used in this paper:

F_s = cone penetrometer sleeve friction resistance (MPa);

q_t = cone penetrometer tip resistance (MPa);

U_t = cone penetrometer dynamic pore pressure (MPa);

w_{opt} = optimum water content (%);

$\gamma_{d,\max}$ = maximum dry density (kN/m^3); and

% by weight = percent by weight.

References

American Society for Testing and Materials (ASTM). (1995). "Standard test method for performing electronic friction cone and piezocone penetration testing of soils." *ASTM D5778-95*, West Conshohocken, Pa.

American Society for Testing and Materials (ASTM). (1996). "Standard test method for density of soil and soil-aggregate in place by nuclear methods (shallow depth)." *ASTM D2922-96*, West Conshohocken, Pa.

American Society for Testing and Materials (ASTM). (1998). "Standard test method for particle size analysis of soils." *ASTM D422-63 (Re-approved 1998)*, West Conshohocken, Pa.

American Society for Testing and Materials (ASTM). (2000a). "Standard test method for laboratory compaction characteristics of soil using modified effort." *ASTM D1557-00*, West Conshohocken, Pa.

American Society for Testing and Materials (ASTM). (2000b). "Standard test method for laboratory compaction characteristics of soil using standard effort." *ASTM D698-00*, West Conshohocken, Pa.

Delaware Department of Transportation (DelDOT). (2001). "Standard specifications for road and bridge construction." Dover, De.

Duffield Associates. (2001). "Subsurface investigation: Wilmington Harbor North, dredged material confined disposal facility." *Contract No. DACW61-98-D-008, Task No. 27, Prepared for US Corps of Engineers-Philadelphia District*, Philadelphia.

Grubb, D. G., Gallagher, P. M., Wartman, J., Carnivale, M., III, and Liu, Y. (2006). "Laboratory evaluation of crushed glass–dredged material blends." *J. Geotech. Geoenviron. Eng.* 132(5), 562-576.

Maher, A. (2001). "Final geotechnical report: OENJ/NJDOT roadway embankment pilot project at parcel G of the OENJ Redevelopment Site, Elizabeth, Union County, New Jersey." *Rep. Prepared for NJ Maritime Resources, NJ Department of Transportation, Sadat Associates and OENJ Corp*.

New Jersey Department of Transportation (NJDOT). (2001). "Standard specifications for road and bridge construction." Trenton, N.J.

PA State Climatologist (2004). "Hourly observations of PHL Weather Station, June 2004." The Pennsylvania State Climatologist, College of Earth and Mineral Sciences, The Pennsylvania State Univ., State College, Pa. ⟨http://pasc.met.psu.edu/PA_Climatologist/phl/phljunh04.html⟩.

Pennsylvania Dept. of Environmental Protection (PADEP). (1995). "Land recycling and environmental remediation standards act, Act 2 of 1995." Harrisburg, Pa.

Pennsylvania Department of Environmental Protection (PADEP). (2003). "Bureau of Waste Management, Special Conditions General Permit WMGR083." Harrisburg, Pa.

Pennsylvania Department of Environmental Protection (PADEP). (2004). "Management of Fill." *Document No. 258-2182-77*, Bureau of Land Recycling and Waste Management, Harrisburg, Pa. http://164.156.71.80/WXOD.aspx?fs =2087d8407c0e0000800005da000005da&ft=1⟩.

Pennsylvania Department of Transportation (PennDOT). (1995). "Pennsylvania Test Method No. 1: Method of test for probability sampling." *Field test manual, Publication 19/1995*, Harrisburg, Pa.

Pennsylvania Department of Transportation (PennDOT). (2004). "Specification." *Publication 408/2003 (Change 2, Effective 10/1/04)*, Harrisburg, Pa.

Randrup, T. B., and Lichter, J. M. (2001). "Measuring soil compaction on construction sites: A review of surface nuclear gauges and penetrometers." *J. Arboriculture*, 27(3), 109–117.

Robertson, P. K., and Campanella, R. G. (1983). "Interpretation of cone penetrometer tests, Part I: Sand." *Can. Geotech. J.*, 20(4), 718–733.

Science Applications International Corporation (SAIC). (2002). "Geotechnical investigation report, Fort Mifflin Disposal Area, Cells B and C, Philadelphia, PA." *Contract No. DACW61-00-D-007, Task No. 14, Rep. Prepared for: US Corps of Engineers-Philadelphia District, Philadelphia, Pa*, Exton, Pa.

Troxler Electronic Laboratories, Inc. (2001). "Application brief: The importance of the application of necessary moisture correction factors to field compaction tests made with nuclear moisture gauges." Research Triangle Park, N.C.

U.S. Army Corps of Engineers (USACE). (2005). "Navigation data center: FY 2004 Analysis of dredging costs." *CEIWR-NA*, Alexandria, Va ⟨http://www.iwr.usace.army.mil/ndc/dredge/dredge.htm⟩ (revised 5/26/2005).

U.S. Environmental Protection Agency (USEPA). (1983). "Methods for chemical analysis of water and wastes." *EPA-600/4/79-020*, Cincinnati.

U.S. Environmental Protection Agency (USEPA). (1991). "Synthetic precipitation leaching procedure (SPLP)." *Federal Register*, 1312(No. 55; March 29), 11798, Washington, DC.

U.S. Environmental Protection Agency (USEPA). (1998). *Test methods for evaluating solid wastes, Physical/chemical methods*, 3rd Ed., Washington, D.C.

U.S. Environmental Protection Agency (USEPA). (1999a). "National primary drinking water standards." *EPA-F-94-001*, Washington, D.C.

U.S. Environmental Protection Agency (USEPA). (1999b). "Toxicity characteristic." *Code of Federal Regulations*, *40CFR261.24*.

Wartman, J., Grubb, D. G., and Nasim, A. S. M. (2004). "Select engineering characteristics of crushed glass." *J. Mater. Civ. Eng.*, 16(6), 526–539.

Weston Inc. (2002). "Dredged material characterization report, Fort Mifflin Confined Disposal Facility—Area A, Philadelphia, Pennsylvania." *Rep. Prepared for Sunoco, Inc., Philadelphia, Pa*, West Chester, Pa.