COMMONWEALTH OF PENNSYLVANIA  
DEPARTMENT OF TRANSPORTATION  

PENNDOT RESEARCH  

ENGINEERING-RELATED PROPERTIES OF GLASS BLENDED WITH VARIOUS SOILS  

STATE-WIDE  
Assignment 46  

ABORATORY EVALUATION OF SELECT  
CRUSHED  

December 2001  

OPEN END CONTRACT No. 440094 (w/Apex Environmental)  

FINAL REPORT
Executive Summary

A previous study conducted by the Pennsylvania Department of Transportation (PENNDOT) examined the basic geotechnical characteristics of crushed glass for use in transportation applications (Wartman et al., 2001). The results of this study indicated that the engineering and performance properties of crushed glass typically equaled or exceeded those of most natural aggregates of similar gradation. However, the shear strength tests results suggested that when compacted, the crushed glass exhibited relatively little cohesion. PENNDOT proposed to use crushed glass as fill material for a planned parking lot expansion at the Harrisburg International Airport. Due to the modest cohesion of the crushed glass, however, the stability of unsupported shallow depth utility trenches and excavations in the crushed glass became a concern. Accordingly, PENNDOT requested that the current study be performed to evaluate the possibility of adding small to moderate amounts of clayey soil (10% to 50%) to the crushed glass to increase its cohesive strength. Conversely, interest also arose on whether glass cullet could enhance the properties of marginal geotechnical media such as quarry spoils, dredge materials, etc. Several basic physical and mechanical properties of four different soil-glass blends were evaluated.

The laboratory investigation considered two issues: 1) to improve trench stability, crushed glass was blended with two natural clayey soils to improve its cohesive characteristics; and, 2) to improve strength characteristics of select marginal soils, crushed glass was blended with two quarry spoils.

The following tests were conducted to evaluate the positive impacts of blending crushed glass with the aforementioned geotechnical media.

- Water Content (ASTM D-2216)
- Modified Proctor Compaction Tests (ASTM D-1557)
- Sieve and Hydrometer Analyses - (ASTM D-421 and D-422)
- Direct Shear Tests (ASTM D-3080)

The results indicate that the cohesive strength of the crushed glass may be increased by 50% to 100% by the addition of clayey soils. This increase in cohesive strength will enhance the stability of unsupported trench excavations in these materials.

In the unblended condition, the previous PENNDOT study (Wartman et al. 2001) suggested that approximately 1 m deep unsupported trenches could be excavated in the compacted crushed glass. The current study indicates that if blended with 20% or more fine grained soil, deeper unsupported trenches could be temporarily excavated in the crushed glass. The excavation depth is generally proportional to soil content, and ranges from approximately 1.5 m at 20% soil content to about 2.4 m at 50% soil content. The increase in cohesive strength was accompanied by a decrease in frictional strength slight (about 5 to 15%). However, the overall strength and compaction characteristics of the crushed glass-soil blends considered in this study are similar to those of natural soils having similar gradations.

When considering the addition of crushed glass to marginal soils to improve their strength characteristics for engineering construction, this study determined the following positive benefits: (1) addition of crushed glass to fine grained soil resulted in substantial increases in maximum dry density values and lower water requirements and (2) considerable frictional strength was added to the fine grained soils through addition of crushed glass.

The laboratory test results for each soil are summarized in the following tables.
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Crushed Glass-King of Prussia Soil

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Crushed Glass-Quarry Fines

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Crushed Glass-Quarry Screenings

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</thead>
<tbody>
<tr>
<td>Water Content</td>
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<tr>
<td>$\gamma_{\text{d,max}}$ and $W_{\text{opt}}$</td>
<td>Mod. Proctor Compaction</td>
<td>19.90 kN/m$^3$</td>
<td>20.40 kN/m$^3$</td>
<td>20.50 kN/m$^3$</td>
<td>20.60 kN/m$^3$</td>
<td>21.1 kN/m$^3$</td>
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<tr>
<td>$\phi_{ds}$</td>
<td>Direct Shear Test</td>
<td>43.8'</td>
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<td>48.4'</td>
<td>51.1'</td>
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<tr>
<td>Cohesion ($C_{ds}$)</td>
<td>Direct Shear Test</td>
<td>17.0 kPa</td>
<td>21.4 kPa</td>
<td>16.6 kPa</td>
<td>16.9 kPa</td>
<td>16.9 kPa</td>
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</tbody>
</table>
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1.0 INTRODUCTION AND BACKGROUND

A memorandum of understanding (MOU) between the Pennsylvania Department of Environmental Protection (PADEP) and the Department of Transportation (PENNDOT) created an interagency program that encourages and provides resources for the incorporation of recycled materials in PENNDOT construction and maintenance projects. A variety of recycled materials are contemplated and evaluated by the program, including crushed glass. The previous PENNDOT study examined the basic geotechnical characteristics of crushed glass in transportation applications (Wartman et al., 2001). PENNDOT subsequently proposed to use crushed glass as fill material for a planned parking lot expansion at the Harrisburg International Airport. However, due to the modest cohesion of the crushed glass (Wartman et al. 2001), the stability of unsupported shallow depth utility trenches and excavations became a concern. Accordingly, a second laboratory was undertaken (this study) to assess several basic physical and mechanical properties of four different soil-glass blends to explore the extent to which soil blending could enhance the cohesive behavior of glass. Conversely, the idea also arose to evaluate how glass improved the usable characteristics of marginal soils. The present study was made possible by support provided by Apex Environmental, Inc. (Apex) under its Open-End contract No. 440094 with the PENNDOT Bureau of Environmental Quality (BEQ). The crushed glass and quarry spoils used in this study were provided by D. M. Stoltzfus & Son, Inc., and Haines & Kibblehouse, Inc., respectively.

Wartman et al. (2001) recently completed a laboratory evaluation for PENNDOT of select engineering-related properties of crushed glass from two suppliers located in southeastern Pennsylvania. In each case, the glass was crushed to an American Association of State Highway and Transportation Officials (AASHTO) No. 10 gradation. The two sources of crushed glass were found to have very similar geotechnical properties even though they were generated by two very different processes: quarry crushing versus recycling center screening operations. Moreover, the testing results on the crushed glass indicated that its engineering and performance properties typically equaled or exceeded those of most natural aggregates of similar gradation. However, the shear strength tests results suggested that when compacted, crushed glass exhibited relatively little cohesion. Due to the modest cohesion of the crushed glass, the stability of unsupported shallow depth utility trenches and excavations was therefore a concern.

Accordingly, and to promote the use of crushed glass in civil engineering construction, consideration of the favorable drainage, high frictional but moderate cohesive strength of the crushed glass lead to the development of a second investigation. This laboratory investigation focused on two main issues: 1) to improve trench stability, crushed glass was blended with two natural clayey soils to improve its cohesive characteristics; and, 2) to improve strength characteristics of select marginal soils, crushed glass was blended with two marginal soils. To improve cohesive behavior, the crushed glass was blended with commercially available kaolinite, and a natural soil obtained in King of Prussia, Pennsylvania. Marginal soils include such things as dredge, river, mining and quarry spoils, and industrial byproducts such as fly and incinerator ashes.

Specifically, a variety of aggregates are quarried in Pennsylvania, producing spoil materials that cannot be readily used by PENNDOT and other construction interests. These spoils, typically fines, are either used for backfilling quarry excavations or are blended into other aggregate products that have minimal fines requirements. In many cases, quarry spoils simply accumulate in large quantities and add to the operational costs of aggregate production. As quarries have equipment and quality control procedures to crush and uniformly blend glass with quarry spoils, as well as existing distribution and sales networks for aggregate and fill materials, the partnership between glass recyclers and aggregates industry seemed a natural fit to solve a joint materials management problem. Blending of glass with marginal soils offers the possibility to market a synthetic structural fill material with a variety of end uses. Notwithstanding this objective, emphasis was nevertheless placed on proportionally high utilization of crushed glass, so blending involved small to moderate amounts of soil materials (10-50% by weight).
1.1 Sample Collection

Kaolinite

The kaolinite (K) was packaged 23 kg paper sacks and shipped to Drexel University from the Huber Corporation mineral processing facility in Macon, Georgia.

King of Prussia Soil

On 20 July 2001, Drs. Dennis Grubb (Apex) and Joseph Wartman (Consultant) collected the King of Prussia (KP) soil sample from a PENNDOT construction site near the Interstate 76 – State Route (SR) 202, Section 400 reconstruction project (N40.08027, W 75.39851). Mr. William Freese of Allen A. Myers Company facilitated sample collection. The KP soil may be characterized as a dark brown silty-sand. The KP soil was excavated from a roadway expansion area, placed in several sealed 210-liter plastic bags, and was transported to Drexel University.

Quarry Fines

On 14 September 2001, Dr. Grubb (Apex) collected quarry fines (QF) from the Chestnut Ridge Sand Quarry (Kunkletown, PA) that is owned and operated by Haines & Kibblehouse, Inc (H&K). Soil collection activities were coordinated and facilitated by Mr. Bruce Haas of H&K. The main products of the quarry include concrete, mortar, and asphalt sands at an average plant capacity of 3,000 tons/day. Quarry spoils result from the clayey fines occurring in the sand deposit that are liberated during a wet screening process, and are settled using a NALCO Optimer 9806 flocculant. The QF soil may be characterized as a tan sandy silt that is generated on the order of 300 to 450 tons/day (10-15% of total production). Representative samples of the QF soil were collected and placed in 210-liter steel drums. The drums were sealed to prevent loss of moisture during shipping to Drexel University.

Quarry Screenings

On 14 September 2001, quarry screenings (QS) were collected by Dr. Grubb (Apex) from the Pottstown Trap Rock Quarry (Douglassville, PA) that is owned and operated by H&K. Soil collection activities were coordinated and facilitated by Mr. Bruce Haas of H&K. The main products of the quarry presently include 2A/2RC subbase, and AASHTO No. 8, 9 and 57 aggregates at plant production rates of approximately 700,000 tons/year. The QS soils may be described as gray coarse to fine sands with some gravel passing the 1/8” to 3/16” screens, and are produced in the amount of 142,000 tons/year. Presently this material has no dedicated use unless it is blended in small quantities with other aggregate products. However, while these screenings do qualify as Bituminous Type 3B according to H&K, there is no local asphalt plant in the vicinity of the quarry that could accept these materials in a cost effective fashion. Representative samples of the QS soil were collected and placed in 210-liter steel drums. The drums were sealed to prevent loss of moisture during shipping to Drexel University.

2.0 LABORATORY TESTING PROGRAM

Upon receipt at Drexel University, the sample containers were logged, and labeled to indicate the supplier and container number (e.g. “quarry fines”). For brevity, this report will refer to the samples only by their abbreviated designations. The laboratory tests were performed at Drexel University’s Roy F. Weston Geotechnical and GeoEnvironmental Research Laboratory. As discussed in the following sections, a select series of tests were performed on the crushed glass blended with 10%, 20%, 35%, and 50% soil (by dry weight). A series of tests were also performed on unblended soil specimens (i.e. “100% soil” tests) to
establish a baseline standard. In some instances, tests were also performed on unblended crushed glass specimens (“100% glass”) to assess the repeatability of the Wartman et al. (2001) test results, or to extend these results to a different stress range of interest.

2.1 Test Procedures and Results

2.1.1 General Procedures

The glass and soil specimens were typically oven- or air-dried, and then blended by hand in a large mixing bowl. The soil-glass blends were mixed until they visually appeared to be of uniform consistency. The soil-glass blends were preserved at a low moisture content in plastic bags during the testing program.

2.1.2 Laboratory Test Results

Water Content (ASTM D-2216)

A water content test was performed on each soil in its as-received condition. Additional water content tests were performed on the soils after they were oven- or air-dried and blended with the crushed glass. Note that because blended soils were dried, their water content is not representative of these materials in their in-situ condition. The results (see Table 1) indicate that the quarry fines had a high water content, suggesting that these materials were at or near saturation in their as-received condition. The other soil materials had moderate to low as-received moisture contents. Values presented for the crushed glass (CG) are taken from Wartman et al. (2001) unless otherwise noted.

<table>
<thead>
<tr>
<th>Soil Type</th>
<th>CG</th>
<th>K Soil</th>
<th>KP Soil</th>
<th>QF Soil</th>
<th>QS Soil</th>
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<td>4.4%</td>
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<td>--</td>
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<td>20% soil</td>
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<td>--</td>
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<td>2.5%</td>
<td>1.4%</td>
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Sieve, Hydrometer and Atterberg Limit Analyses (ASTM D-421, D-422, and D4318-93)

Sieve analyses were conducted on the soil-glass blends, and both sieve and hydrometer analyses were performed on the “as-received” soil samples to classify the specimens according to the USCS (United Soil Classification System) [ASTM D-2487]. Figures 1 through 4 present the grain size distribution curves for the as received K, KP, QF and QS soil samples and soil-glass blends, respectively. Figure 1 indicates that the K soil is entirely fine grained (100% passing No. 200 sieve) in its as-received condition. Figure 2 suggests that the KP soil is generally similar in gradation to the crushed glass. Note that the grain size distributions of the CG-KP soil blends are slightly coarser than those of the unblended parent materials. This is somewhat counterintuitive, and probably reflects the minor variability in grain size distribution of the KP soil and CG. The as-received QF soil is shown in Figure 3 to be predominately fine-grained. The QS soil appears to similarly graded to crushed glass, but slightly more uniform (Figure 4).

Table 2 presents the results of the liquid and plastic limit tests (Atterberg Tests) on the K soil and the fine-grained portions of the KP, QF, and QS soils. The results indicate that kaolinite exhibited some plasticity.
The fine-grained portion of the KP and QF soils exhibited only modest plasticity. The fine-grained portion of the QS soil was nonplastic.

Table 3 categorizes the soil and soil-glass specimens based on the USCS. The KP and QS soils were similar in gradation to the crushed glass, and hence, the soil-glass specimens of these materials typically have the same (or similar) classifications as the unblended materials. The finer soils (K and QF soils) contained enough silt and clay sized particles to shift the USCS classification of the crushed glass in to the fine-grained region of the soil classification chart. Appendix A provides more details on the USCS and potential construction applications for soils having different USCS classifications. Based on PENNDOT publication 408/2000, the KP, QF, QS, and CG soils all qualify as Section 206.2 embankment materials.

### Table 2- Atterberg limits of soils

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### Table 3- USCS classifications of soil and soil-glass specimens

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</table>

Modified Proctor Compaction Tests (ASTM D-1557)

Modified Proctor compaction tests were performed on the soils and soil-glass blends. Figures 5 through 8 show the compaction moisture-density relationships for each of the soil blends. For comparison purposes, zero aid voids curves (ZAV, maximum dry density as a function of moisture content for a fully saturated sample) are also shown for specific gravity (SG) values of 2.48 and 2.70, which are representative for crushed glass (Wartman et al. 2001) and typical soils (Lambe and Whitman 1969), respectively. Note that the compaction data points for the unblended KP and QS soils slightly exceed the ZAV lines, indicating that the SG of these soils may exceed the assumed value of 2.7. The compaction tests were typically performed using 5 moisture-density points. For some samples, additional points were developed to better define the compaction curves. The moisture-density curves shown in Figures 5 through 8 exhibit the characteristic convex shape of natural aggregates, suggesting that the CG-soil blends behave in a manner similar to natural aggregates. The CG-soil blend curves generally clustered together, while the fine grained soil compaction curves are shifted toward the lower density, higher water content range of the graphs. This is commensurate with the observations of others (e.g. Bardet 1997) who have noted that fine grained plastic soils typically have lower compacted unit weights and higher optimum water contents than coarser materials. Third or fourth degree polynomial curves were fitted to the data shown in Figures 5 through 8 to compute the maximum dry density ($\gamma_{d,\text{max}}$) and optimum water content ($W_{\text{opt}}$) values (Table 4).
Given the differences in gradation between the CG and soils, higher densities and lower optimum water contents generally result due to better packing and infilling of voids between the coarser particles. This effect is most pronounced with the CG, K, and QF blends. This phenomenon is to be differentiated from increases in $\gamma_{d,\text{max}}$ or soil density that result from increases in specific gravity. For example, the QS soil and CG have very similar gradations suggesting that the particle configurations would also be similar when blended, i.e., void infilling is not the principle cause of increased $\gamma_{d,\text{max}}$, or soil density. Hence, all of the compaction curves have a similar shape and are vertically stacked (i.e., same $W_{\text{opt}}$), with the 100% QS soil and 100% CG having the highest and lowest $\gamma_{d,\text{max}}$, respectively. This effect is clearly shown of Figure 8.

<table>
<thead>
<tr>
<th>Soil</th>
<th>Property</th>
<th>10% soil</th>
<th>20% soil</th>
<th>35% soil</th>
<th>50% soil</th>
<th>100% soil</th>
</tr>
</thead>
<tbody>
<tr>
<td>K</td>
<td>$\gamma_{d,\text{max}}$ (kN/m$^3$)</td>
<td>20.75</td>
<td>20.50</td>
<td>20.07</td>
<td>18.50</td>
<td>15.75</td>
</tr>
<tr>
<td></td>
<td>$W_{\text{opt}}$ (%)</td>
<td>7.7</td>
<td>7.6</td>
<td>7.6</td>
<td>9.8</td>
<td>16.0</td>
</tr>
<tr>
<td>KP</td>
<td>$\gamma_{d,\text{max}}$ (kN/m$^3$)</td>
<td>20.83</td>
<td>20.40</td>
<td>20.60</td>
<td>20.10</td>
<td>19.5</td>
</tr>
<tr>
<td></td>
<td>$W_{\text{opt}}$ (%)</td>
<td>8.0</td>
<td>8.0</td>
<td>7.5</td>
<td>9.0</td>
<td>12.3</td>
</tr>
<tr>
<td>QF</td>
<td>$\gamma_{d,\text{max}}$ (kN/m$^3$)</td>
<td>20.68</td>
<td>20.40</td>
<td>20.87</td>
<td>20.10</td>
<td>18.8</td>
</tr>
<tr>
<td></td>
<td>$W_{\text{opt}}$ (%)</td>
<td>8.2</td>
<td>8.2</td>
<td>6.8</td>
<td>9.0</td>
<td>11.8</td>
</tr>
<tr>
<td>QC</td>
<td>$\gamma_{d,\text{max}}$ (kN/m$^3$)</td>
<td>19.90</td>
<td>20.40</td>
<td>20.50</td>
<td>20.60</td>
<td>21.1</td>
</tr>
<tr>
<td></td>
<td>$W_{\text{opt}}$ (%)</td>
<td>8.1</td>
<td>9.2</td>
<td>9.8</td>
<td>9.8</td>
<td>11.0</td>
</tr>
</tbody>
</table>

Note: An additional 3-point compaction test was performed on the 100% crushed glass. The computed maximum dry density value (19.68 kN/m$^3$ at w.c. = 10.0%) is approximately 7% higher than that determined by Wartman et al. (2001). This difference may reflect the natural variability of the crushed glass.

Direct Shear Tests (ASTM D-3080)

The soil and soil-glass specimens were tested to evaluate their internal friction angle ($\phi_{ds}$) and cohesion (c) by direct shear (ds). Each sample was compacted in the direct shear box to 90% (+/- 2.4%) of its $\gamma_{d,\text{max}}$ based on ASTM D1557. The specimens were placed in several lifts and compacted using a rubber-tipped pestle. The direct shear tests were performed under three normal stresses commensurate with shallow to moderate overburden conditions (20 to 30 feet). The tests were performed at a shear rate of 1.2 mm/minute, yielding a typical time to failure of about 8 to 10 minutes, where failure was defined as the shear stress corresponding to the largest ratio of peak stress to normal stress.

The measured displacement-stress ratio relationships are shown in Figures 9 through 12. The data is presented in term of stress ratios as this parameter was used to define “failure” (see above). The displacement-stress curves for the both soil and soil-glass specimens were generally similar, although the unblended (or high soil content blend) specimens appear to exhibit slightly greater sensitivity than the soil-glass blends (sensitivity = peak strength/residual strength). Because they exhibit post-peak strength reduction, sensitive soils are susceptible to progressive failure mechanisms (i.e., rapid progression of shear failure from highly stressed soil zones). The direct shear data indicates that all of the soils and CG-soil blends are of low to negligible sensitivities. Considering that the Mohr-Column failure surface
flattens with increasing normal stress, the data shown in Figures 9 through 12 indicate that stress ratios of the low normal stress tests are more elevated than corresponding high normal stress tests.

Figures 13 through 16 show the normal stress-shear stress relationship computed from the direct shear test data for the each of the four soils and soil-glass blends. At lower normal stresses, the total strength of the soil-glass blends generally exceeds that of the crushed glass alone. At higher stresses, the opposite trend is generally observed. This is the result of increased cohesive strength, which is most pronounced at low normal stresses, and a decreased frictional strength, which more strongly influences total strength at larger normal stresses. Table 5 presents a summary of the friction angles and cohesion values determined from a linear regression of the data. The linear regressions were based on three to four normal stress-shear stress points for each sample. The coefficients of variation ($R^2$) all exceeded 0.98, indicating that the regression lines fit the data well.

It is noted that the QF soil blends typically had the highest strengths of the fine grained soil blends. It is possible that this results from the addition of a commercial-grade flocculent to the QF soil during the quarry processing (see Section 1.1). Interactions between the clay minerals and flocculent would increase the chemical attraction between the clay particles, having the net effect of increasing the shear strength of QF soil blends.

<table>
<thead>
<tr>
<th>Soil</th>
<th>Property</th>
<th>10% soil</th>
<th>20% soil</th>
<th>35% soil</th>
<th>50% soil</th>
<th>100% soil</th>
</tr>
</thead>
<tbody>
<tr>
<td>K</td>
<td>Friction angle (°)</td>
<td>44.3</td>
<td>37.9</td>
<td>33.0</td>
<td>36.2</td>
<td>24.8</td>
</tr>
<tr>
<td></td>
<td>Cohesion (kPa)</td>
<td>8.0</td>
<td>22.0</td>
<td>27.1</td>
<td>29.0</td>
<td>47.2</td>
</tr>
<tr>
<td>KP</td>
<td>Friction angle (°)</td>
<td>41.5</td>
<td>42.2</td>
<td>38.0</td>
<td>37.6</td>
<td>32.1</td>
</tr>
<tr>
<td></td>
<td>Cohesion (kPa)</td>
<td>21.2</td>
<td>16.1</td>
<td>21.5</td>
<td>23.1</td>
<td>32.5</td>
</tr>
<tr>
<td>QF</td>
<td>Friction angle (°)</td>
<td>47.7</td>
<td>47.7</td>
<td>46.9</td>
<td>40.3</td>
<td>39.0</td>
</tr>
<tr>
<td></td>
<td>Cohesion (kPa)</td>
<td>14.7</td>
<td>17.0</td>
<td>14.5</td>
<td>27.8</td>
<td>26.6</td>
</tr>
<tr>
<td>QS</td>
<td>Friction angle (°)</td>
<td>43.8</td>
<td>44.3</td>
<td>46.5</td>
<td>48.4</td>
<td>51.1</td>
</tr>
<tr>
<td></td>
<td>Cohesion (kPa)</td>
<td>17.0</td>
<td>21.4</td>
<td>16.6</td>
<td>16.9</td>
<td>16.9</td>
</tr>
</tbody>
</table>

Note: Several additional direct shear tests were performed on the 100% crushed glass. The measured friction angles ranged from 30° to 55°. The measured cohesion varied in the range of about 5 to 15 Kpa. This difference may reflect the natural variability of the crushed glass, its grain size distribution, compacted density, or moisture content.

2.2 Discussion

Figure 17 compares variations in soil compaction properties as a function of soil content for each blend. While there is some scatter to the data, several trends are apparent:

- The $\gamma_{d,\text{max}}$ of the soil-glass blends generally increases with soil content for low soil content blends (10% to 35%), but decreases with soil content at higher soil content blends (greater than 35%).
- The $W_{\text{opt}}$ of the soil-glass blends generally decreases with soil content for low soil content blends (10% to 35%), but increases with soil content at higher soil content blends (greater than 35%).

It is likely that the increasing $\gamma_{d,\text{max}}$ at low to moderate soil contents is a result of (1) the soil-glass blends becoming better graded; and, (2) the increasing average unit weight of soil-glass specimens. The average
unit weight should continually increase with increasing soil content due to differences in specific gravity: $SG_{glass}$ ~2.48 versus $SG_{soil}$ ~ 2.70. However, well-graded soils typically have higher $\gamma_{d,max}$ values then poorly-graded soils (Lambe and Whitman, 1969; Bardet et al. 1997). These two offsetting factors are thus reflected in the experimental data: the $\gamma_{d,max}$ at the higher soil contents decrease owing to the soil-glass specimens becoming more poorly graded. The trends observed for the $W_{opt}$ on Figures 5 through 8 reflect the same phenomena: as the $\gamma_{d,max}$ increases, the moisture-density curves shift up and to the left (typically bordering the ZAV curves) corresponding to a reduction in the $W_{opt}$. The opposite trend occurs as the maximum dry density decreases, and the moisture-density curves shift down and towards the right.

Figure 18 presents variation in soil strength properties as a function of soil content. Examination of this figure suggests several trends:

- The friction angle of the K, KP and QF soil blends generally tends to decrease with increasing soil content. The friction angle of the QS soil blends remains the same or slightly increases with increasing soil content.
- The cohesion ($c$) generally increases (K, KP, QF soils) or remains the same (QS soil) with increasing soil content.

Wartman et al. (2001) suggested that the frictional strength of crushed glass largely results from its angular nature. Recognizing this, it is possible to suggest the following explanation for the trends shown in Figure 34: cohesive soil added to the crushed glass “coats” the glass particles (at low soil contents), or completely infills the space between the particles (at higher soil contents), effectively resulting in the physical separation of the glass particles (i.e., glass particles “float” in a matrix of soil). Accordingly, the decrease in $\phi_{ds}$ could result from (1) a reduction in the influence of the particle angularity of the glass as soil fills (or “coats”) the asperities on the glass surface; and (2) “soil-to-soil” contact friction that is less than “glass-to-glass” contact friction. The increasing cohesion results from the addition of cohesive material to the crushed glass. Note that the QS soil, which is comprised of non-plastic angular particles of similar gradation, has relatively little effect on the strength of the crushed glass.

3.0 PRACTICAL IMPLICATIONS

3.1 Providing Cohesion to Crushed Glass

An objective of this laboratory study was to investigate the possibility of enhancing the trench stability of CG by blending it with fine grained soils to increase its cohesion. In the unblended condition, the previous laboratory results (Wartman et al. 2001) suggest that approximately 1 m deep unsupported trenches could be excavated in the compacted CG. The current study indicates that if blended with 20% or more fine grained soil (K, KP and QF soils), deeper unsupported trenches could be temporarily excavated in the CG. The unsupported trench depth is generally proportional to soil content, and ranges from approximately 1.5 m at 20% soil content to about 2.4 m at 50% soil content. Note that the Occupational Safety and Health Association (OSHA) trench and excavation regulations may require contractors to employ trench support at lesser depths.

It should be noted that the increase in CG cohesive strength described above is accompanied by a 5% to 15% decrease in frictional strength for the K, KP and QF blends. Despite this decrease in strength, the friction characteristics remain very good. Friction angles of the CG blends were about greater than or equal to $35^\circ$, which is comparable to most natural aggregates. Nevertheless, in situations in which the frictional strength of the soil is important (e.g. retaining walls, shallow foundations, etc.) the designer should consider the tradeoffs between increased cohesive strength and decreased frictional strength when recommending a soil-glass blend. It is also important to note that the strengths presented in this report are
total stress values determined by ASTM D3080, and the CG-soil blend may have lower strengths under fully saturated conditions (i.e., at low effective stresses).

Each of the soils employed in this study are readily available in Pennsylvania. With the exception of the QS (for which there a negligible increase in cohesive strength), all of the materials are suitable for blending with CG. It is believed that the results of this study can be generally extrapolated to other similar clayey soil-CG blends; however, designers are advised to perform confirmatory laboratory tests using site-specific materials and test conditions (e.g. relative compaction, water content) for important projects, such as those involving relatively deep excavations, worker safety issues (about 1 m or greater), or those involving large quantities of fill (10 m$^3$ and greater).

### 3.2 Improving Marginal Soils by Addition of Crushed Glass

When considering the addition of CG to marginal soils to improve their strength characteristics for engineering construction, Figures 17 and 18 suggest positive benefits of adding CG to clayey soils and quarry spoils.

- Addition of GC to the K, KP, QF soils resulted in increases in $\gamma_{d,max}$ values and lower water requirements.
- Considerable frictional strength was added to the K, KP, and QF soils through addition of CG.

The experimental data suggests that the frictional strength gains of the K, KP, and QF soils were of the magnitude that blending with CG (~50% glass) enabled these materials to be attractive candidates for use as structural fill, backfill and embankment construction. These applications make use of large volumes of materials, and would seem to be a very appropriate use for these blends instead of using virgin aggregates, top soil, and other earth materials that have greater benefits elsewhere. Such use of glass-marginal soil blends may potentially improve the economic position of both the recycling and quarry operations, and would preserve virgin aggregate and soil supplies for other more desirable, controlled, performance-based or higher profit applications.

It is worth noting that the CG and QS soil had little impact on each other than minor changes in $\gamma_{d,max}$, and the friction angles appeared to be slightly less for the blends over the pure materials, perhaps due to the nature of the particle shapes of the pure materials. The QS soil particles were typically longer, flatter and had a higher aspect ratio than the CG particles, which resembled angularly surfaced spheres. It is possible that when combined these different particle shapes result in an unusual geometric arrangement, with the net effect being a reduction the $\phi_{ds}$ of the blends. Nevertheless, the experimental data suggests that by itself or blended, the QS soil is a very strong frictional material that could be used in a variety of structural applications (fills, embankments, subgrades, etc.).

### 4.0 CONCLUSIONS

Several conclusions are drawn from this laboratory evaluation of select engineering-related properties of crushed glass blended with various soils.

- The cohesive strength of the CG may be increased by 50% to 100% by the addition of clayey soils (e.g. K, KP and QF soils). This increase in cohesive strength will enhance the stability of unsupported trench excavations. It is noted that the increase in cohesive strength is accompanied by a modest (about 5 to 15%) decrease in frictional strength.
- The engineering characteristics of the CG-soil blends considered in this study are similar to those of natural soils of similar gradations.
The addition of CG to the marginal clayey soils (K, KP and QF soils) markedly improved their frictional strength characteristics. This finding suggests that the engineering strength properties of marginal materials (e.g. dredge, mining and quarry spoils) may be significantly enhanced through the addition of CG. This warrants additional research.

5.0 REFERENCES

Figure 1 – Grain size distribution of K, CG, and soil-CG blends
Figure 2 – Grain size distribution of KP, CG, and soil-CG blends
Figure 3 – Grain size distribution of QF, CG, and soil-CG blends
Figure 4 – Grain size distribution of QS, CG, and soil-CG blends
Figure 5 – Modified Proctor moisture-density relationships for K, CG, and soil-CG blends
Figure 6 – Modified Proctor moisture-density relationships for KP, CG, and soil-CG blends
Figure 7 – Modified Proctor moisture-density relationships for QF, CG, and soil-CG blends
Figure 8 – Modified Proctor moisture-density relationships for QS, CG, and soil-CG blends
Figure 9 – Displacement-shear diagrams for the K and K-CG blends
Figure 9 – Displacement-shear diagrams for the K and K-CG blends (continued)
Figure 10 – Displacement-shear diagrams for the KP and KP-CG blends
Figure 10 – Displacement-shear diagrams for the KP and KP-CG blends (continued)
Figure 11 – Displacement-shear diagrams for the QF and QF-CG blends
Figure 11 – Displacement-shear diagrams for the QF and QF-CG blends (continued)
Figure 12 – Displacement-shear diagrams for the QS and QS-CG blends
Figure 12 – Displacement-shear diagrams for the QS and QS-CG blends (continued)
Figure 13 – Shear stress-normal stress data for K, CG, and soil-CG blends
Figure 14 – Shear stress-normal stress data for KP, CG, and soil-CG blends
Figure 15 – Shear stress-normal stress data for QF, CG, and soil-CG blends
Figure 16 – Shear stress-normal stress data for QS, CG, and soil-CG blends
Figure 17 – Soil compaction properties versus soil content.
Figure 18 – Soil strength properties versus soil content.
Appendix A

(Bardet 1997)