Select Engineering Characteristics of Crushed Glass

Joseph Wartman, M.ASCE1; Dennis G. Grubb, M.ASCE2; and A. S. M. Nasim3

Abstract: Select engineering characteristics of crushed glass produced using two processing techniques (crushing versus screening) to an American Society of State Highway and Transportation Officials No. 10 gradation were experimentally evaluated. The crushed glass samples were classified as well graded sands with gravel (SW) and exhibited excellent strength and workability characteristics. The low specific gravity (2.49) contributed to crushed glass having compacted maximum dry densities on the order of 16.6–16.8 and 17.5–18.3 kN/m3 by the standard and modified Proctor compaction tests, respectively. Direct shear friction angles were measured between 47 and 62° at normal stresses ranging from 0 to 200 kPa. Friction angles obtained by drained triaxial shear were on the order of 48° for similar stress ranges. Measured hydraulic conductivities were on the order of 1–6 × 10−4 cm/s. The results indicate that crushed glass is a readily available, freely draining, environmentally clean, relatively low cost material whose engineering performance properties generally equal or exceed those of most natural aggregates. Despite these favorable characteristics, there are many real and perceived barriers to increasing the beneficial use of crushed glass, and key examples are provided in an effort to illustrate these unnecessary barriers.

DOI: 10.1061/(ASCE)0899-1561(2004)16:6(526)

CE Database subject headings: Glass; Recycling; Material properties; Aggregates.

Introduction

In 1998, an estimated 11 million t of glass entered the waste stream but only 29% of this material was recycled (USEPA 2000). In other words, 7.8 million t went into landfills, seemingly defeating the purpose of curbside collection and the investments of environmental agencies to improve recycling on the collection end. While regulations, laws, and public pressure drive the collection of recyclables, the identification and development of secondary markets for glass, however, is often beyond the influence of environmental agencies.

This paper focuses on the geotechnical characteristics and factors limiting the beneficial use of two general classes of glass that enter the waste stream and landfills: glass cullet and waste industrial glass. Glass cullet, at least in the State of Pennsylvania is defined as “postconsumer material” comprised of the mixed colored glass fragments resulting from the breakage of glass containers (predominantly food, juice, beer, and liquor bottles) that cannot be reused by bottle manufacturers. Occasionally, glass cullet will contain fragments of broken ceramics (coffee mugs, china plates, pottery) though these are not viewed to compromise the overall geotechnical performance of crushed glass. Waste industrial glass includes such materials as broken, obsolete, and/or off-specification glass from the manufacturing of plate, window, and analytical glassware, etc., but is generally considered to exclude glass derived from automobiles, lead crystal, TV monitors, lighting fixtures, and electronics applications due to their composition and coatings. Waste industrial glass is often regulated as residual waste, whereas there are frequently no regulatory constraints placed on glass cullet. Crushed glass comprised of glass cullet and/or waste industrial glass is virtually identical in every respect, and both must be crushed to provide consistent products or commonly accepted gradations such as those recognized by the American Association for State and Highway Transportation Officials (AASHTO) or other organizations.

Part of the motivation for undertaking this study is that crushed glass could be quite valuable on the local scale because a controlling cost of many civil engineering applications and construction materials is the transportation. Crushed glass passing the 9.5 mm (3/8 in.) sieve closely resembles natural or quarried aggregates and does not retain the remnant shape of the original container or application shape, unless one or more of the dimensions is smaller than the sieve opening. Therefore, while crushed glass is perceived to have many strength and drainage applications (Table 1), its reuse potential is hindered by the fact that there is limited knowledge concerning its engineering parameters. In addition, the engineering parameters have been perceived to vary on a supplier by supplier basis depending on the processing equipment used to control the gradation of the crushed glass. This work is an effort to bridge these information gaps.

Previous Studies

Most of the previous research on construction applications of crushed glass has pertained to its use in concrete or asphalt paving materials. Many of these studies have investigated the reactions between silica contained in the glass and alkalis in cement pastes [i.e., alkali–silica reaction or (ASR)], which has a deleterious ef-
effect on concrete quality (e.g., Schmidt and Saia 1963; Johnston 1974; Figg 1981; Polley et al. 1998; and Dyer and Dhir 2001). Studies on glass-amended asphalt mixtures, sometimes termed “glasphalt,” have typically focused on asphalt debonding or “stripping” from the glass aggregate (e.g., Malisch et al. 1975; Day and Schaffer 1989; Chesner 1992; FHWA 1998).

Several researchers have studied the engineering properties of soil-crushed glass blends and/or unblended crushed glass. Dames & Moore (1993) performed a series of physical property, compaction, and strength tests to study the effect of crushed glass content on the properties of soil-crushed glass blends. The crushed glass used in the study was field processed using conventional crushing equipment to 6.3 and 19.5 mm minus gradations. The glass was blended with two processed soils, consisting of either a 25.4 mm minus gravelly sand, or a 31.8 mm minus crushed rock. A variety of geotechnical tests were conducted on blended specimens having crushed glass contents of 15 and 50%. Additionally, select tests were performed on the unblended soil and crushed glass specimens. The results indicated that the crushed glass had a specific gravity of about 2.5, standard and modified Proctor compaction maximum densities of about 16.2 and 18.1 kN/m³, respectively, Los Angeles abrasion wear values in the range of 30–42%, and direct shear internal friction values of about 51°. Dames & Moore (1993) concluded that in general, the addition of crushed glass had no negative impact on the properties of the two soils considered in the study. Shin and Sonntag (1994) summarized the Dames & Moore study indicating that crushed glass is an excellent supplement or replacement for natural aggregates in many construction applications. Henry and Morin (1997) evaluated the frost susceptibility of crushed glass (−14 mm) and two soil-crushed glass blends using ASTM D5918 (ASTM 1996a). They concluded that crushed glass had a negligible to very low frost susceptibility, and that the addition of crushed glass to the soil did not increase its frost susceptibility. Hagerty et al. (1993) studied the behavior of clean, laboratory processed crushed glass (<0.95 mm), determining that highly angular materials such as crushed glass experience more particle crushing under one-dimensional high-stress loads than similar, but less angular materials (e.g., glass beads).

### Experimental Study

#### Materials

Representative samples of crushed glass were collected from two suppliers. Samples were placed in plastic 210 L drums and were sealed and shipped to Drexel Univ. Figs. 1 and 2 show representative “as-received” samples of the crushed glass from Suppliers I and II, respectively.

Supplier I is a commercial quarry and aggregate supplier located in southeastern Pennsylvania. A secondary business effort involves the collection, stockpiling, processing, and resale of glass materials from local recycling organizations and nearby in-

<table>
<thead>
<tr>
<th>Structural applications</th>
<th>Drainage applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base course</td>
<td>Foundation drainage</td>
</tr>
<tr>
<td>Subbase</td>
<td>Drainage blankets</td>
</tr>
<tr>
<td>Embankments</td>
<td>French/interceptor drains</td>
</tr>
<tr>
<td>Structural fill</td>
<td>Well packing media</td>
</tr>
<tr>
<td>Nonstructural fill</td>
<td>Septic field media</td>
</tr>
<tr>
<td>Utility bedding and backfill</td>
<td>Leachate collection media</td>
</tr>
<tr>
<td>Retaining wall backfill</td>
<td>Sand filters (wastewater)</td>
</tr>
<tr>
<td>Antiskid Material</td>
<td>Soil vapor extraction media</td>
</tr>
<tr>
<td>Alternative daily landfill cover</td>
<td></td>
</tr>
</tbody>
</table>

**Table 1. Anticipated Uses of Crushed Glass**

![Fig. 1. Crushed glass from Supplier I. Inset photograph shows a closeup of the material (scale in cm)](scale in cm)
A series of laboratory tests were performed to evaluate the basic physical properties of the crushed glass, including the “as-received” water and debris content, specific gravity, grain size distribution, and minimum and maximum density. The physical properties of the crushed glass samples and relevant test protocols are summarized in Table 2. The reported water contents are average values based on six tests performed on specimens obtained from different locations in the bulk shipping containers. There was relatively little variation in water content between specimens from each supplier.

Gravimetric debris content tests were performed on the crushed glass. For each supplier, three 2 kg bulk specimens were collected from different locations within the bulk shipping container, oven dried at 46 °C for 24 h, weighed, and then evenly spread out in a flat aluminum pan. Debris (nonglass materials, e.g., bottle caps, labels, plastic tops, etc.) was visually identified and manually removed. The debris content was computed as the dry weight of debris divided by the dry weight of crushed glass. The debris contents reported in Table 2 are averaged over triplicate specimens.

Specific gravity tests on the crushed glass yielded values of 2.48 and 2.49 for Suppliers I and II, respectively. These values are consistent with the values of 2.49–2.52 reported by FHWA (1998), and are about 10–15% less than those of most natural aggregates (Lambe and Whitman 1969). Minimum and maximum density tests were performed, and the reported average values (Table 2) are based on a minimum of four specimens from each supplier.

A series of sieve analyses were conducted on specimens from
Table 2. Summary of Physical and Engineering Properties of Crushed Glass

<table>
<thead>
<tr>
<th>Test/Index</th>
<th>Supplier I</th>
<th>Supplier II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water content (%)</td>
<td>2.36</td>
<td>4.22</td>
</tr>
<tr>
<td>[range]</td>
<td>[2.03–2.60]</td>
<td>[3.49–5.32]</td>
</tr>
<tr>
<td>Debris content (%)</td>
<td>0.34</td>
<td>1.82</td>
</tr>
<tr>
<td>[range]</td>
<td>[0.0–0.75]</td>
<td>[0.62–3.41]</td>
</tr>
<tr>
<td>Specific gravity ($G_s$)</td>
<td>2.48</td>
<td>2.49</td>
</tr>
<tr>
<td>[range]</td>
<td>[1.14–1.16]</td>
<td>[1.23–1.30]</td>
</tr>
<tr>
<td>Maximum density (g/cm³)</td>
<td>1.79</td>
<td>1.74</td>
</tr>
<tr>
<td>[range]</td>
<td>[1.77–1.80]</td>
<td>[1.72–1.75]</td>
</tr>
<tr>
<td>Median grain size $D_{50}$ (mm)</td>
<td>2.24</td>
<td>3.0</td>
</tr>
<tr>
<td>[range]</td>
<td>[1.85–2.62]</td>
<td>[2.70–3.30]</td>
</tr>
<tr>
<td>Coefficient of uniformity, $C_u$</td>
<td>6.2</td>
<td>7.2</td>
</tr>
<tr>
<td>[range]</td>
<td>[4.3–10.0]</td>
<td>[5.4–7.0]</td>
</tr>
<tr>
<td>Sand content (0.075–4.75 mm) (%)</td>
<td>91.3</td>
<td>70.0</td>
</tr>
<tr>
<td>[range]</td>
<td>[89.5–93.0]</td>
<td>[66.5–74.0]</td>
</tr>
<tr>
<td>Fines content (&lt;0.075 mm) (%)</td>
<td>3.2</td>
<td>1.2</td>
</tr>
<tr>
<td>[range]</td>
<td>[0.5–5.0]</td>
<td>[0.2–2.0]</td>
</tr>
<tr>
<td>USCS classification</td>
<td>ASTM D2487-98</td>
<td>SW</td>
</tr>
<tr>
<td>AASHTO classification</td>
<td>AASHTO M43-88</td>
<td>No. 10</td>
</tr>
<tr>
<td>LA abrasion (wt. %)</td>
<td>24%</td>
<td>—</td>
</tr>
<tr>
<td>Sodium sulfate soundness (wt. %)</td>
<td>6.38%</td>
<td>7.1%</td>
</tr>
<tr>
<td>Hydraulic conductivity (cm/s)</td>
<td>$1.61 \times 10^{-4}$</td>
<td>$6.45 \times 10^{-4}$</td>
</tr>
<tr>
<td>[range]</td>
<td>[1.36 \times 10^{-4}–1.85 \times 10^{-4}]</td>
<td>[6.42 \times 10^{-4}–6.64 \times 10^{-4}]</td>
</tr>
<tr>
<td>Modified Proctor</td>
<td>ASTM D1557-00</td>
<td></td>
</tr>
<tr>
<td>$\gamma_{d,\text{max}}$ (kN/m³)</td>
<td>18.3</td>
<td>17.5</td>
</tr>
<tr>
<td>$w_{\text{opt}}$ (%)</td>
<td>9.7</td>
<td>11.2</td>
</tr>
<tr>
<td>Standard Proctor</td>
<td>ASTM D698-00</td>
<td></td>
</tr>
<tr>
<td>$\gamma_{d,\text{max}}$ (kN/m³)</td>
<td>16.8</td>
<td>16.6</td>
</tr>
<tr>
<td>$w_{\text{opt}}$ (%)</td>
<td>12.8</td>
<td>13.6</td>
</tr>
<tr>
<td>Direct shear</td>
<td>ASTM D3080-98</td>
<td></td>
</tr>
<tr>
<td>Internal friction (deg)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\sigma_s$ (kPa)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0–60</td>
<td>$61–63^\circ$</td>
<td>$59–62^\circ$</td>
</tr>
<tr>
<td>60–120</td>
<td>$58–61^\circ$</td>
<td>$55–59^\circ$</td>
</tr>
<tr>
<td>120–200</td>
<td>$63–68^\circ$</td>
<td>$47–55^\circ$</td>
</tr>
<tr>
<td>Consolidated drained triaxiala internal friction (deg)</td>
<td>USACOE</td>
<td>48°</td>
</tr>
</tbody>
</table>

Table 2 indicates that the crushed glass from Supplier II was coarser and contained a higher fraction of fine gravel and coarse sand than the material from Supplier I. Although there is variability in the grain size distribution among the tested specimens from Supplier II, the material was sufficiently uniform that all specimens were classified as “SW,” or well-graded sand, based on the USCS, and “Number 10” based on the AASHTO systems. With the exception of one specimen which classified as poorly graded sand (SP), all of the material from Supplier I classified as “SW” based on the USCS. All of specimens from Supplier I classified as an AASHTO No. 10 aggregate.

Fig. 4 compares the grain size distributions of individual crushed glass specimens in their “as-received” and “postcompaction” conditions following modified Proctor compaction. The upper portion of the figure quantifies the change in grain size as the measured increase (difference) in particle fineness. Samples exhumed from the compaction molds were more fine grained resulting from compaction-induced particle breakage. The Supplier II specimens experienced a greater reduction in particle size most likely due to Supplier II’s initially coarser gradation and the bittre naturality of glass. Despite particle breakage, the shifts in
gradation were not sufficient to change the USCS or AASHTO classification of crushed glass from either of the suppliers.

**Durability and Weathering Resistance Tests**

Los Angeles (LA) abrasion, freeze–thaw, and sodium sulfate soundness tests were performed to assess the durability and weathering resistance of the crushed glass. The LA abrasion test (ASTM C131) is commonly used in highway and materials engineering to assess the abrasion resistance of construction aggregates. The crushed glass yielded LA abrasion wear values of 24% (Supplier I) and 25% (Supplier II) which are less than the range of 30–42% provided by FHWA (1998). These wear values are slightly higher than those of most common aggregates, which typically range from about 12 to 20%, are below the maximum allowable value of 30% permitted by many State Departments of Transportation (DOT) specifications.

Freeze–thaw cycle tests assess particle breakdown and decomposition due to freezing-related expansion of water in the microfractures of solids. Six 1,000 g specimens of crushed glass were subjected up to 120 cycles of repeated freezing and rapid (heating-induced) thawing. The grain size distribution was measured after 0, 10, 20, 30, 60, and 120 cycles of freezing and thawing. The particle size ($D_{10}$, $D_{50}$, $D_{60}$) indices were routinely evaluated, where the numbered subscripts denote the percent passing by weight. The coefficient of uniformity ($C_u$), an index of material uniformity defined as $D_{60}/D_{10}$, was also monitored. Materials that are well graded and uniformly graded are defined as those having $C_u>6$ and $C_u<4$, respectively. Often small amounts of material are lost during sieving and grain size laboratory testing procedures. As such, it was not possible to accurately perform repeated grain size distribution tests on a single test specimen. Fig. 5 presents the test results for $D_{10}$, $D_{50}$, $D_{60}$, and $C_u$ versus number of freeze–thaw cycles, and a baseline “as-received” specimen not subjected to freezing and thawing. While Fig. 5 shows slight variations in grain size indices, the lack of an apparent trend suggests that the crushed glass is not susceptible to freeze–thaw related degradation. In other words, the gradation did not become progressively finer as would be expected if the material was deteriorating or degrading.

Sodium sulfate soundness testing was completed on each crushed glass sample. The results were 6.38 and 7.1 wt. % for Suppliers I and II, respectively, which is well below the 12% limit established for coarse aggregates used in concrete applications.

**Compaction Tests**

Standard and modified Proctor compaction tests were performed on the crushed glass samples, as summarized in Fig. 6. Zero air voids curves (i.e., maximum dry density as a function of moisture content for a fully saturated sample) incorporating specific gravities of 2.485 (glass) and 2.65 (typical soil or aggregate) are shown for reference purposes. The compaction tests were typically performed using 5–6 moisture-density points. Table 2 summarizes the maximum dry density ($\gamma_{d,max}$) and optimum water content ($w_{opt}$) for each crushed glass sample. For comparison, FHWA (1998) reports typical modified compaction densities of 17.7–18.6 kN/m$^3$ for glass cullet with optimum water contents in the range of 5.7–7.5%. As with natural aggregates, the modified Proctor data of the crushed glass exhibit $\gamma_{d,max}$ values that exceeded those of the standard Proctor values by approximately 7.5%. The moisture–density curves exhibit the characteristic convex shape of natural aggregates, suggesting that crushed glass compacts similarly to natural aggregates. The flatness of the curves suggest stable compaction characteristics and good workability over a wide range of water contents given that crushed glass is relatively insensitive to moisture content.
Hydraulic Conductivity

Constant head hydraulic conductivity tests were performed on the crushed glass samples. Each test specimen was compacted in a rigid wall permeameter to a dry density equal to 90% ±1% of its $\gamma_{d,\text{max}}$ based on the modified Proctor test data. This level of compaction corresponds to relative density values of 88 and 77% for the Supplier I and II specimens, respectively. The testing procedure entailed initially spraying (moisture conditioning) the specimens with tap water followed by placement in a 6.1 cm high, 15.2 cm diameter rigid wall permeameter using thin lifts, and compaction with a rubber tipped pestle. Table 2 reports hydraulic conductivity values of $1.61 \times 10^{-4}$ and $6.45 \times 10^{-4}$ cm/s for Supplier I and II materials, respectively, averaged over triplicate samples. As expected, the hydraulic conductivity values for the coarser Supplier II material were slightly higher than the Supplier I material. The measured hydraulic conductivity values for both materials are within the typical range for compacted natural soils and aggregates having SW designations (e.g., NA VFAC 1986). The FHWA (1998) reports fine glass cullet having hydraulic conductivities as high as $6 \times 10^{-2}$ cm/s. The measured values suggest that crushed glass is a relatively free draining material that should perform well in filtration and drainage applications.

Shear Strength

A series of consolidated, drained direct shear and triaxial compression tests were performed to assess the shear strength characteristics of the crushed glass. The tests were performed on crushed glass specimens compacted to 90% ±1% of their $\gamma_{d,\text{max}}$ values based on the modified Proctor compaction results. Direct shear tests were conducted on 6–7 specimens from each supplier over a wide range of normal stresses ($\sigma_n$) (15–190 kPa) to assess the degree of nonlinearity in the Mohr–Coulomb failure envelope. The tests were performed using a 10.2 cm by 10.2 cm by 5.1 cm deep direct shear device. The sample preparation procedure included spraying (moisture conditioning) followed by placement in the direct shear box using thin lifts that were compacted with a rubber tipped pestle. The samples were then saturated with tap water to eliminate capillary tension and a normal stress was then applied for several hours before testing. The specimens were sheared at a rate of 1.2 mm/min yielding a time to failure (peak shear stress) of about 4–6 min and displacements on the order of 3–5 mm. The crushed glass exhibited dilatant behavior during shearing with the specimens tested under higher confining stresses experiencing the highest levels of dilatancy.

To illustrate the nonlinearities in the direct shear data (Fig. 7), the failure envelope was represented using a best-fit second order polynomial in lieu of the typical linear Mohr–Coulomb envelope. The coefficients of variation ($R^2$) were greater than 0.95, indicating that the regressions fit the data well even for assumed cohesion ($c$) intercepts of zero. However, the crushed glass exhibited a minor degree of apparent cohesion in triaxial compression, possibly due to particle adhesion resulting from label glues, residual sugars or other cohesive (gummy) substances. Hence, the zero cohesion assumption is a simplification made to demonstrate the non-linearities in the material. Highly angular materials, such as crushed glass, are known to exhibit significant nonlinearity. Internal friction angles ($\phi$) based on conventional linear Mohr–Coulomb criteria are presented for different ranges of normal stresses in Table 2. These data are larger than the direct shear friction angles of 51–53° reported by FHWA (1998).

A second series of shear strength tests were performed under...
drained triaxial compression. The tests were performed on isotropically consolidated specimens using an automated triaxial testing, control and data acquisition system. The specimen sizes varied slightly between tests, but were about 13.8 cm high and 7.0 cm in diameter. Axial load, displacement, specimen volume change, and internal pore pressures were measured during testing at a rate of 20 Hz. Crushed glass specimens were prepared in a manner consistent with the direct shear tests. After compaction, specimens were placed under vacuum, and the split mold was removed. Preliminary testing indicated that the crushed glass particles caused small punctures in the 0.3 mm thick latex membrane surrounding the specimen. To remedy the situation, a layer of grease was applied to the outside of the membrane, and a second 0.3 mm membrane was placed over the specimen. To account for the stiffening effect of the two membranes, a correction factor was applied to the measured strength [ASTM D4767 (ASTM 1995)]. After preparation, the specimen was mounted in the triaxial cell, flooded with tap water, and then backpressure satu-

Fig. 5. Grain size indices and $C_u$ as function of freeze–thaw cycles for crushed glass
rated. The specimens were tested under three confining pressures ranging from 26 to 140 kPa, equivalent to overburden depths of 1.5–10 m. The specimens were tested under a strain-controlled loading rate of 1.25 mm/min to an axial strain of approximately 18–20%, yielding a typical time to failure (peak deviator stress) of about 10–15 min.

Fig. 8 shows deviator stress and volumetric strain as a function of axial strain for crushed glass from both suppliers. The deviator stress ($\sigma_1-\sigma_3$) is defined as difference between the maximum ($\sigma_1$) and minimum ($\sigma_3$) principle effective stresses. The Supplier I specimens reached their peak deviator stresses at about 5–8% axial strain ($e_3$). The coarser Supplier II specimens reached their peak deviator stresses at slightly larger axial strains (about 7–10%). Crushed glass specimens from both suppliers generally exhibited a limited degree of strain softening. Fig. 8 also shows the volumetric behavior of the specimens during triaxial tests. The crushed glass from both suppliers was dilatant (i.e., exhibiting negative volumetric strain) and the greater dilatancy of the crushed glass from Supplier I was attributed to its slightly higher relative density.

Fig. 9 presents the triaxial test data in the common Mohr’s circle format with best fit linear Mohr–Coulomb failure envelopes for crushed glass. The triaxial tests yielded internal friction angles ($\phi$) of 48 and 47° for the crushed glass from Suppliers I and II, respectively. As expected, these internal friction values are about 10% less than the direct shear test data for comparable confining stresses due to differences in boundary conditions between the tests. The Mohr–Coulomb failure envelopes shown in Fig. 9 indicate that the materials exhibited a modest level of cohesion. It is believed that these cohesion intercepts are the combined result of (1) a linear representation of a nonlinear shear strength failure envelope, and (2) apparent cohesion resulting from adhesive label glues, sugars, and other substances. It was often observed that wet, gummy glass particles often adhered together when at least one of the glass particles had a thin surface covering of glue, paper (bottle label), or both.

In summary, the direct shear and triaxial compression test results indicate that the crushed glass was dilatant and exhibited high internal friction. As discussed above, apparent cohesion may be related to adhesion of the glass particles from label glues and/or other cohesive substances and should be neglected. The direct shear tests indicate that internal friction was reduced under high confining stresses. Hence, care must be taken to ensure that strength parameters selected for design are appropriate for the anticipated stress conditions. Note, however, that even conservative estimates of the internal friction angle of crushed glass make it equal to or greater than corresponding natural soil or aggregates under similar compactive efforts.

### Leaching Tests

Toxicity characteristic leaching procedure (TCLP) (U.S. EPA 1991b) and synthetic precipitation leaching procedure (SPLP) (U.S. EPA 1991a) tests for metals were performed on the as-received crushed glass from each supplier. The TCLP and SPLP tests are used to simulate metals leaching under the conditions associated with typical landfill and soil conditions, respectively. By the TCLP and SPLP tests, a material is designated as a “hazardous waste” if any detected metal occurs at concentrations in excess of 100 times the drinking water standard. Table 3 presents the leaching data versus the USEPA primary drinking water standards (U.S. EPA 1999).

The more aggressive TCLP test results indicated trace concentrations of barium in the leachates from the Supplier I glass sample, and chromium and lead in the Supplier II glass sample. It is not clear why the crushed glass from Supplier I contained barium, though this may be attributed to the coloring and specialty ingredients used in some commercial and industrial glassware. While the exact source of the chromium and lead cannot be known in the glass from Supplier II, it is not unreasonable to attribute the trace chromium and lead to the presence of label printing pigments, wine bottle capping materials, broken ceramics and crystal (lead glass) that may have appeared in the supplied samples. The SPLP test did not produce measurable concentrations of metals above their detection limits in either glass sample, except for mercury, which could be the result of waste thermometer glass materials that may have entered the waste glass stream.
Discussion

Real and Perceived Barriers to Using Crushed Glass

In reviewing the measured properties of crushed glass, it becomes clear that glass has excellent potential for use as an aggregate in strength and drainage applications. And yet the U.S. EPA (2000) data indicates that 7.8 million t of glass is landfilled annually. This begs the question of how to increase the beneficial use of crushed glass in civil engineering and construction since these industries consume large quantities of materials. There are three main interrelated barriers to this issue: contracting mechanisms, existing nonperformance (material specific) based specifications, and the unnecessary cross referencing of specifications. A convenient example illustrating the general problem regarding crushed...
glass is to consider that large metropolitan areas issue waste management contracts for refuse and curbside collection of recycled materials, and through another department purchase aggregate for road construction. For example, one suburban Philadelphia recycler accepting glass accumulated approximately 1,000 t/month of glass cullet, but experienced trouble identifying reuse applications. Consequently, the facility paid approximately $18/t to dispose of the crushed glass at a New Jersey landfill where it was used as daily cover; a price significantly less than the typical landfill disposal cost of $50/t. However, the facility could have tripled its acceptance of glass based on plant capacity.

The cost of curbside collection and the lack of, or depressed nature of, secondary glass markets may have therefore contributed to New York City’s recent decision to suspend glass collection.

Table 3. Toxicity Characteristic (TCLP) and Synthetic Precipitation (SPLP) Leaching Procedure Results

<table>
<thead>
<tr>
<th></th>
<th>U.S. EPA drinking water standard$^a$</th>
<th>Hazardous waste designation$^b$</th>
<th>TCLP Supplier I</th>
<th>TCLP Supplier II</th>
<th>SPLP Supplier I</th>
<th>SPLP Supplier II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arsenic</td>
<td>0.05</td>
<td>5.0</td>
<td>&lt;0.10</td>
<td>&lt;0.10</td>
<td>&lt;0.10</td>
<td>&lt;0.10</td>
</tr>
<tr>
<td>Barium</td>
<td>2.0</td>
<td>100</td>
<td>0.151</td>
<td>&lt;0.10</td>
<td>&lt;0.10</td>
<td>&lt;0.10</td>
</tr>
<tr>
<td>Cadmium</td>
<td>0.005</td>
<td>1.0</td>
<td>&lt;0.01</td>
<td>&lt;0.10</td>
<td>&lt;0.10</td>
<td>&lt;0.10</td>
</tr>
<tr>
<td>Chromium</td>
<td>0.1</td>
<td>5.0</td>
<td>&lt;0.03</td>
<td>0.0772</td>
<td>&lt;0.03</td>
<td>&lt;0.03</td>
</tr>
<tr>
<td>Lead</td>
<td>0.015</td>
<td>5.0</td>
<td>&lt;0.10</td>
<td>0.128</td>
<td>&lt;0.10</td>
<td>&lt;0.10</td>
</tr>
<tr>
<td>Mercury</td>
<td>0.002</td>
<td>0.2</td>
<td>&lt;0.0002</td>
<td>&lt;0.0002</td>
<td>0.00024</td>
<td>&lt;0.0002</td>
</tr>
<tr>
<td>Selenium</td>
<td>0.05</td>
<td>1.0</td>
<td>&lt;0.20</td>
<td>&lt;0.20</td>
<td>&lt;0.20</td>
<td>&lt;0.20</td>
</tr>
<tr>
<td>Silver</td>
<td>0.05</td>
<td>5.0</td>
<td>&lt;0.02</td>
<td>&lt;0.02</td>
<td>&lt;0.02</td>
<td>&lt;0.02</td>
</tr>
</tbody>
</table>

Note: All data in milligrams per liter (mg/L).


$^b$SW-846, Chapter 7.4 (Revision 3, December 1994).
tion and recycling (“Recycling—waste of time” 2002). However, New York’s decision is somewhat hard to understand considering that at the same time cities purchase embankment material and/or aggregates for construction at raw material costs of $2–$7/t, plus transportation ($5/ton for 30 km radius), or up to $12/t. The quantities of both glass and earth materials handled by cities are easily in the hundreds of thousands of tons, making the appropriate substitution of glass in earthwork applications a very viable approach to managing city financial resources (with a net revenue swing of up to $62/t). However, while the economics are compelling and the use of crushed glass could be easily justified from a performance basis in a large number of urban embankment, fill, retaining wall, wharf, dock construction, and aggregate applications, the contracts for waste management, construction, and purchasing are issued by different city departments.

While often it may appear that government procurement practices are key handicaps to increasing beneficial use, this ignores the practices that hold sway in the engineering and construction community. In other words, even if cities adopted a holistic approach to materials and contracts management, many current engineering design and construction codes either deter or completely prevent the use of crushed glass in beneficial use applications. The civil and construction industry, because of its obvious concern with public welfare and safety, is generally risk-adverse and resistant to change unless a distinct cost and/or performance advantage can be realized (which would occur in cities and coastal plain areas lacking aggregate quarries but having captive glass sources). It is also a feature of the civil/construction enterprise that they make use of time-tested specifications, and DOT specifications are often employed or referenced even for nontransportation applications. This practice has been a disservice to using recycled materials, and a move toward performance specifications could eliminate this bias. It is also important to recognize that the civil and construction engineering fields matured over some 200 years based on a system that emphasized raw, virgin materials, and consequently, the entire professional framework, and its acquisition and distribution networks were developed as such.

The key to understanding problems like this pertains to the specifications themselves. The trickle down effect of this is, for example, that the local municipal engineer who also serves as the recycling coordinator cannot approve the “common sense” use of crushed glass for septic field drainage media because the governing Department of Environment Protection (DEP) regulations require the use of DOT-approved aggregates. Ironically, while crushed glass is chemically inert (noncalcaceous) and is perfectly suited for septic field applications, the crushed glass cannot pass many DOT aggregate specifications because they are geared for concrete and asphalt applications where glass is considered a deleterious material.

Density, Aggregates and Embankment Materials

Many civil engineers associated increased soil density with increased soil strength and vice versa. While this is generally true, it is then not surprising that many State DOT regulations establish minimum acceptable density criteria for embankment material and aggregates with the unintended consequence of eliminating strong lightweight materials from consideration. For example, Maryland DOT (MDOT 2001) Section 916 establishes a $d_{l,max}$ no less than 15.72 kN/m$^3$ for all soil and soil aggregate borrow by AASHTO T180, Method C (i.e., ASTM D1557). Delaware DOT (DEL DOT 2001) regulations (Section 209) set a lower limit on $d_{l,max}$ 14.4 kN/m$^3$ for all borrowed materials. While crushed glass demonstrates excellent frictional strength, the density criterion presents a serious challenge for glass owing in part to its lower specific gravity. Worse, these minimum density specifications are ill suited for coastal communities with captive glass markets, a limited supply of quarried aggregates, and where lightweight materials are preferred for embankment construction over soft compressible soil deposits. Thus, Ocean City, Md. has a very active glass recycling program and contractors often choose glass for pipe backfill and other non-DOT applications because of the cost savings (~$5/t) over aggregates transported from inland quarries.

Pennsylvania has a different approach to embankment material and aggregates. PennDOT (PennDOT 2000) Publication 408, Section 206.2. (a) establishes $d_{l,max}$ of 95 lb/ft$^3$ (15.22 kN/m$^3$) by ASTM D698 for natural soil materials used in embankment construction with additional constraints placed on gradation (>35% passing No. 200 sieve) and plasticity. However, crushed glass is technically not soil, and it therefore qualifies for use as embankment material in all proportions under the granular, random and suitable embankment material classifications of the subsection. These embankment categories allow for broad acceptance of materials including slags, quarry fines, incinerator and fly ashes, construction and demolition debris, etc. Many states like Pennsylvania base compaction criteria on a minimum percent compaction or percent density based on a material’s compaction properties, and not a universally mandated value (in kN/m$^3$).

Though strong lightweight aggregates are addressed by PennDOT (PennDOT 2002) Publication 408, Section 703.2, glass is intentionally treated as a deleterious material and is explicitly excluded from cement concrete and bituminous wearing courses. The use of crushed glass is limited to 4 wt. % by two of three aggregate quality types (A, B), and to 10 wt. % for all other uses [Section 703.2(c)(10). The NY DOT (NY DOT 1995) Section 703 aggregate specifications are very similar, and glass is totally excluded from the section, as aggregates are specifically referred to by their geologic or industrial source.

While the materials-specific nature of DOT specifications is gradually giving way to performance specifications, it is important nevertheless to realize that DOT embankment and aggregate specifications were developed to avoid certain stability and incompatibility issues, and these concerns may have little or no relevance in non-DOT applications. It is therefore incumbent on nontransportation professionals to ascertain the actual intent of the DOT specifications before referencing them as a matter of practice, preference, or convenience. Force fitting DOT specifications to other applications without realizing the technical objectives, criteria, and hidden costs (and time) implied by the DOT procedures and specifications can bar recycled materials from appropriate end uses. Ironically, even environmental agencies—chartered with increasing recycling rates—occasionally promulgate regulations that impinge on recycled materials use. For example, the key characteristics of drainage media in septic field applications are gradation, hydraulic conductivity and chemical inertness, the governing regulations typically being issued by state DEPs. Reproduced below are excerpts from Title 25 Pennsylvania Code, Chapters 73, the Regulations for Sewage Disposal Facilities (2001), where the underlined portions of the current regulation demonstrate the ubiquitous reference to DOT standards, as is common in civil engineering practice:

1. Section 73.55(c) Sand. Sand suppliers shall provide certification in writing to the sewage enforcement officer and permitted, with the first delivery to the job site from every sand source listing the amount of sand delivered, and that all sand
supplied meets the requirements posted in the Department of Transportation specifications Publication No. 408, section 703. The size and grading shall meet bituminous concrete sand Type No. 1 or No. 3 requirements from a Department of Transportation certified stockpile. The sieve analysis shall be conducted in accordance with PTM No. 616 and No. 100.

2. Section 73.162(b)(4)(iv) … Coarse aggregate used in the transition layer shall meet the Type B requirements posted in the Department of Transportation specifications Publication No. 408, section 703, Table B. Size and grading shall meet AASHTO No. 8 requirements, as described in … Table C, from a Department of Transportation certified stockpile.

These DOT specifications introduce a variety of problems. First, calcareous aggregates (limestone, etc.), which are not appropriate for use in sewage applications and aggressive environments for obvious reasons, are not prohibited by PennDOT Publication 408, Section 703. Also, Pennsylvania Test Methods (PTMs) developed by the PennDOT Bureau of Construction and Materials are additionally cited, an obscure reference for those not conducting business with PennDOT. Equivalent ASTM standards are more commonly referenced. The AASHTO gradations are often referenced when specifying aggregates and soils for strength or drainage applications, but this infrequently introduces problems unless additional quality standards are applied. Crushed glass is strongly disadvantaged from potential use in septage applications for the additional following reasons:

1. While mineralogically identical to most sands, crushed glass does not meet the basic material (source) description for aggregates as defined in PennDOT Pub. 408, Section 703. Put simply, crushed glass is not sand.

2. Even if the PennDOT source material definitions were interpreted liberally, Type B aggregate quality limits the glass content to 4 or 10 wt. %. Blending and testing to guarantee percentage limits are costly.

3. PennDOT certification implies an onsite quality assurance/quality control (QA/QC) materials testing program that costs to the typical Pennsylvania quarry on the order of $25,000–30,000/year to maintain, and furthermore requires a company listing per specific aggregate type in PennDOT Publication 34, Bulletin 14, Aggregate Producers.

While quarry operations can easily adsorb the costs of DOT certification, recyclers simply do not have financial resources to adsorb this cost, even though Table 2 shows that the engineering properties of the crushed glass processed at quarries and recycling facilities are virtually identical.

The financial implications of the current PADEP regulations are staggering. The typical quarry price of AASHTO No. 8 aggregate and bituminous sands (B1 and B3) are on the order of $7/t (Pennsylvania prices). Bituminous sands are roughly equivalent to an AASHTO No. 10 gradation, for which crushed glass is generally the same price ($7/t) and often less. Assuming local delivery, the sale price of crushed glass would be on the order of $10/t versus a landfill disposal cost of $50/t (landfilling), or a net revenue swing of approximately $60/t.

The typical sand mound uses 100 t of sand and represents $700 in lost economic opportunity to glass recycling facilities. With 67 Pennsylvania counties each constructing an estimated annual average of 100 sand mounds, the annual market size is about 670,000 t, or a $4.7 million dollar industry. Assuming 100% capture by crushed glass, modification of this single set of state regulations could increase the national glass recycling rate by an additional 7%, based on the national estimate of 11 million t (U.S. EPA 2000).

Pennsylvania has become a leader in the beneficial use of recycled materials and industrial byproducts by virtue of its Act 101 (1988). Through research and joint efforts, PADEP and PennDOT continue to identify and remove barriers to recycling in transportation applications. While regulations are hard to change, PADEP has issued guidance allowing the substitution of crushed glass for aggregates with third party laboratory certification based on this work. In this way, a crushed glass stockpile could be certified with a 1 week turnaround time for approximately $200 and the entire DOT regulatory framework is avoided without compromising the performance of the septage field application. Certification would accompany the bill of sale, as is the usual practice in the aggregate industry.

The provided example illustrates the complicated nature of the recycling problem, i.e., the devil is in the details. And while we have illustrated how Pennsylvania has identified and reconciled the problem to increase recycling, examples like this exist in every state, in every branch of engineering and construction. It is hoped that this data set on crushed glass and the economics involved serve as motivation for policy makers, planners and engineers to thoroughly examine and eliminate unnecessary barriers to the beneficial use of crushed glass.

Conclusions

Select engineering characteristics of crushed glass produced using two processing techniques (crushing versus screening) to an AASHTO No. 10 gradation were experimentally evaluated. The crushed glass samples were classified as well graded sand with gravel (SW) and exhibited excellent strength and workability characteristics. The low specific gravity (2.485) contributed to crushed glass having compacted maximum dry densities on the order of 16.6–16.8 and 17.5–18.3 kN/m³, by the standard and modified Procter compaction test, respectively. Direct shear friction angles were measured between 47 and 62° at normal stresses ranging from 0 to 200 kPa. Friction angles obtained by triaxial shear were on the order of 48° for a similar stress ranges. Measured hydraulic conductivities were on the order of 1–6 × 10⁻⁶ cm/s. These characteristics suggest that crushed glass can be used for many civil, construction, and geotechnical engineering applications, including compacted fill, trench backfill, retaining wall, or mechanically stabilized earth (MSE) wall backfill, and roadway subbase among others. A move toward performance specifications and the elimination of other unnecessary real and perceived barriers against recycling glass will enable crushed glass to be increasingly used in these applications.

Both crushed glass suppliers were able to provide crushed glass with consistent, reproducible properties. The engineering characteristics of the crushed glass varied slightly between suppliers, although it appears that these variations were more closely related to grain size distribution than the parent glass characteristics or processing procedures. This suggests that as long as crushed glass meets AASHTO No. 8 or 10 classifications, its properties will be comparable to or exceed those of natural aggregates of the same gradation, regardless of the processing procedures (i.e., quarry crushing equipment versus recycling equipment screening).

Acknowledgments

The Strategic Environmental Management Program Office of the Pennsylvania Department of Transportation provided financial
support for this research. D.M. Stoltzfus & Son, Inc. (Talmage, Pa.), and Todd Heller, Inc. (Northampton, Pa.), provided matching funds and the raw materials for the testing program. Kenneth J. Thornton, (PennDOT), Mark Arnold (Stoltzfus), and Todd Heller are thanked for their cooperation. James Gustine and Vincente Morales are thanked for their assistance in experimentation. LA Abrasion testing was completed by Construction Technology Laboratories, Skokie, II. Sodium sulfate soundness testing was completed by Valley Forge Laboratories, Devon, Pa. The TCLP and SPLP tests were completed by Lancaster Laboratories, Lancaster, Pa. The views expressed here are solely those of the writers and endorsement is not implied by the project sponsors.

Notation

The following symbols are used in this paper:

- $C_u$ = coefficient of uniformity;
- $D_{10}$ = diameter in particle size distribution curve corresponding to 10% finer by weight (cm);
- $D_{50}$ = diameter in particle size distribution curve corresponding to 50% finer by weight (cm);
- $D_{60}$ = diameter in particle size distribution curve corresponding to 60% finer by weight (cm);
- $w_{opt}$ = optimum water content (%);
- $\gamma_{d,max}$ = maximum dry density (kN/m$^3$);
- $e_a$ = axial strain (%);
- $\sigma_n$ = effective normal stress during triaxial shear testing (kPa);
- $\sigma_a$ = applied effective normal stress during direct shear testing (kPa);
- $\sigma_1$ = maximum principle effective stresses (kPa);
- $\sigma_3$ = minimum principle effective stresses (kPa);
- $\sigma_1-\sigma_3$ = deviator stress (kPa); and
- $\phi$ = friction angle (deg).

References


538 / JOURNAL OF MATERIALS IN CIVIL ENGINEERING © ASCE / NOVEMBER/DECEMBER 2004


