A Tool Kit for the Use of Post-Consumer Glass as a Construction Aggregate

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A Tool Kit for the Use of Post-Consumer Glass as a Construction Aggregate

FINAL REPORT

Prepared for:

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1. Introduction

Purpose of the Tool Kit

Since the publication of the Clean Washington Center's (CWC) Glass Feedstock Evaluation Project in 1993, engineers and construction contractors have implemented a number of projects, in Washington State and elsewhere, using glass as an aggregate feedstock. Also during the last four years, a number of additional studies have been conducted to examine the use of glass as a construction aggregate. Despite these important developments, acceptance has been slow for the use of glass as an aggregate by construction professionals

This **Glass Construction Aggregate Tool Kit** has been developed for project owners, designers, contractors, material suppliers, and specifying and permitting agencies. Its purpose is to increase the quality and focus of information available on the use of glass as a construction aggregate in order to increase the confidence with which glass may be used as a replacement for mineral aggregates, and in other speciality applications. This Toolkit updates and consolidates technical engineering information on recycled glass aggregates based on previous research and in-situ material performance. The Toolkit also couples the technical information with examples of successful uses of glass in specific construction applications.

Previous Investigations Evaluated

This publication is the product of the efforts of many organizations and individuals. The majority of this toolkit represents a consolidation of the Clean Washington Center's *Glass Feedstock Evaluation Project, Volumes 1-5*, prepared by Dames & Moore, Inc. in 1993

Information and test results from the following publications has been incorporated into the consolidated Glass Feedstock Evaluation:

1. Florida Department of Transportation, *Developing Specifications for Waste Glass and Waste-to-Energy Bottom Ash as Highway Fill Materials, Volume 2 of 2 (Waste Glass).*

Prepared by the Florida Institutue of Technology, Melbourne, Florida, 1995.

3. Clean Washington Center, *Best Practices in Glass Recycling.* Prepared in cooperation with Soil and Environmental Engineers, Inc. and Re-Sourcing Associates, Inc., Seattle, Washington, 1996.

4. Browning-Ferris Industries of Ohio, *Laboratory Testing Results, Glass and Rubber Samples, Lorain County Landfill.* Prepared by Woodward-Clyde Consultants, Oberlin Ohio, 1993.

5. Browning-Ferris Industries of Ohio, *Pulverized Glass Test Pad, Lorain County Sanitary Landfill*, Project No. 93-1359. Prepared by Paul C. Rizzo and Associates, Inc, Oberlin, Ohio, 1994.

6. Henry, Karen and Morin, Susan Hunnewell, U.S. Army Cold Regions Research Engineering Laboratory, *The Frost Susceptibility of Crushed Glass Used as a Construction Aggregate.* Draft Report, Febraury, 1997.

7. Clean Washington Center, *Crushed Glass as a Filter Medium for the Onsite Treatment of Wastewater.* Prepared by Stuth and Company, Maple Valley, WA., 1977.

Information in the Toolkit

The Glass Construction Aggregate Toolkit provides the information to successfully use recycled glass in value-added construction applications, organized as follows:

➢ **Technical Information - Sections 2,3, and 4.** This Toolkit incorporates information from a number of ground-breaking testing and research reports on the use of glass. Sections 2, 3, and 4 are focused on those issues that have proven to be the most critical of those affecting the use of glass in construction applications: geotechnical and engineering properties; physical, chemical, and environmental properties; and equipment guidelines. Each section contains realistic recommendations for construction aggregate users, suppliers, and designers based on experiences and lessons learned.

Throughout these sections, the toolkit refers to samples of glass cullet that were used to test material properties, engineering characteristics, and environmental impacts during the CWC and FDOT studies. The chart below describes the sample names and sample configurations for the major studies referenced.

Samples Referenced in the Toolkit

Cullet Sample Number	Debris Levels[1]	Cullet Contents (%)	Cullet Gradations	Collection and Sorting Source
CWC Glass Feedstock Study				
CA-14	High	15, 50, 100	¼" minus ¾ minus	Blue Bags - Commingled Bottles/Cans/Paper
CA-15	High	15, 50, 100	¼" minus ¾ minus	Curbside - Commingled Only - Non-color sorted
AZ-01	High	15, 50, 100	¼" minus ¾ minus	Dropbox/Barrels - Unattended
OR-05	High	15, 50, 100	¼" minus ¾ minus	Curbside - Commingled Glass Only - Color Sorted at Curb
WM-10	High	15, 50, 100	¼" minus ¾ minus	Curbside - Commingled With Other Containers - Negative Sort
CA-13	High	15, 50, 100	¼" minus ¾ minus	Redemption
OR-01	High	15, 50, 100	¼" minus ¾ minus	Dropbox/Barrels - Unattended
WM-14	High	15, 50, 100	¼" minus ¾ minus	Blue Bags - Commingled Bottles/Cans/Paper
WM-11	Medium	15, 50, 100	¼" minus ¾ minus	Curbside - Commingled With Other Containers - Mixed Fraction
BFI-06	Medium	15, 50, 100	¼" minus ¾ minus	Curbside - Commingled Glass Only - Facility Sorted - Positive Sort

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[1] High Debris Levels = 5%-15%
Medium Debris Levels = 1% - 5%
Low Debris Levels = <1%

Samples Referenced in the Toolkit

Cullet Sample Number	Debris Levels[1]	Cullet Contents (%)	Cullet Gradations	Collection and Sorting Source
CA-09	Medium	15, 50, 100	¼” minus ¾minus	Curbside - Commingled With Other Containers - Positive Sort
BFI-07	Medium	15, 50, 100	¼” minus ¾minus	Curbside - Commingled Glass Only - Facility Sorted - Negative Sort
OR-12A	Medium	15, 50, 100	¼” minus ¾minus	Deposit Collection
AZ-02	Medium	15, 50, 100	¼” minus ¾minus	Dropbox/Barrels - Attended
AZ-06	Medium	15, 50, 100	¼” minus ¾minus	Curbside - Commingled Glass Only - Positive Sort
OR-12	Medium	15, 50, 100	¼” minus ¾minus	Deposit Collection
WM-09	Medium	15, 50, 100	¼” minus ¾minus	Curbside - Commingled With Other Containers - Positive Sort
MN-08	Low	15, 50, 100	¼” minus ¾minus	Curbside - Commingled Glass Only - Mixed Cullet Fraction
WA-11	Low	15, 50, 100	¼” minus ¾minus	Curbside - Commingled With other Containers - Mixed Fraction
WA-10	Low	15, 50, 100	¼” minus ¾minus	Curbside - Commingled With Other Containers - Negative Sort
MN-04	Low	15, 50, 100	¼” minus ¾minus	Curbside - source Separated by Consumer
WA-09	Low	15, 50, 100	¼” minus ¾minus	Curbside - Commingled With Other Containers - Positive Sort
WA-15	Low	15, 50, 100	¼” minus ¾minus	Furnace Ready Cullet - Beneficiated
Florida Department of Transportation Study				
WPBMRF	Medium	100	ASTM D 448 #8, #9, #10	West Palm Beach Material Recycling Facility

Samples Referenced in the Toolkit				
Cullet Sample Number	**Debris Levels[1]**	**Cullet Contents (%)**	**Cullet Gradations**	**Collection and Sorting Source**
BSMG	Medium	100	ASTM D 448 #8, #9, #10	Southeast Recycling Corporation (Brevard Shredded Mixed Glass)

- **Model specifications for specific aggregate applications - Section 5.** The authors evaluated guidelines and specifications developed in several studies, and have modified them based on a comparison to the specifications used in the case history and in-situ performance. Section 5 presents model specifications for several end-use applications.

- **Lessons Learned from previous uses of glass in construction applications - Section 6.** This Toolkit has the benefit of learning from years of in-field use of glass. **Section 6** presents case histories of five projects in Washington, and four projects in other states. Information for these case histories was collected by interviewing project owners, designers, contractors, material suppliers, specifying and permitting agencies, or a combination of all. Washington State projects were visited in person, and photographs are included in the Appendix.

  The resulting case history portfolio of successful uses of glass in construction applications includes project descriptions/characteristics and valuable in-field lessons learned. Material specifications and construction information have been detailed as part of each case history, when available. Cost information has been captured to the extent that the documentation maintains the proprietary aspects of the project.

2. Geotechnical and Engineering Properties

This section of the Toolkit presents material properties of glass cullet and the engineering characteristics of cullet aggregate. Table 1 lists potential applications for cullet along with the level of importance (H=High, L=Low) material properties and engineering characteristics have on the performance of cullet in these applications.

Table 1
Construction Application and Property Matrix

	Material Properties				**Engineering Characteristics**		
Applications	**Specific Gravity**	**Gradation**	**Workability**	**Durability**	**Compaction**	**Permeability**	**Shear Strength**
General Backfill							
Non-Loaded Conditions	H	H	H	L	L	L	L
Fluctuating Loads	H	H	H	H	H	L	H
Heavy, Stationary Loads	H	H	H	L	H	L	H
Roadways							
Base, Subbase	H	H	H	H	H	H	H
Embankments	H	H	H	L	H	L	H
Utilities							
Pipe Trench Bedding/Backfill	H	L	H	L	H	L	L
Conduit Bedding & Backfill	H	L	H	L	H	L	L
Fiber Optic Cable Bedding & Backfill	H	L	H	L	H	L	L
Drainage							
Foundation Drainage	H	H	H	L	H	H	L
Drainage Blanket	H	H	H	L	H	H	L
French Drains	H	H	H	L	H	H	L
Septic Fields	H	H	H	L	H	H	L

Table 1
Construction Application and Property Matrix

	Material Properties				Engineering Characteristics		
Applications	**Specific Gravity**	**Gradation**	**Workability**	**Durability**	**Compaction**	**Permeability**	**Shear Strength**
Leachate Treatment	H	H	H	L	H	H	L
Miscellaneous							
Landfill Cover	H	L	H	L	H	L	L
Underground Tank Fill	H	L	H	L	H	L	L

1. Material Properties

Specific Gravity

Specific gravity, a measure of a material's density, is a widely used parameter in establishing the density-volume relationship of a soil mass. Typical values of specific gravity for natural aggregate are 2.65 to 2.68 (Bowles, 1988), and typical values for commercial glass are 2.49 to 2.51 (BCIT, 1991; HWA, 1992). Since density relates directly to engineering properties such as compaction and shear strength, specific gravity is an important baseline property.

The CWC's Glass Feedstock Evaluation conducted fourteen specific gravity tests on on samples comprised of two cullet sources, three cullet contents (100%, 50%, and 15%), and two cullet sizes (1/4 inch minus and 3/4 inch minus). Crushed rock was the natural aggregate used in all of the mixed samples. Two repetitive tests were conducted for statistical analysis. Additionally, specific gravity tests were conducted on the two types of natural aggregate (gravelly sand and crushed rock) with no added cullet.

Advantage

The specific gravity of glass cullet test results show that at the same weight, 10% to 15% more volume of glass aggregates can be shipped compared with natural aggregates, resulting in lower shipping costs.

The Glass Feedstock Evaluation test results indicate that the specific gravities of the coarse cullet range from 1.96 to 2.41 and the specific gravity of the fine cullet range from 2.49 to 2.52. The difference in these ranges is believed due to the difference in the test procedure used for the coarse and fine cullet and the difference in the debris levels of these cullet samples. These values agree with values obtained in the testing performed in the Florida Department of

Transportation (FDOT) Study. The 3/4 inch minus CA-14 cullet tested by the CWC had a debris content of about 5% by visual classification, while the 1/4 inch minus CA-14 cullet had a debris content of 2%-3%, both by visual classification. Both the 3/4 inch minus and 1/4 inch minus gradations of the WA-09 cullet had about 1% debris, by visual classification. The lowest specific gravity of 1.96 measured for the one sample of 3/4 inch minus cullet reflects the higher debris level of the sample, while the specific gravity of the other sample of 3/4 inch minus cullet was 2.41.

The specific gravities of the 1/4 inch minus cullet are close to the typical value of glass. This closeness confirms the fact that both 1/4 inch minus cullet samples had a low debris level. On the other hand, the specific gravity of the WA-09 cullet was slightly higher than the CA-14 cullet. This difference may be the result of slight difference in debris level of these two cullet samples.

The specific gravities of the crushed rock and gravelly sand ranged from 2.60 to 2.83. These values are typical of natural aggregate and were higher than those of the cullet. The specific gravities of the mixed samples were found in between those of the 100% cullet and 100% natural aggregate.

The difference in the specific gravities of the cullet and natural aggregate and the difference in the specific gravities of the CA-14 and WA-09 cullet samples are believed to affect the relative density and the unit weight of the compacted samples. These effects are presented in the sections that follow.

Relative Density

Relative density is a measure of a soil mass's density relative to its possible range of density. For cohesionless, granular material such as cullet, the possible range of density is determined by the maximum density and minimum density index tests. The standard methods for determining these values are ASTM D 4253 (maximum density) and D 4254 (minimum density). The maximum and minimum index density results can be used to correlate with density determinations from compaction tests such as the Proctor and WSDOT 606. The relative density procedure used in the CWC’s Glass Feedstock Evaluation was a vibratory procedure that did not create much crushing of the cullet particles. This produced different results than the Proctor compaction tests, which produced substantial crushing of the cullet particles.

The CWC's Glass Feedstock Evaluation conducted fourteen maximum and fourteen minimum index density tests using the ASTM D 4253 and ASTM D 4254 test procedures, respectively. The tests were conducted on samples comprised of two cullet sources (WA-09 and CA-14), three cullet contents (100%, 50%, and 15%), and two cullet gradations (1/4 inch minus and 3/4 inch minus). The gravelly sand was the natural aggregate used in all of the mixed samples. Additionally, two repetitive tests were conducted for statistical analysis.

Table 2
Relative Density Test Results

Cullet Sample Number[2]	Type of Natural Aggregate	Cullet Content (%)	Cullet Gradation	
Maximum index Density				**Maximum Index Density (pcf)**
CA-14		100	¼" minus	98.4
CA-14		100	¾" minus	90.9
WA-09		100	¼" minus	106.6
WA-09		100	¾" minus	109.3
CA-14	gravelly sand	50	¼" minus	122.6
CA-14	gravelly sand	50	¾" minus	130.0
WA-09	gravelly sand	50	¼" minus	126.7
WA-09[3]	gravelly sand	50	¼" minus	126.7
WA-09[3]	gravelly sand	50	¼" minus	128.8
CA-14	gravelly sand	15	¼" minus	137.9
CA-14	gravelly sand	15	¾" minus	137.0
WA-09	gravelly sand	15	¼" minus	135.9

Table 2
Relative Density Test Results

Cullet Sample Number[2]	Type of Natural Aggregate	Cullet Content (%)	Cullet Gradation	
WA-09	gravelly sand	15	¾" minus	140.3
Minimum Index Density				**Minimum Index Density (pcf)**
CA-14		100	¼" minus	81.2
CA-14		100	¾" minus	76.8
WA-09		100	¼" minus	86.3
WA-09		100	¾" minus	89.5
CA-14	gravelly sand	50	¼" minus	102.3
CA-14	gravelly sand	50	¾" minus	105.9
WA-09	gravelly sand	50	¼" minus	102.7
WA-09[3]	gravelly sand	50	¼" minus	102.5
WA-09[3]	gravelly sand	50	¼" minus	104.2
WA-09	gravelly sand	50	¾" minus	104.4
CA-14	gravelly sand	15	¼" minus	116.6
CA-14	gravelly sand	15	¾" minus	115.8
WA-09	gravelly sand	15	¼" minus	114.2
WA-09	gravelly sand	15	¾" minus	116.5

NOTE:
1. All tests performed using the ASTM D 4254 test procedure.
2. CA-14 is the high debris level sample. WA-09 is the low debris level sample.
3. Repetitive test for statistical analysis.

The data indicates that the maximum index density of the test samples was affected largely by the cullet content, and to a lesser degree by the cullet size and debris level. The trend of increasing density with decreasing cullet content is also true for the minimum index density.

When a maximum density test was conducted using Proctor compaction energy in accordance with ASTM D 698-83 for the FDOT Study, glass particles spilled from the mold as the compaction hammer contacted the waste glass surface. It was assumed that this phenomenon could be attributed to the low surface tension and rigidity of the glass particles. The study thus concluded that the conventional Proctor moisture-density relationship did not exist.

Maximum densities obtained using the Modified Marshall-Proctor method during the FDOT Study produced results close to those of the CWC's Glass Feedstock Evaluation The grain size distribution of the glass determined from a sample after compaction indicated no change in grain size distribution and therefore no significant degradation of the particles. The Modified Marshall-Proctor method for compaction was found to be satisfactory to determine the maximum densities of glass aggregate.

Durability

The durability of a material has historically been regarded as essential to good aggregate for roadways. Durability relies on hardness, toughness, and abrasion resistance. The properties of hardness and toughness are closely related. Hardness is made up, in part, by abrasion resistance and toughness is generally understood to mean the power possessed by a material to resist fracture under impact.

Crushing and grinding of cullet are expected to occur during mixing, transportation, placement and compaction. To evaluate the durability of cullet and cullet-aggregate mixtures, the CWC's Glass Feedstock Evaluation conducted Los Angeles (L.A.) abrasion tests using standard method ASTM C 131. At present, most highway agencies specify a limit on abrasion resistance of aggregate based on the Los Angeles test. The test results, along with those of the sieve analysis provide valuable insight into the suitability of the material for roadway base course and fill under fluctuating loads.

The first sample was comprised of 100% WA-09 cullet with a gradation of 1/4 inch minus. A second sample consisted of 100% WA-09 cullet with a gradation of 3/4 inch minus. A third sample consisted of 100% CA-14 cullet having a gradation of 1/4 inch minus. The fourth sample was 100% crushed rock. The test results are presented in Table 3, below.

Table 3
L. A. Abrasion Test Results[1.]

Cullet Sample Number[2.]	Type of Natural Aggregate	Cullet Content (%)	Cullet Gradation	Percent Loss

Table 3
L. A. Abrasion Test Results[1.]

Cullet Sample Number[2.]	Type of Natural Aggregate	Cullet Content (%)	Cullet Gradation	Percent Loss
WA-09	-	100	¼" minus	29.9
WA-09	-	100	¾" minus	41.7
CA-14	-	100	¼" minus	30.9
-	crushed rock	0	-	13.6

Notes: 1. All tests performed using the ASTM C 131 test procedure.
2. CA-14 is the high debris level sample. WA-09 is the low debris level sample.

No tests were conducted for mixed cullet-aggregate samples. However, it is reasonable to assume that the percent loss of mixed samples would lie somewhere between the percent loss of the two components. The percent loss of the 100% cullet samples represents the worse condition if the materials are used as a construction aggregate. The CWC test results indicate that cullet was not as sound, mechanically, as crushed rock. The percent loss of the 1/4 inch minus cullet was about 30%, and that of the 3/4 inch minus cullet was about 42%. These losses were at least two times greater than that of the crushed rock.

Of course, natural aggregate durability is dependent on the characteristics of the local supply. For example, a study conducted by the U.S. Army's Cold Regions Research Engineering Laboratory in New Hampshire conducted L.A. Abrasion tests on 30% by weight glass-70% aggregate and 100% aggregate. Test results indicated that the percent wear of 100% aggregate samples ranged from 33% to 52.3%, while the cullet-aggregate mix ranged from 25.3% to 31.2%. The first of the two aggregates used in the New Hampshire test was classified as a well-graded sand with gravel, and the second as a poorly graded sand with gravel.

As mentioned above, the percent losses of the 100% cullet results in the CWC study represent a worse case scenario. The test values for 100% cullet samples in that study were relatively close to the normal limiting values for roadway aggregate. For instance, the Washington

State Department of Transportation (WSDOT) specifies that the not-to-exceed value for a crushed surface course is 35% and the value for ballast is 40%. From the CWC test results shown in Table 3, the 100% ¼-inch minus cullet will meet this requirement. Based on the results of 100% ¾-inch minus cullet, it is projected that 50% ¾-inch minus cullet will also meet this requirement.

The CWC study also shows that the debris level appears to have an effect on the percent loss. This can be seen from the slightly higher loss of the CA-14, 1/4 inch minus cullet than the WA-09, 1/4 inch minus cullet. The difference was small since the difference in the debris level of these two materials was small.

Soundness

The soundness of aggregates, or their resistance to the forces of weathering, is another important consideration in the selection of a material for roadway construction. The primary exposure is freezing and thawing. Most aggregate specifications from northern states include a provision for soundness. The most common soundness requirement for aggregates is based on exposure to sodium or magnesium sulfate solution (ASTM C 88). Container glass is inert to exposure to these solutions. As such, the CWC's Glass Feedstock Evaluation found that soundness is a property which can not be measured for cullet. It is more appropriate to use the L.A. abrasion test to determine the degradation properties of cullet .

2. Engineering Characteristics

In the CWC Glass Feedstock Evaluation Engineering Performance Testing Program, samples were tested by investigating three independent variables. These included cullet content in the aggregate mix (15, 50, or 100% by weight), aggregate mix gradation (1/4" minus or 3/4" minus), and relative debris level (high or low). The lower bound of cullet content (15% by weight) was selected to correspond to the maximum use content for cullet specified in the Washington and California departments of transportation specifications prior to the CWC study. The mix gradations of 1/4" minus and 3/4" minus were intended to cover the majority of applications for cullet aggregates. By varying the relative debris levels, it was possible to investigate the sensitivity of the chemical and engineering properties to this parameter.

Compaction

The compaction characteristics of engineering fill include the relationship of the density and moisture content, the effect of compaction method on this relationship, the potential of gradation change during the compaction process, and the sensitivity of the material to weather (moisture change) conditions. Since almost all engineering fill requires compaction during placement, the characteristics are relevant to almost all potential cullet applications. By testing materials of different constituents with different compaction methods, the compaction characteristics of cullet and cullet mixtures can be evaluated. Compaction test results and curves can be used to develop a data base for correlation with other materials. The results of the compaction densities can also be compared with the densities from the relative density tests. Through a common parameter - dry density - other engineering properties such as shear strength, can be correlated, and the sensitivity of these properties to the material constituents and compaction methods can be studied. The CWC Glass Feedstock Evaluation study used three compaction test methods:

- ASTM D 698, the standard Proctor test.
- ASTM D 1557, the modified Proctor test.
- Washington Department of Transportation (WSDOT) test method 606.

Proctor tests are widely used for field control of fill materials. Typically, engineers will specify the materials be compacted to a state such that the field density exceeds a specific percentage of the maximum density obtained from the Proctor tests. Since the engineering properties of the fill materials are related to their density, controlling this parameter in the field ensures the engineering performance (strength for instance) of the materials.

ASTM D 698 results represent the effects of light compaction equipment. It uses impact compaction, and the input energy produced in the laboratory is comparable to light field compaction equipment. The test results are typically used for the field control of unloaded or lightly loaded fill. ASTM D 1557 results represent heavy impact compaction conditions. Test input energy is comparable to heavy compaction equipment. The test results are used for the field control of heavily loaded conditions. WSDOT test method 606 is used for the field control of base course material for roadway construction. The test uses vibratory compaction and its effort and mechanism are comparable to vibratory compaction equipment.

In the Proctor test, a sample is compacted in a mold by a steel hammer, weighing 5.5 and 10 pounds for the standard and modified tests, respectively. Field compaction equipment, on the other hand, does not use impact compaction. Generally, the difference in compaction modes between laboratory and field is not critical if the materials are granular, natural materials. However, when a material consists of fragile or angular particles, the difference in compaction may be significant.

Advantage

The small gradation change seen during the hydrostatic compression and triaxial shear tests implies minimal breakage of the cullet under normal working loads. In other words, the cullet particles, like the crushed rock particles, have adequate strength to behave like an elastic body which deforms under hydrostatic loads, and displaces or rotates near shear planes.

A previous study found that the standard Proctor test created minor crushing of the cullet particles (Metro Testing Laboratory, 1991). The degree of crushing is expected to increase with increasing cullet content and particle size. The degree of change in gradation was investigated by conducting a sieve analysis after each compaction test. The gradation change created by each compaction method was then determined.

Compaction quality control of construction aggregates is usually achieved through control of the in-situ density. Nuclear density gages are commonly used to measure in-situ density. The standard test methods are: ASTM D 2922 for density, and ASTM D 3017 for moisture content. See Part 3 - "Field Testing" - of this Section for a discussion of compaction quality control using nuclear density gages.

The CWC's Glass Feedstock Evaluation compaction tests were conducted on samples consisting of two sources (WA-09 and CA-14), three cullet contents (100%, 50%, and 15%), and two cullet sizes (1/4 inch minus and 3/4 inch minus). For each method, repetitive tests were conducted for statistical analysis. Also, tests on 100% natural aggregate were conducted for comparison.

Standard Proctor:

A total of 15 Standard Proctor tests were conducted using the ASTM D 698 test procedure. The test results are summarized in Table 3. Plate 29 (following page) shows the relationships between the moisture contents and the dry densities of the compacted samples. Plate 29 contains the results of samples with the same cullet debris level and size but different mix percentages. For ease of comparison, the result for the non-cullet sample is also plotted. Two repetitive tests were conducted for statistical analysis. These results are not plotted, but are included in Table 4 below.

Table 4
Standard Proctor Compaction Test Results[1.]

Cullet Sample Number[2.]	Type of Natural Aggregate	Cullet Content (%)	Cullet Gradation	Maximum Dry Density (pcf)	Optimum Moisture Content (%)
CA-14		100	¼" minus	104.4	4.7
CA-14		100	¾" minus	99.3	5.5
WA-09		100	¼" minus	104.9	5.0
WA-09		100	¾" minus	107.5	5.3
CA-14	gravelly sand	50	¼" minus	119.5	6.5
CA-14	gravelly sand	50	¾" minus	124.6	6.0
WA-09	gravelly sand	50	¼" minus	121.4	6.0
WA-09[3.]	gravelly sand	50	¼" minus	121.0	6.6
WA-09[3.]	gravelly sand	50	¼" minus	121.8	5.3
WA-09	gravelly sand	50	¾" minus	126.7	5.7
CA-14	gravelly sand	15	¼" minus	126.5	6.5
CA-14	gravelly sand	15	¾" minus	130.5	5.7
WA-09	gravelly sand	15	¼" minus	127.0	8.6
WA-09	gravelly sand	15	¾" minus	130.5	6.0
-	gravelly sand	0	-	132.5	8.8

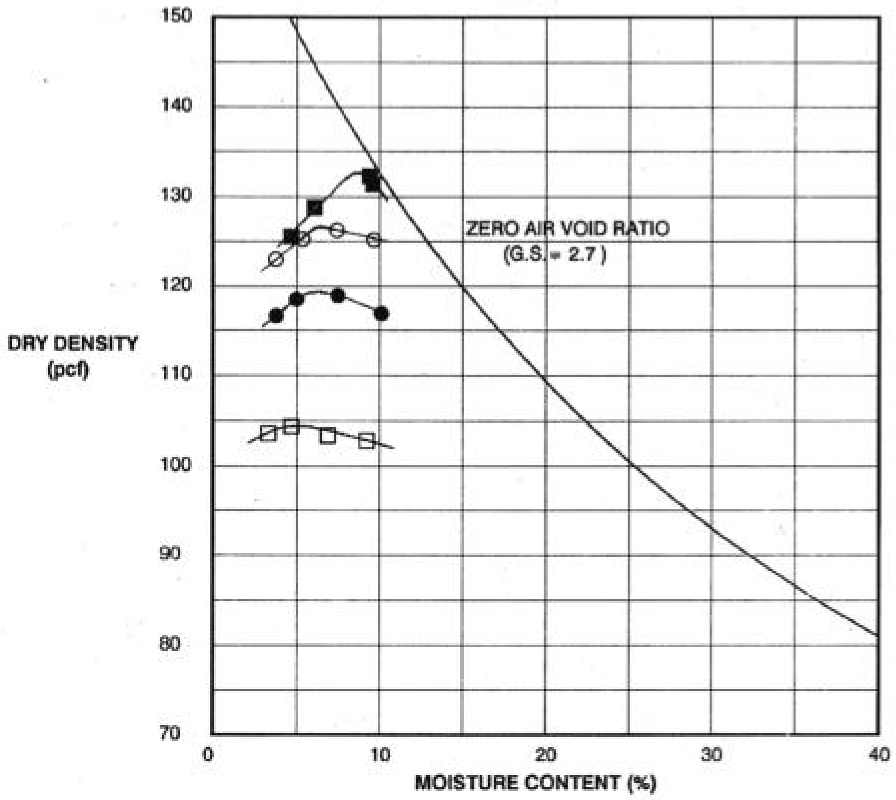
Notes:
1. All tests performed using the ASTM D 698 test procedure.
2. CA-14 is the high debris level sample. WA-09 is the low debris level sample.
3. Repetitive test for statistical analysis.

Plate 29 and the data summarized in Table 5 indicate that the compacted density of the test samples was affected largely by the cullet content, and to a lesser degree by cullet size and debris level. These effects are summarized below:

1. The density increases with decreasing cullet content.

2. The optimum moisture content increased slightly with decreasing cullet content.
3. In general, all the moisture-density curves are relatively flat. The only exception to this was the sample comprised of 100% WA-09, 3/4 inch minus cullet.

COMPACTION TEST



SYMBOL	DESCRIPTION	TEST METHOD	OPTIMUM MOISTURE(%)	MAX. DRY DENSITY(pcf)
○	15% cullet & 85% gravelly sand	ASTM D698	6.5	126.5
●	50% cullet & 50% gravelly sand	ASTM D698	6.5	119.5
□	100% cullet	ASTM D698	4.7	104.4
■	100% gravelly sand	ASTM D698	8.8	132.5

REMARKS: Sample composed of cullet (CA-14, 1/4 inch minus) and gravelly sand.

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Plate 29

maximum dry densities and their corresponding moisture contents.Plate 34 contains the results of samples composed of the same cullet debris level and size but different mix percentages. For ease of comparison, the result of the crushed rock sample is also plotted. Two repetitive tests were conducted for statistical analysis. These results are not plotted but are summarized in Table 5.

Table 5
Modified Proctor Compaction Test Results[1]

Cullet Sample Number[2]	Type of Natural Aggregate	Cullet Content (%)	Cullet Gradation	Maximum Dry Density (pcf)	Optimum Moisture Content (%)
CA-14		100	¼" minus	111.0	5.6
CA-14		100	¾" minus	111.4	7.5
WA-09		100	¼" minus	113.0	5.2
WA-09		100	¾" minus	117.8	6.0
CA-14	crushed rock	50	¼" minus	126.0	9.2
CA-14	crushed rock	50	¾" minus	125.3	6.2
CA-14[3]	crushed rock	50	¾" minus	127.3	6.7
CA-14[3]	crushed rock	50	¾" minus	126.6	6.5
WA-09	crushed rock	50	¼" minus	130.0	6.5
WA-09	crushed rock	50	¾" minus	134.5	7.0
CA-14	crushed rock	15	¼" minus	138.5	5.5
CA-14	crushed rock	15	¾" minus	138.6	6.0
WA-09	crushed rock	15	¼" minus	138.5	6.7
WA-09	crushed rock	15	¾" minus	140.0	6.0
-	crushed rock only	0	-	142.5	7.3
-	gravelly sand	0	-	133.9	9.0

Notes:
1. All tests performed using the ASTM D 1557 test procedure.
2. CA-14 is the high debris level sample. WA-09 is the low debris level sample.
3. Repetitive test for statistical analysis.

The test results shown in the plate and table indicate similar trends and effects as those observed from the Standard Proctor tests. The compacted density of the test samples was affected largely by the cullet content, and to a lesser degree by the cullet size and debris level. These effects are described below.

1. The density increased with decreasing cullet content.

2. All the moisture-density curves were relatively flat.

3. The densities of the low debris WA-09 samples were slightly higher than those of the high debris CA-14 samples.

4. The sample of 100% CA-14, 3/4 inch minus cullet had the lowest density. All other samples with 3/4 inch minus cullet had a higher density than the samples with 1/4 inch minus cullet. This difference is more obvious for the WA-09 cullet samples than the CA-14 cullet samples.

WSDOT 606: A total of 15 compaction tests were conducted using the WSDOT 606 test procedure. The test procedure involves compacting the coarse fraction (retained on No. 4 sieve) and the fine fraction (passing No. 4 sieve) of the sample separately using a vibratory compactor. The dry density and specific gravity of the two fractions of the samples are used to generate a curve of maximum density versus percent passing the U.S. No. 4 sieve. The resulting plot was different than that obtained from the Proctor compaction tests, which relates dry density to moisture content. The curve generated from the WSDOT 606 test method accounts for fluctuations in gradation so that the maximum dry density can be obtained easily in the field. The curve excludes the effect of moisture on the maximum dry density. This exclusion, however, tends to have a minimal effect on the maximum density since the compaction characteristics of these materials are relatively insensitive to the moisture content.

The maximum density curves are generated using a computer program developed by WSDOT. The maximum dry density and weighed free moisture content of each test sample are summarized in Table 6. The weighed free moisture content was obtained by combining the free moisture contents of the two compacted (coarse and fine) samples using their corresponding proportions.

Table 6
WSDOT 606 Compaction Test Results[1].

Cullet Sample Number[2]	Type of Natural Aggregate	Cullet Content (%)	Cullet Gradation	Maximum Dry Density (pcf)	Optimum Moisture Content (%)

Table 6
WSDOT 606 Compaction Test Results[1].

Cullet Sample Number[2.]	Type of Natural Aggregate	Cullet Content (%)	Cullet Gradation	Maximum Dry Density (pcf)	Optimum Moisture Content (%)
CA-14		100	¼" minus	103.5[5.]	6.8[5.]
CA-14		100	¾" minus	123.2	4.1
WA-09		100	¼" minus	106.3[5.]	6.4[5.]
WA-09		100	¾" minus	124.0	5.7
CA-14	crushed rock	50	¼" minus	134.2	6.3
CA-14	crushed rock	50	¾" minus	130.3	4.6
WA-09	crushed rock	50	¼" minus	134.6	6.3
WA-09[3.]	crushed rock	50	¼" minus	133.9	5.4
WA-09[3.]	crushed rock	50	¼" minus	134.9	6.3
WA-09	crushed rock	50	¾" minus	133.7	5.4
CA-14	crushed rock	15	¼" minus	137.9	5.5
CA-14	crushed rock	15	¾" minus	137.9	6.0
WA-09	crushed rock	15	¼" minus	139.9	5.1
WA-09	crushed rock	15	¾" minus	139.2	4.8
-	crushed rock	0	-	143.2	4.6

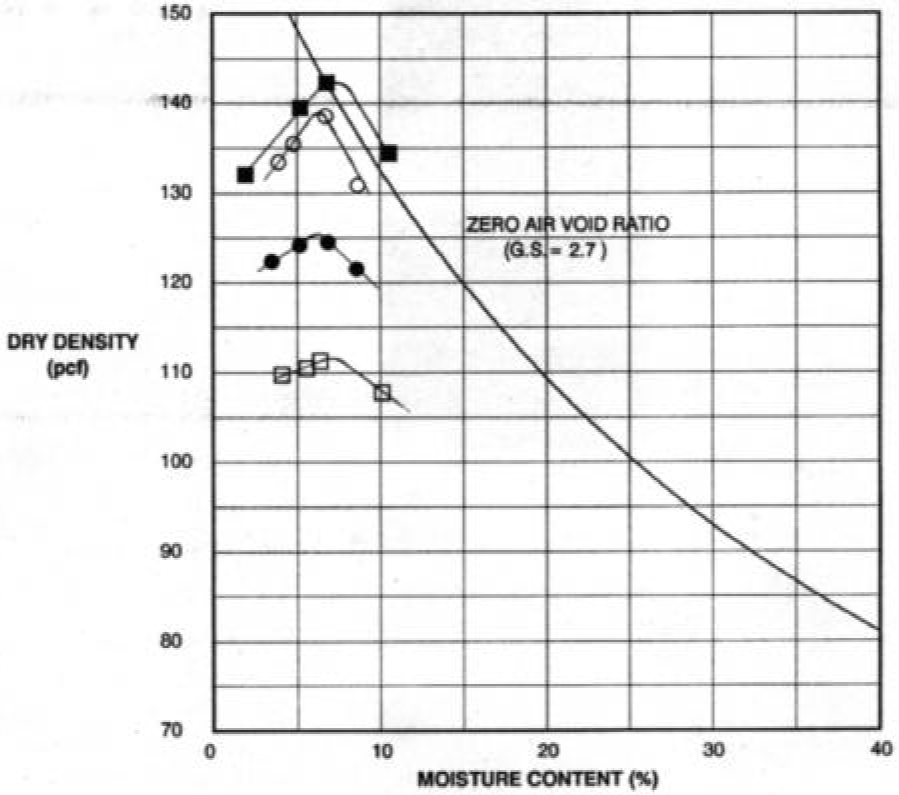
Notes:
1. All tests performed using the WSDOT 606 test procedure.
2. CA-14 is the high debris level sample. WA-09 is the low debris level sample.
3. Repetitive test for statistical analysis.
4. See text for details.
5. Test conducted on No.4 minus material only.

Table 6 indicates that the factors affecting the density of the compacted samples were similar to those identified from the Proctor tests, that is, the compacted density of the test samples was affected largely by the cullet content, and to a lesser degree by the cullet size and debris level. These effects are described below.

1. The density increased with decreasing cullet content.

2. In general, the densities of the low debris samples were higher than those of the high debris samples.

COMPACTION TEST



SYMBOL	DESCRIPTION	TEST METHOD	OPTIMUM MOISTURE(%)	MAX. DRY DENSITY(pcf)
○	15% cullet & 85% crushed rock	ASTM D1557	6.0	138.6
●	50% cullet & 50% crushed rock	ASTM D1557	6.2	125.3
□	100% cullet	ASTM D1557	7.5	111.4
■	100% crushed rock	ASTM D1557	7.2	142.0

REMARKS: Sample composed of cullet (CA-14, 3/4 inch minus) and crushed rock.

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Plate 34

Compaction Test Results Summary: The above compaction test results reveal several important facts regarding the compactability and workability of the cullet samples. These facts are described below.

Advantage

Insensitivity to moisture content also indicates that glass aggregates can be placed in the field over a wider range of moisture conditions than natural aggregates.

1. In general, the Proctor compaction curves of the cullet samples are relatively flat, which indicates that the compacted density was not sensitive to moisture content. This insensitivity to moisture content also indicates that glass aggregates can be placed in the field during inclement weather. Thus, construction downtime during such periods can be reduced to a minimum.
2. The maximum density values obtained from the Modified Proctor and WSDOT 606 compaction tests are about equivalent. The former method uses an impact type of compaction whereas the latter uses a vibratory type. Both methods simulate the compaction efforts of heavy compaction field equipment.

Gradation

One of the important classifications of aggregates is based on size. The gradation of a material can affect its engineering performance in many ways. For example, well-graded materials can generally be compacted to a denser state, thus will have a higher strength but lower permeability than poorly-graded materials.[2]

Many applications such as roadway and engineering fill use gradation as the primary or sole criteria for acceptance. Specifications dictate the distribution of particle sizes for a particular application. For example, the specified gradation for a road aggregate varies according to the purpose for which it is to be used (subbase, base, etc.). Gradation will be one of the major factors in determining the suitability of cullet for use as a construction material.

Aggregate gradation is obtained by sieve analysis. The test is conducted by shaking the aggregate through a stack of Standard U.S. sieves with specified openings. The gradation is established by measuring the portion of material retained on each sieve.

The CWC Glass Feedstock Evaluation conducted a total of 55 sieve analyses using the modified ASTM D 422 test procedure. The test

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[2] A well-graded material has a good representation of particle sizes over a wide range. A poorly-graded one has an excess or deficiency of certain grain sizes, or has mostly the same particle size.

procedure did not include washing the samples on a #200 screen prior to sieving. The wash step was excluded to more closely mimic actual screening operations, and to avoid removal of possible residue from the cullet surface. The CWC Glass Feedstock Evaluation sieve analyses are broken down as follows:

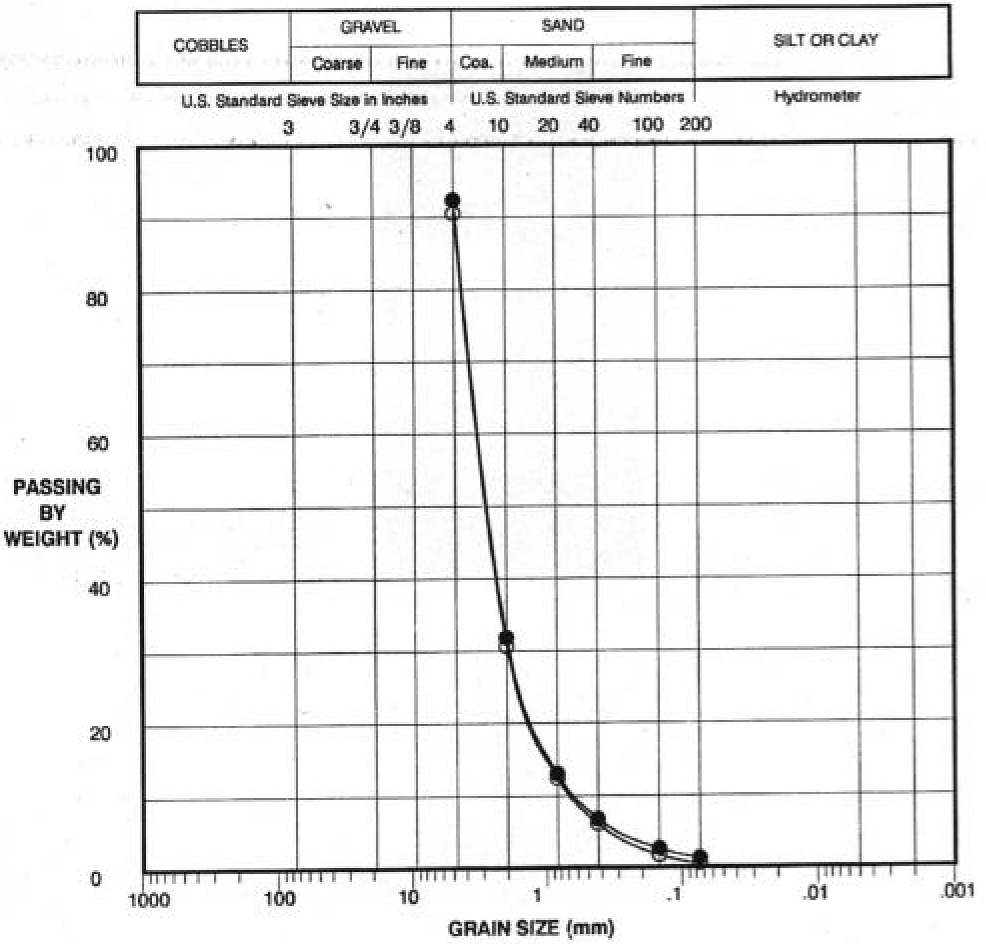
- Three tests were conducted on gravelly sand natural aggregate. Due to the large quantity (approximately 2,000 pounds) of the material used in the test program, the three tests were conducted on different batches in order to evaluate the consistency of the gradation between different batches.

- Three tests were conducted on crushed rock natural aggregate. As for the gravelly sand, the tests were conducted to evaluate the gradation consistency between batches.

- Two tests were performed to evaluate the effect of washing the cullet sample on the resulting gradation. One test was performed on a sample that was washed on a #200 sieve as specified in the standard test procedure, the other was performed on a non-washed sample.

- Sixteen tests were conducted on samples before and after compaction using the Standard Proctor compaction method (ASTM D 698). The tests were conducted to evaluate the gradation change due to the compaction procedure. Cullet in the test samples varied from 15% to 100% in content, and from 1/4 inch minus to 3/4 inch minus in gradation. The test results are presented in Plate 4 and 7.

- Sixteen tests were conducted on samples before and after compaction using the Modified Proctor method (ASTM D 1557). The tests were conducted to evaluate the gradation change due to the compaction procedure. Cullet in the test samples varied from 15% to 100% in content, and from 1/4 inch minus to 3/4 inch minus in gradation. The test results are presented in Plate 15.



GRAIN SIZE DISTRIBUTION

SYMBOL	DESCRIPTION	% GRAVEL	% SAND	% FINES
○	Before Compaction	0.0	99.4	0.6
●	After Compaction	0.0	98.7	1.3

REMARKS: Sample composed of 100% cullet (CA-14,1/4 inch minus).
Curves depict sample gradation before and after compaction using the ASTM D698 test procedure.

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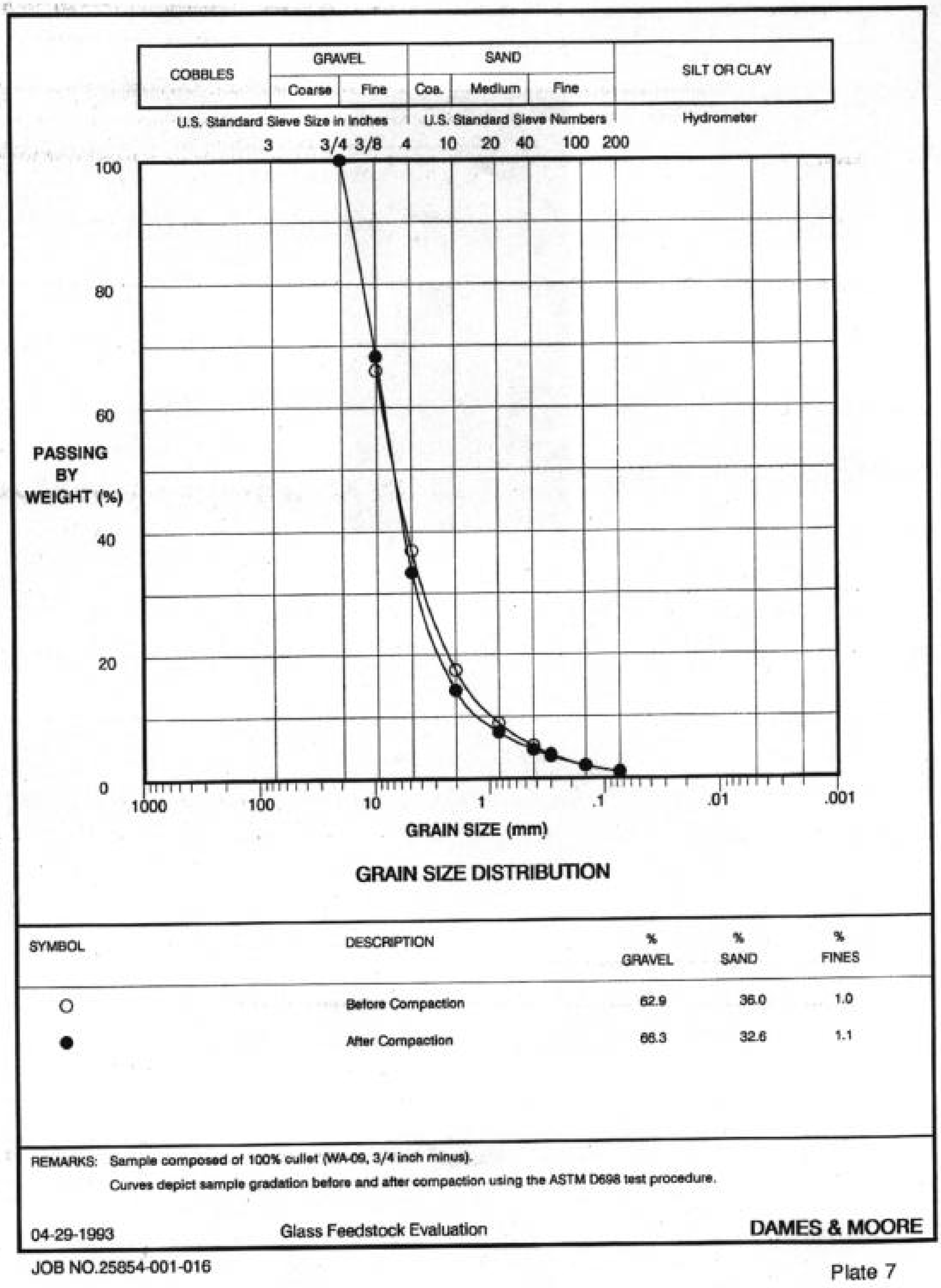
Plate 4



GRAIN SIZE DISTRIBUTION

SYMBOL	DESCRIPTION	% GRAVEL	% SAND	% FINES
○	Before Compaction	62.9	36.0	1.0
●	After Compaction	66.3	32.6	1.1

REMARKS: Sample composed of 100% cullet (WA-09, 3/4 inch minus).
Curves depict sample gradation before and after compaction using the ASTM D698 test procedure.

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Glass Feedstock Evaluation

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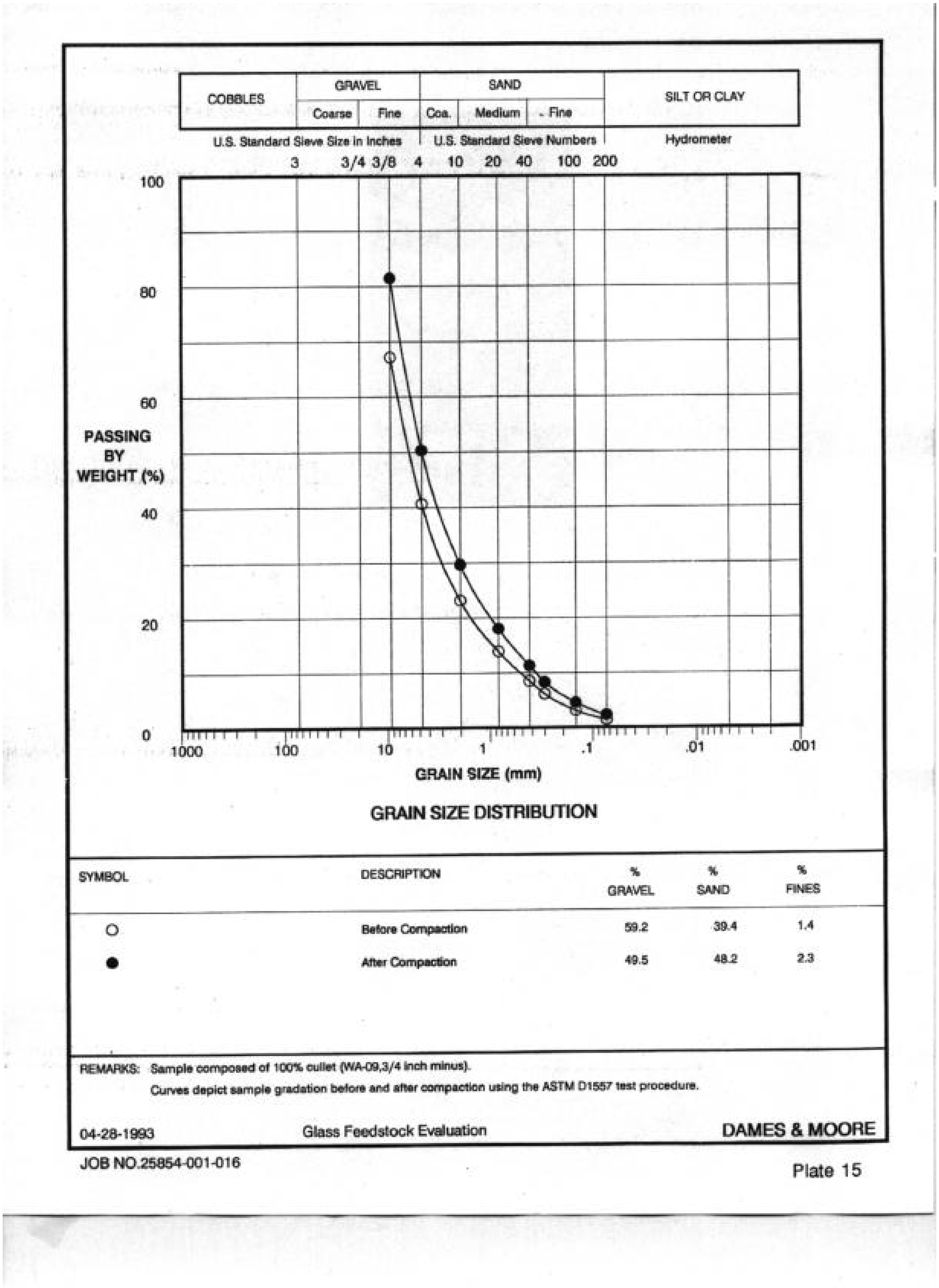
Plate 7



GRAIN SIZE DISTRIBUTION

SYMBOL	DESCRIPTION	% GRAVEL	% SAND	% FINES
○	Before Compaction	59.2	39.4	1.4
●	After Compaction	49.5	48.2	2.3

REMARKS: Sample composed of 100% cullet (WA-09,3/4 inch minus).
Curves depict sample gradation before and after compaction using the ASTM D1557 test procedure.

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Plate 15

- Eight tests were conducted on samples before and after compaction using the WSDOT 606 method. The tests were conducted to evaluate the gradation change due to the compaction procedure. Cullet gradation was held at 3/4 inch minus, while the cullet content was varied from 50% to 100%. Both crushed rock and gravelly sand natural aggregates were used.

- A total of six tests were conducted on three samples before and after they were subjected to the combined process of hydrostatic compression and triaxial shearing. The test samples consisted of 50% cullet with a 3/4 inch minus cullet size.

- One test was conducted in the early part of the gradation test program to check the possibility of using only one quarter of the compaction sample for the post-compaction gradation test. This result indicated a substantial difference in gradation change than the test conducted on a whole compaction sample (see Plate 15). The comparison indicated the need to conduct the sieve analyses on a whole compaction sample. As a result, almost all of the gradation tests performed before and after the compaction tests were conducted on the whole compaction sample. The exception to this were the tests conducted on the Standard Proctor test samples having 15% and 50% cullet contents and 1/4 inch minus and 3/4 inch minus sizes. In these cases, only one quarter of the compaction samples was used for the post-compaction sieve analysis. The small change in gradation seems to confirm the adequacy of gradation test on one quarter of the sample.

The significance of the gradation test results is discussed below.

1. The natural aggregates used in the test program had good repeatability in gradation.

2. Not washing the sample induced very minimal change in gradation.

3. The Standard Proctor compaction method (ASTM D 698) represents the effects of light field compaction equipment. The gradation test results (Plate 4) indicates that this compaction method produces essentially no gradation changes for all samples tested.

4. The Modified Proctor compaction method (ASTM D 1557) represents the effects of heavy impact field compaction equipment. The test results indicate obvious gradation change for the majority of the samples. The degree of change depends mostly on the size of the cullet. The cullet content of the mixed sample and the cullet debris level also affected the change, but to a lesser degree.

   The size effect can be seen by looking at plate 15. The data indicates that slight changes occurred to the 1/4 inch minus cullet sample whereas obvious change occurred to the 3/4 inch minus cullet sample. In other words, most of the changes occurred in the coarse and medium sizes. The fines content increased slightly but the maximum fines content were generally less than five percent. Plate 15 also indicates that the degree of gradation change decreased with decreasing cullet content.

   Plate 15 also suggests that the degrees of gradation change were higher for the CA-14 cullet (high debris content sample) than the WA-09 cullet (low debris content sample).

5. The WSDOT 606 compaction method represents the effects of vibratory field compaction equipment. The gradation test results indicate that this compaction method produced essentially no gradation changes in the samples, including the sample comprised of 100%, 3/4 inch minus cullet.

6. The gradation test results also indicate that the processes of hydrostatic compression and triaxial shearing produced essentially no gradation changes for samples comprised of 50% 3/4 inch minus cullet.

The above gradation test results indicate that significant gradation change occurs only when 100% cullet samples were subjected to heavy impact compaction. All the other test conditions produced little or no gradation change. These results imply the feasibility of using all three compaction methods for the field control of fill materials comprised of cullet. Since these compaction methods mimic the compactive effort of field equipment, minimal gradation change would also imply minimal difference in the engineering properties of the laboratory-compacted samples as compared with those of the field-compacted cullet. This result would substantiate engineering designs that use the properties derived from laboratory samples.

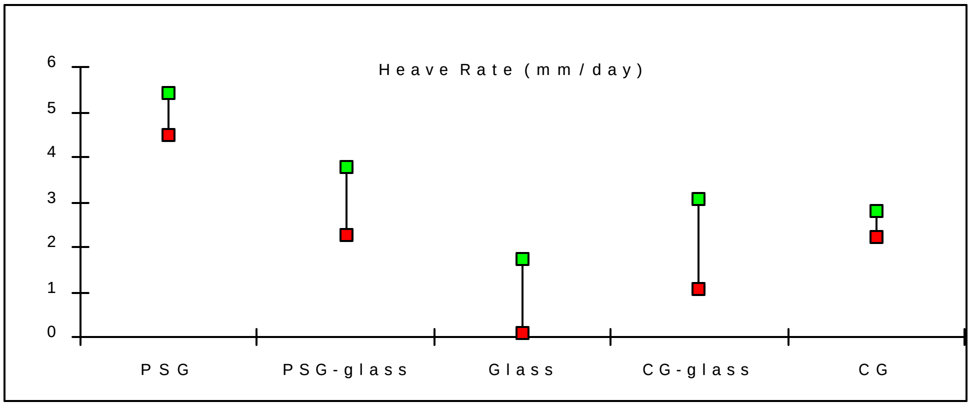
The only exception to the above general statement is for the condition of 100% cullet subject to heavy impact compaction. However, this type of compaction would normally be used for fill materials that would be subjected to dynamic or heavy stationary loads. These loading conditions would preclude the use of 100% cullet.

Also, the most common criteria for establishing the frost susceptibility of soils is based on particle size. The U.S. Army Cold Regions Research Engineering Laboratory Study conducted tests of the frost susceptibility of crushed glass used as a construction aggregate. Their research yielded frost susceptibility classifications of crushed, recycled glass for purposes of using it as a backfill or in unbound aggregate layers in geotechnical structures.

Advantage

The fines in glass aggregate do not clump and retain water like the fines in natural aggregates; therefore, glass aggregate is less likely to "wick" and retain water, a cause of frost susceptibility.

The frost susceptibility for 100% glass cullet specimens and 30% by weight glass cullet-aggregate specimens was determined using ASTM D 5918. Results of the New Hampshire study indicate the the cullet had negligible to very low frost susceptibility, and did not increase the frost susceptibility of the aggregate. Based on a comparison of grain size distributions of the cullet and aggregate with the work of others, including the CWC Glass Feedstock Evaluation, it was concluded that the material tested represented typical cullet for which the engineering properties described in this toolkit have been determined. The following chart shows that adding 30% by weight recycled glass containing less than 1% particles finer than 0.075 mm to either of two local gravels lowered the heave rate of the gravel mixture.



PSG=Perry Stream Gravel (Pittsburg, NH)

CG = Concord Gravel (Concord, NH)

Permeability

The permeability or hydraulic conductivity of a fill material plays a decisive role in drainage applications. The rate of fluid flowing through a soil mass relates directly to its permeability. In hydrogeologic studies of natural and processed materials, permeability is usually the most important property. In engineering practice, the permeability of a fill material often plays a decisive role in material selection, particularly for applications related to drainage. For granular fill material, high permeability is usually more beneficial than low. The exception to that may be for leachate treatment where a specific range of permeability may be required.

The permeability of a granular material depends on its gradation and density. Generally, a well-graded material is less permeable due to its lower void ratio. It is believed that permeability is also a function of surface texture, which affects drag or friction between the fluid and particle surface. As a result, a mix of aggregate and "smooth" cullet may have a higher permeability than that of "rough" natural sand and gravel.

There are two typical laboratory tests available for the determination of permeability - constant head and falling head tests. The former is used principally for coarse-grained soils (clean sands and gravels) with permeabilities greater than 1 x 10^{-4} centimeters per second (cm/s), and the latter is used primarily for fine-grained soils (silt and clay) with permeabilities less than 1 x 10^{-4} centimeters per second (cm/s).

A total of 28 constant head permeability tests were conducted during the CWC Glass Feedstock Evaluation. The tests were conducted on samples comprised of two cullet sources (WA-09 and CA-14), three cullet contents (100%, 50% and 15%), two cullet sizes (1/4 minus and 3/4 inch minus), and two relative compaction levels (90% and 95% of the ASTM D 698 maximum density). Two of the tests were conducted on gravelly sand compacted to relative compaction levels of 90% and 95%. Additionally, two repetitive tests were conducted for statistical analysis.

Twenty-four of the tests were conducted using a constant head permeameter test apparatus in accordance with the ASTM D 2434 test procedure. However, four test samples (100%, 3/4 inch minus, WA-09 and CA-14 cullet samples, compacted to 90% and 95% relative compaction) were found to have a permeability that was greater than the maximum value that the apparatus could measure. As a result, the four tests were conducted with the samples placed and compacted in a PVC pipe measuring 4 inches in diameter and 34 inches in length. A wire mesh was attached to the bottom of the pipe to retain the sample and to ensure a free draining condition. A burette was mounted at the side of the pipe to control the head of water.

Table 7
Soil Permeability Classifications

Degree of Permeability	Range of Permeability k, (cm/sec)
High	greater than 10^{-1}
Medium	10^{-1} to 10^{-3}
Low	10^{-3} to 10^{-5}
Very Low	10^{-5} to 10^{-7}
"Impermeable"	less than 10^{-7}

Test results indicate that the permeabilities of the cullet samples increased with increasing cullet content, cullet size, and debris level but decreased with increasing degree of compaction. This trend is consistent with the permeabilities of the 100% gravelly sand compacted to the 90% and 95% compaction levels. For engineering purposes, the permeability of soils or aggregates can be categorized into the five groups depicted in Table 7, at left. (Terzarghi and Peck, 1967). Test results are shown in Table 8, below.

Table 8
Constant Head Permeability Test Results[1].

Cullet Sample Number[2]	Type of Natural Aggregate	Cullet Content (%)	Cullet Gradation	Approximate Relative Compaction	Dry Density (pcf)	Permeability (10^{-2} cm/sec)
CA-14		100	¼" minus	90% of ASTM D 698	94.9	6.0
CA-14[4]		100	¾" minus	90% of ASTM D 698	89.6	26.0
WA-09		100	¼" minus	90% of ASTM D 698	93.6	6.4
WA-09[4]		100	¾" minus	90% of ASTM D 698	95.9	18.0
CA-14	gravelly sand	50	¼" minus	90% of ASTM D 698	108.1	4.4
CA-14	gravelly sand	50	¾" minus	90% of ASTM D 698	113.2	4.8
WA-09	gravelly sand	50	¼" minus	90% of ASTM D 698	110.1	5.2
WA-09[3]	gravelly sand	50	¼" minus	90% of ASTM D 698	110.0	5.5
WA-09[3]	gravelly sand	50	¼" minus	90% of ASTM D 698	110.3	5.0
WA-09	gravelly sand	50	¾" minus	90% of ASTM D 698	114.4	5.6
CA-14	gravelly sand	15	¼" minus	90% of ASTM D 698	115.4	2.6
CA-14	gravelly sand	15	¾" minus	90% of ASTM D 698	118.9	3.1
WA-09	gravelly sand	15	¼" minus	90% of ASTM D 698	114.0	2.6
WA-09	gravelly sand	15	¾" minus	90% of ASTM D 698	117.3	4.3
-	gravelly sand	0	-	90% of ASTM D 698	120.7	2.4
CA-14		100	¼" minus	95% of ASTM D 698	98.6	4.4
CA-14[4]		100	¾" minus	95% of ASTM D 698	93.2	23.0
WA-09		100	¼" minus	95% of ASTM D 698	99.7	4.8
WA-09[4]		100	¾" minus	95% of ASTM D 698	102.9	6.5
CA-14	gravelly sand	50	¼" minus	95% of ASTM D 698	113.8	4.1
CA-14	gravelly sand	50	¾" minus	95% of ASTM D 698	119.1	4.5
WA-09	gravelly sand	50	¼" minus	95% of ASTM D 698	115.8	3.5
WA-09	gravelly sand	50	¾" minus	95% of ASTM D 698	120.6	4.1
CA-14	gravelly sand	15	¼" minus	95% of ASTM D 698	119.7	1.4
CA-14	gravelly sand	15	¾" minus	95% of ASTM D 698	124.2	2.5
WA-09	gravelly sand	15	¼" minus	95% of ASTM D 698	121.2	2.2
WA-09	gravelly sand	15	¾" minus	95% of ASTM D 698	124.5	3.4
-	gravelly sand	0	-	95% of ASTM D 698	126.7	1.4

Notes:
1. All tests performed using the ASTM D 2434 test procedure, unless noted otherwise.
2. CA-14 is the high debris level sample, and WA-09 is the low debris level sample.
3. Repetitive test for statistical analysis.
4. Modified test procedure. See report text for details.

Table 9
Range of Permeabilities for Waste Glass Meeting ASTM D 448 #8, #9, #10 and WPBMRF Gradations

ASTM D 448 Gradations	Permeability Range (cm/sec)
#8 Lower Limit	5-7
#8 Average	6-8
#8 Upper Limit	4-8
#9 Lower Limit	4-8
#9 Average	4-10
#9 Upper Limit	1-3
#10 Lower Limit	0.7-2
#10 Average	0.003-0.01
#10 Upper Limit	0.003-0.02
WPBMRF	0.3-5

Based on this classification, the cullet samples tested exhibited medium permeability, except for three of the 3/4-inch minus cullet samples, which exhibited high permeability. These samples were 100% CA-14 and WA-09 cullets compacted to 90% of their maximum dry density, and 100% CA-14 cullet compacted to 95% of its maximum dry density.

The FDOT study evaluated the relationship between permeability and density. The range of permeabilities for waste glass meeting ASTM gradations #8, #9, and #10 classification at upper, average and lower limit of gradations, and West Palm Beach Material Recycling Facility (WPBMRF) waste glass are listed in Table 9.

The variation of permeability for ASTM #8, #9, #10, and WPBMRF gradations with respect to density was studied (Syed, 1993). The FDOT study found that an inverse relationship does exist between density and permeability. The relationship between permeability and density showed less than one order of magnitude (cm/sec) difference between the permeabilities at the minimum and maximum density. Fine-grained soils inherently have much larger variations
(Holtz and Kovacs, 1981).

Related Research: Beginning in 1994, the CWC sponsored a two-year study of the use if glass in septic treatment sand filters. Before starting that study, relative infiltration tests were performed on C-33 concrete sand, which is the standard material specified for sand filters in Washington State. The results were compared with recycled container glass processed by the same sand processor and meeting C-33 gradation specifications.

Advantage

The permeability characteristics of glass aggregate make it an excellent medium for drainage applications. Retaining wall backfill, drainage blankets, and leachate collection are examples of

The results of those tests indicated that the sand had a relative infiltration rate of 95 seconds per inch, while the glass infiltration rate was 9 seconds per inch — nine times the infiltration speed. The large difference in infiltration rates was attributed to two things. First, some of the fines in sand tend to be clay-like materials which contribute to clogging, while all of the fines in glass, especially 8 mesh and smaller, tend to be more cubical and less rounded than sand. This may mean that the glass does not pack as densely as sand. This characteristic of glass compared with sand has been seen in other infiltration studies.[3]

Shear Strength

For certain applications, aggregate is the primary load carrying medium. The shear strength of an engineering material is an important property for design of earthen structures such as embankments, roadway base courses, and engineering fill. Therefore it is extremely important to consider the factors which influence the load supporting capacity of an aggregate mass. These factors are grouped under the term "interparticle friction," since this is the primary mechanism by which the load is carried by a compacted aggregate mass. A number of factors contribute to interparticle friction, namely, 1) particle surface texture, 2) particle shape, 3) void ratio (degree of compaction), 4) particle size, and 5) particle gradation.

Of these factors, it is believed that the most important single factor contributing to interparticle friction is particle surface texture. Generally speaking, in a compacted aggregate mass, rather than points of contact, areas of aggregate abutt each other. Hence the surface texture of the aggregate will greatly influence the resistance to displacement of two particles. As the surface roughness increases, the interparticle friction, as manifested by the angle of internal friction, f, increases considerably.

Angularity of particles may influence to a lesser degree the interparticle friction. Particle angularity does influence the compaction of aggregate mixtures in that a mixture containing angular aggregate will compact under a given compactive effort to a lesser degree than will a mixture containing rounded aggregate. It is possible however, that cullet - a relatively angular material - may permit a greater degree

Advantage

Adding finer cullet to coarser natural aggregates may improve the strength characteristics of the natural aggregate alone by increasing the "particle packing." Concrete aggregate processors use this characteristic to develop stronger recycled concrete/ recycled glass blends.

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ter Medium for the Onsite Treatment of Wastewater," 1977, CWC. Prepared
aple Valley, WA.

of compaction, particularly when heavy rollers area used. A mix made with the rounded aggregate may actually shove and push excessively under the roller and "decompact". As a result, adding cullet to rounded aggregates may improve their strength characteristics.

Particle gradation will influence internal friction to a certain extent. The denser the aggregate, the more contact areas in the compacted aggregate mass; hence, the greater the frictional resistance.

Void ratio, or degree of packing (compaction), will influence internal friction in the same manner as gradation; that is, the lower the void ratio or the greater degree of packing for a given aggregate gradation, the greater will be the frictional resistance of the aggregate mass.

Typically, the shear strength is defined as the ultimate stress level that the material can sustain. For some cases, such as base course or materials under fluctuating loading, the determination of shear strength is also based on an acceptable magnitude of shear strain. Strain is an indication of the deformation that a material undergoes while being stressed. In either case, the strength needs to be interpreted from the stress-strain behavior of the material.

For granular materials, shear strength is usually expressed in terms of the interparticle friction angle. Based on a review of the literature, there is little shear strength data for cullet. Limited direct shear test data indicates a friction angle at the peak stress of f=55° (Mohr-Coulomb failure criteria) (BCIT,1991). This is about 20 percent higher than dense natural aggregate. From a soil mechanics point of view, a 55° friction angle implies a rough surface texture and a very high degree of interlocking between particles. Based on current knowledge of the brittleness of the glass particles, the implied strength may not be reliable. The limited available data suggests the need for a better way of defining cullet shear strength.

Five tests which measured shear strength were conducted on cullet-aggregate mixtures for the CWC Glass Feedstock Evaluation. These included direct shear, triaxial shear, California Bearing Ratio (CBR), Resistance R-Value, and resilient modulus. The direct shear, triaxial shear, and California Bearing Ratio test were duplicated by the FDOT study. In addition, the FDOT study conducted Limerock

Bearing Ratio (LBR) testing. The test conditions and results obtained are described below.

Direct Shear:

The direct shear test is a commonly used method to determine the shear strength of soil and rock. The shear strength of the test material is obtained in terms of the Mohr-Coulomb friction angle, f. The direct shear test generally does not reproduce in-situ stress conditions. However, this drawback is not critical when testing artificial, laboratory-formed samples. As such, the direct shear is a relatively simple, inexpensive test to determine the shear strength of cullet. There is a large data base of direct shear results for natural aggregates and processed materials.

A total of seven sets of direct shear tests were performed during the CWC Glass Feedstock Evaluation using the ASTM D 3080 test procedure. Each set consisted of three shear tests conducted with normal stresses of 1000, 2000 and 3000 psf, respectively. The tests were conducted on samples comprised of two cullet sources (WA-09 and CA-14) and three cullet contents (100%, 50% and 15%). In addition, one test was conducted on a sample composed of 100% gravelly sand. The gravelly sand was the natural aggregate used in all of the mixed samples. The test samples measured 2.5 inches in diameter and one inch in thickness. To avoid the influence of the particle size on the test results, only 1/4 inch minus particles were used in the tests.

Test results indicate that the friction angles of the cullet samples ranged from 49° to 53°, about the same as that of dense and coarse natural aggregate. In addition, cullet content and debris level did not appear to have any effects on the strength of the materials. These comparisons imply that cullet has the similar inter-particle frictional behavior to that of natural aggregate. This behavior is further discussed in the presentation of the triaxial test results.

Four direct shear tests were conducted on each gradation of mixed cullet during the FDOT study. Each consisted of three samples at the same relative density with normal stresses of 1000 psf (49 kPa), 2000 psf (98 kPa), and 4000 psf (196 kPa). This resulted in 52 direct shear tests. Shear strength envelopes for each density and gradation were developed by plotting peak shear strength against corresponding normal stress. These envelopes are somewhat nonlinear. This nonlinearity implies that a constant friction angle should not be used for waste glass unless it is conservatively chosen. Based on the data, a relatively low friction angle would be approximately 34°.

Triaxial Shear:

The triaxial shear test allows three-dimensional loading of a sample. In engineering practice, the test is regarded as superior to the direct shear test for modeling in-situ loading conditions. The triaxial shear test not only determines strength parameters, but also the stress-strain behavior of the tested materials.

The stress-strain-volume change data obtained from the triaxial tests also elucidates the frictional behavior of cullet. For instance, the crushing and particle re-orientation during shearing may generate a series of strain hardening and softening curves. The Mohr-Coulomb failure criteria that is conventionally used for soil and rock may require re-interpretation. Elastic modulus and Poisson's ratio will also be obtained from the triaxial tests. By comparing these values at different stages of shearing, their sensitivity to plastic strain can also be evaluated. To obtain the elastic response, a hydrostatic loading and unloading cycle was performed, and several loading-unloading cycles were performed during shearing in the CWC study.

A total of five sets of static triaxial shear tests were conducted during the CWC Glass Feedstock Evaluation. Each set of tests consisted of three samples. Each sample was first subjected to a hydrostatic compression test and then sheared under a constant confining pressure. The confining pressures for the three samples were 5, 10 (or 15 in one case) and 20 psi. The tests were conducted on samples comprised of one cullet source (WA-09), two cullet contents (50% and 15%), and two cullet sizes (1/4 inch minus and 3/4 inch minus). In addition, one test was conducted on samples composed of 100% crushed rock. Crushed rock was used in all the mixed samples.

Sample materials were moisture-conditioned to several percentage points drier than the optimum moisture content. The samples were prepared in a split mold in which a membrane had been placed. Six lifts of sample material was placed and compacted using a vibratory hammer to achieve a dry density close to 95% of the ASTM D 1557 maximum dry density. After sample preparation was completed and the split mold removed, a second membrane was added in an attempt to avoid punctures during testing.

The prepared samples were transferred into a triaxial chamber which was then filled with distilled water. A hydrostatic compression test was then conducted. This test involved loading and unloading the samples by increasing and decreasing the cell or confining pressures between 5 and 35 psi. The volumetric response of the samples during the hydrostatic compression test was recorded.

At the end of the hydrostatic compression test, a constant confining pressure was applied to the sample. The sample was then sheared by the application of a deviator stress. The shear test was performed under a drained condition with a loading rate of 0.02 inches per minute. A load-unload cycle was produced at axial deflections of approximately 0.1, 0.2 and 0.3 inches. The test was continued until failure of the sample occurred or an axial strain of 15% was reached.

Plate 42 presents the curves of hydrostatic pressure versus volumetric strain. These curves were obtained from the test samples which were sheared under a confining pressure of 5 psi after the hydrostatic compression test.

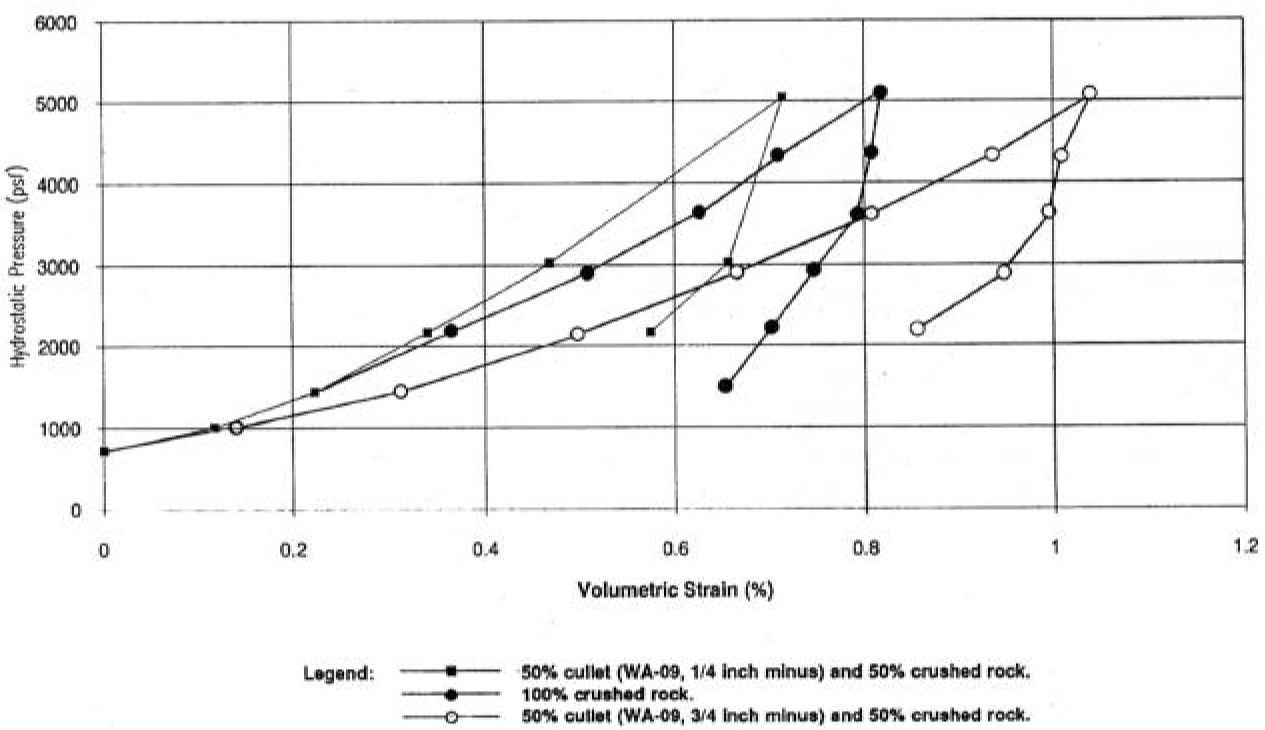
Note that the triaxial test samples measured 2.42 inches in diameter and 5.70 inches in height. This sample diameter is small in comparison to the particle size of 3/4 inch minus. Removal of large particles was not considered because it was felt that the frictional behavior of the material was the main interest of the triaxial test. Keeping the large particles may introduce a higher degree of variation in the strength data. However, since the potential for variation was the same for all samples, the effect of cullet on stress-strain behavior could still be obtained.

Plate 42 shows the volumetric behaviors of cullet and crushed rock samples under hydrostatic loads. The slope of the loading curve represents the bulk modulus of the samples. The plate indicates that for the same cullet content, the bulk modulus of the 1/4 inch minus cullet sample is higher than the bulk modulus of the 3/4 inch minus cullet. When viewing the plate, it can be seen that the bulk modulus of the samples are not sensitive to the cullet content. Also, the bulk modulus of the crushed rock sample lies between those of the cullet samples.

The permanent or plastic volumetric strain of a granular material is the result of particle re-orientation or crushing at contacts. The magnitude of the plastic strain is indicated by the strain difference between the load and unload curves. Plate 42 indicates that the plastic strain of the 1/4 inch minus cullet sample was slightly less than that of the 3/4 inch minus cullet sample. Also, the plastic strain of the crushed rock sample was about the same as that of the 3/4 inch minus cullet sample. This similarity in the magnitude of the plastic strain implies an important fact. That is, the crushing or breakage of the 3/4 inch minus cullet particles is minimal under the level of load applied. This implication can be substantiated by the fact that crushing or breakage of the crushed rock did not occur under the level of applied load.

From the mechanics point of view, the 1/4 inch minus cullet samples were stiffer than the 3/4 inch minus cullet and 100% crushed rock samples. Also, the 1/4 inch minus cullet exhibited less plastic straining than the other two types of sample. The better mechanical behavior of the 1/4 inch minus cullet samples can be explained by the assumption that the 1/4 inch minus cullet samples were more well graded than the other two types of samples. This assumption can be validated indirectly by comparing the gradation of the 100%, 1/4 and 3/4 inch minus cullet samples (see Plate 7). As indicated in these gradations, the 1/4 inch minus sample contained mostly sand-size or "filler" particles and the 3/4 inch minus sample contained mostly gravel-size particles. Since the crushed rock also contained mostly gravel-size particles, the mixed samples with the 1/4 inch minus cullet were likely more well-graded than those with the 3/4 inch minus cullet.

The data also indicates that adding cullet to crushed rock reduced the initial tangent modulus slightly. This reduction seems to be smaller for the 3/4 inch than the 1/4 inch minus cullet. However, the slope of the unloading-reloading curves (shown in the original CWC Glass Feedstock Evaluation) which normally represents the elastic modulus of the materials, appeared to be unaffected by the addition of the cullet.



Volumetric Strain Versus Hydrostatic Pressure

HYDROSTATIC COMPRESSION TEST

Glass Feedstock Evaluation Project

PLATE 42

Job No. 25854-001-016

DAMES & MOORE

The CWC Glass Feedstock Evaluation also showed the curves of axial strain versus volumetric strain. These curves indicate that all the test specimens showed a distinct shear dilatency effect. The degree of dilatency resembles those of the dense natural aggregates. Mohr-Coulomb diagrams in the CWC Glass Feedstock Evaluation show three Mohr circles and a failure envelope. The strength of the material is represented by the friction angle or slope of the envelope. As previously mentioned, the small diameter of the test specimens could have causes some variation in the peak strength. This variation is somewhat indicated in the Mohr-Coulomb diagrams. However, even with the variation, it is still clear that the friction angles of the cullet-added materials range from 42° to 46°, which are similar to that of the crushed rock. Also, it appears that there is a reduction in strength for the materials with 50% cullet.

California Bearing Ratio (CBR):

The CBR test was at one time a common test for evaluating the strength of subgrade, subbase, and base course of rigid and flexible pavements. Similar to direct shear data, a large database of CBR values is available for natural and processed aggregates. The tests on cullet allow comparison to existing information for other aggregates.

A total of nine CBR tests were performed using the ASTM D 1883 test procedure during the CWC Glass Feedstock Evaluation. The tests were conducted on samples comprised of one cullet source (WA-09), two cullet contents (50% and 15%), and two cullet sizes (1/4 inch minus and 3/4 inch minus). Crushed rock was used in all of the mixed samples. In addition, one test was conducted on a sample comprised of 100% crushed rock.

The CBR tests were conducted using a 6 inch diameter mold. The test specimens were prepared using two compaction methods. The first method corresponds to the compaction procedures used in the ASTM D 1557 method. The second method corresponds to the compaction procedures used in the WSDOT 606 test. The former employs an impact type of compaction while the latter uses a vibratory type of compaction. The CBR test specimens were compacted to about 95% of the maximum dry density obtained from each compaction method.

The purpose of using the two compaction methods in specimen preparation is to study the effect of compaction method on the CBR value. According to the test data, the CBR values of the specimens prepared using the impact compaction method were higher than those of the specimens prepared using the vibratory compaction method. The discrepancy increased as the cullet content increased. On the other hand, the CBR values of the samples with 15% cullet content were about the same as that of the crushed rock sample, regardless the method of compaction used in the specimen preparation.

The CBR value is a common parameter used in flexible pavement design. Typical values of a compacted granular material range from 40 to 80 (Department of Transportation, State of New York). The Glass Feedstock Evaluation test results indicate that the CBR values of all the cullet-added samples were within this typical range. The test data also indicate that adding 15% cullet to the crushed rock did not produce a noticeable difference in the CBR value. However, as the cullet content increased to 50%, an obvious reduction in the CBR value was shown. For those samples prepared using the impact compactor, this reduction was about 25% when the cullet content increased from 15% to 50%. A much higher reduction was noted for samples prepared using the vibratory compactor. The reduction in this case was about 50%. This discrepancy implies the importance of choosing the correct specimen preparation method for materials with cullet content over 15%.

Resistance "R"-Value:

The resistance R-value is used by some agencies as a criteria for pavement design and for acceptance of aggregates for base course. The R-value test utilizes a kneading compactor for specimen preparation. Vertical and horizontal loads are applied to the specimen by a stabilometer. The R-value is calculated based on the observed vertical and horizontal loads and horizontal deformation. The R-value is used to determine the potential strength of subgrade, subbase, and base course materials.

A total of five R-Value tests were performed during the CWC Glass Feedstock Evaluation using the Washington State Department of Transportation (WSDOT) 611 test procedure. This test procedure is a modification of the AASHTO T-190 test method. The modification involves using 15 and 25 blows of kneading compaction at pressures of 100 and 250 psi, respectively. These pressures are lower than those specified in the AASHTO T-190 method. The exudation pressure used in both of the above test procedures is 300 psi. Different exudation pressures may be used in other states. However, due to the granular nature of the test materials, it is believed that the exudation pressure will not have an substantial effect on the test results.

The R-Value tests were conducted on samples comprised of one cullet source (WA-09), two cullet contents (50% and 15%), and two cullet sizes (1/4 inch minus and 3/4 inch minus). Crushed rock was used in all the mixed samples. In addition, one test was conducted on a sample comprised of 100% crushed rock.

The test data indicates that the R-Value of all the cullet-added samples ranged from 73 to 77, which were relatively close to an R-value of 78 of the crushed rock sample. It appears that adding cullet to crushed rock reduced the R-Value slightly, and this reduction increased slightly with increasing cullet content. Also, the R-Values of the 1/4 inch minus cullet samples appeared slightly lower than those of the 3/4 inch minus cullet samples.

The R-Value relates indirectly to the strength of the material. The value is commonly used to specify base or sub-base aggregate. For instance, WSDOT specifies a minimum R-Value of 72 for gravel base, Minnesota Department of Transportation specifies a minimum R-Value of 65 for base materials, and CALTRANS specifies a minimum R-Value of 60 for Class 1 sub-base and 78 for Class 2 aggregate base. Generally, the required R-Value is higher for the base than for the subbase materials. From the test results of the cullet samples, it is clear that the cullet added crushed rock, with a cullet content up to 50%, processes adequate strength for both base and sub-base aggregate.

Resilient Modulus (Cyclic Triaxial) Test:

The resilient modulus of an aggregate is determined through a cyclic triaxial test. The resilient modulus is the stiffness of the aggregate after repeated load-unload cycles, which are applied with the triaxial test apparatus. Because of the potential for interparticle crushing of the cullet, cyclic triaxial tests also help to evaluate the effect of particle crushing.

Available test methods for determining resilient modulus are SHRP Protocol P 46 and other methods such as AASHTO T-294 test method (AASHTO, 1992). CWC Glass Feedstock Evaluation authors felt that the AASHTO standard was more applicable to all co-sponsors and thus recommend that tests be conducted according to the AASHTO T 294 method.

The cyclic triaxial test is an expensive test and is not commonly conducted. In engineering practice, the resilient modulus is often obtained from other test values such as CBR. The cyclic triaxial test is used for the evaluation of critical applications such as roadways under fluctuating loads.

A total of five resilient modulus tests were performed during the CWC's Glass Feedstock Evaluation using a modified AASHTO T-294 test procedure. In the modified procedure, an internal load cell was used instead of an external load cell as specified in the AASHTO test standard.

The tests were conducted on samples comprised of one cullet source (WA-09), two cullet contents (50% and 15%), and two cullet sizes (1/4 inch minus and 3/4 inch minus). Crushed rock was used in all the mixed samples. In addition, one test was conducted on a sample comprised of 100% crushed rock.

The test samples were moisture-conditioned to several percentage points drier than the optimum moisture content. The samples were prepared with a membrane mounted in a split mold. Each sample was prepared by compacting the materials in the mold using a vibratory hammer. The dry density of the samples so prepared were 90.6 to 98.9% of the maximum dry density as determined by the ASTM D 1557 test method.

Each sample was tested in a triaxial chamber. A pneumatic pressure of 4 psi was applied to the sample and the drain line connected to the sample was opened. The sample was then subjected to two cyclic loading sequences. In the first sequence the sample was "pre-conditioned" by 1000 cycles of cyclic deviator stress having a magnitude of 8 psi.

Table 10 shows that adding cullet to the crushed rock reduced the resilient modulus and the reduction increased with increasing cullet content. Note that the low modulus value of the 15%, 3/4 inch minus cullet sample was likely caused by the puncturing of the membrane during the test.

Table 10
Resilient Modulus (Cyclic Triaxial) Test Results[1.]

Cullet Sample Number[2.]	Type of Natural Aggregate	Cullet Content (%)	Cullet Size	Dry Density (pcf)	Resilient Modulus (ksi)[3.4.]	Resilient Modulus (ksi)[3.5.]	Parameter A[6.]	Parameter B[6.]
WA-09	crushed rock	50	¼" minus	119.2	29.7	30.8	9.8	0.355
WA-09	crushed rock	50	¾" minus	121.8	32.4	31.5	13.7	0.259
WA-09	crushed rock	15	¼" minus	137.1	33.5	34.6	9.6	0.397
WA-09	crushed rock	15	¾" minus	128.5	22.4[7.]	19.8[7.]	8.3	0.268
-	crushed rock	0	-	131.1	38.3	40.2	12.7	0.358

NOTES:
1. All tests performed using modified AASHTO T 292-91 I test procedure.
2. WA-09 is the low debris sample.
3. Resilient Modulus = A*(Bulk Stress)$^{B.}$
4. At end of preconditioning load.
5. At bulk stress of 25 psi.
6. Parameter used in equation of note 3. above.
7. Membrane punctured during test.

The resilient modulus is a measure of a material's stiffness and can be used for pavement design. The resilient modulus of natural aggregate is typically about 30 ksi at a bulk stress of 25 psi. For a granular natural aggregate, the typical value is 30 ksi at a bulk stress of 25 psi. From the data, it can be seen that even the 50% cullet sample would have a resilient modulus value appropriate for use in a typical pavement design.

One concern regarding the use of cullet-added materials in roadway construction is the ability of cullet to withstand repeated traffic loads without breakdown. To help address this concern, the change of resilient modulus of the cullet samples over the first 1000 cycles may be compared with that of the crushed rock. CWC Glass Feedstock Evaluation data indicates the cullet samples, like crushed rock, did not show appreciable changes in the modulus value. Note that the samples were subjected to a confining pressure of 4 psi and deviator stress of 8 psi in the first 1000 cycles. This stress level is typical of a sub-base material under medium to heavy traffic loads. For the crushed rock material, this stress level is much lower than the level at which crushing or breaking of the crushed rock particles would occur. This implies that the cullet samples, like the crushed rock, did not experience any appreciable breaking or crushing of particles.

Workability

Aggregate workability - the ease with which an aggregate is handled and compacted - is significantly affected by the angularity and shape of the particles. Angularity is a qualitative assessment of the sharpness of edges and corners of a particle. Shape is a qualitative assessment of the flatness and elongation of a particle. These properties will be especially important for cullet.

During the CWC Glass Feedstock Evaluation, workability was assessed directly by evaluating the compaction characteristics and indirectly by evaluating particle angularity and particle shape. The direct evaluation is presented in the Compaction portion of this section. The indirect evaluation is presented herein.

Six samples were visually examined using the ASTM D 2488 test procedure. These samples include the crushed rock, gravelly sand, 1/4 inch minus and 3/4 inch minus WA-09 cullet, and 1/4 inch minus and 3/4 inch minus CA-14 cullet. The results indicate that all of the cullets were angular. The crushed rock particles were subangular and the gravelly sand particles were subround. These degrees of angularity are obtained using the Particle angularity chart from ASTM D2488-90.

The typical cullet thicknesses range from about 1/8 to 1/4 inch. When comparing these thicknesses to the plane dimensions of the cullet, it was found that as much as 20% to 30% of the 3/4 inch minus cullet, but only 1% of the 1/4 inch minus cullet, have a flat or platy shape. However, both sizes of cullet have a low percentage of flat and elongated particles.

The particle shape delineations above imply that the 3/4 inch minus cullet had a much higher potential to cut, puncture, or wedge into the moving parts of construction equipment. On the other hand, similar problems are not likely for the 1/4 inch minus cullet. The low percentage of the flat and elongated particles means a low percentage of needle-sharped particle, implying a low potential of puncturing problems.

Safety

Cuts

The most common health concern regarding the use of cullet aggregates is the potential for skin cuts or penetration. Workers may come into physical contact with cullet particles during transportation or placement of the cullet.

Testing during the CWC Glass Feedstock Evaluation showed that airborne cullet dust did produce some skin irritation of laboratory personnel around cuffs and collars. By wearing gloves and long-sleeve shirts however, this effect was eliminated. It should be noted that laboratory personnel experienced no skin lacerations due to handling the cullet. The 1/4 inch minus cullet was particularly benign from this standpoint. In-field experience has shown that cullet 3/4 inch or smaller presents no greater cut or penetration hazard than fractured natural aggregates such as crushed rock.

Glass Dust

Exposure to glass dust is another health concern with cullet aggregate. The chemical make up of glass cullet originating as post-consumer glass would be anticipated to consist of oxides of silicon, aluminum, iron, calcium, magnesium, sodium, and barium. These compounds are the common components of soda-lime glass, approximately 95 percent of all glass manufactured. Minor, trace inorganic components such as antimony, arsenic, cerium, chromium, cobalt, copper, lead, manganese, platinum, selenium, silver, vanadium, zinc, and zirconium could also be present. These inorganic materials, if present, are generally used in small quantities (generally less than 0.5 percent) and are contained in the vitreous non-leaching matrix. The inorganic materials, particularly lead, are generally used in the production of specialty glass and would not be anticipated to represent a significant percentage of post-consumer glass.

The component present in the greatest quantity is silica. Silica may exist as either an amorphous or crystalline structure. Amorphous silica is not considered to be a significant health hazard. Crystalline silica, on the other hand, has been shown to cause fibrogenic lung disease. To cause fibrogenic lung disease, the silica must be present as particles that are small enough to enter the lungs, a condition that is termed "respirable". Respirable particles range from 0.1 to 10 microns in aerodynamic diameter.

The potential for exposure to respirable particles was assessed in the CWC Glass Feedstock Evaluation using two methods. First, the percentage (mass basis) of cullet with particle sizes ten microns and less was determined by specific gravity. Crystalline silica dust present in amounts greater than one percent may pose health hazards to workers if the dust becomes airborne. The second method used to determine potential hazards of dust exposure was to conduct air monitoring. The Occupational Safety and Health Administration (OSHA) has established a Permissible Exposure Limit (PEL) for exposure to crystalline silica. The PEL is 0.1 mg/M3 time-weighted average. To meet regulatory requirements, exposure to crystalline silica must be less than the PEL.

Testing included the following tasks: evaluating personal protective equipment used in a lab environment, collecting bulk cullet samples to determine percent silica, collecting a personal air sample for respirable crystalline silica, and collecting area samples for total dust. Two workers were observed in the lab during the testing of samples WA-9 and CA-14. Both wore disposable nuisance dust masks, lab coats and neoprene surgical gloves.

A personnel sampling pump was worn by a laboratory technician conducting the compaction tests. Two area samples were collected in the lab - one near the mixing trays and one near the scale used to weigh samples after sieving. Bulk samples of CA-14 and WA-9 1/4 inch minus cullet were collected. The personnel and bulk samples were analyzed for percent crystalline silica by x-ray diffraction according to NIOSH method 7500. The two area samples were analyzed for total dust by NIOSH method 500/600. The sample results are presented in Table 11.

Table 11
Crystalline Silica and Dust Test Results

Sample	Location	Crystalline Silica	Total Dust[3.]

CWC-01	Personnel sample: Daokaun Zhang	<2.8 %[2.]	0.280 mg/m^3
CWC-02	Area sample: near mixing trays		0.351 mg/m^3
CWC-03	Area sample: near analytical scale		0.495 mg/m^3
CWC-04	Blank sample	<0.005 mg	
CWC-05	Blank sample		0.160 mg
CWC-06	Bulk sample: CA-14 1/4" cullet	0.270 %	
CWC-07	Bulk sample: WA-09 1/4" cullet	0.070 %	

Notes
1. The Permissible Exposure Limit is 0.05 mg/m^3 for respirable crystalline silica (per 29CFR1910.1000). However, Federal regulations are not applicable to crystalline silica concentrations less than 1% by mass.
2. Accuracy of test result limited by restricted sampling time.
3. The Permissible Exposure Limit is 10.0 mg/m^3 for nuisance dust. Nuisance dusts are those which do not contain otherwise regulated particulate such as asbestos or dusts which contain greater than one percent silica (per 29CFR1910.1000).

The bulk sample results indicate that both the WA-09 and CA-14 samples contained less than 1% crystalline silica. As such, the cullet was in the “nuisance dust” category with a Permissible Exposure Limit (PEL) of 10 mg/m^3. The personnel sample and two area samples were all below 0.5 mg/m^3 total dust. Therefore, based on the samples taken during this test program, cullet is not considered a health hazard from a standpoint of crystalline silica or dust.

3. Field Testing

Density and Moisture Content

The engineering properties of granular fill materials such as 100% glass cullet, or cullet-soil or cullet-aggregate mixtures, are related in large part to the density of the fill and the gradation of the mixture. The gradation requirement is usually confirmed by laboratory testing prior to the fill operation, whereas the density requirement is typically checked by in-place or field density testing during the operation. Field density testing is performed to confirm that the fill has been compacted to a density that meets or exceeds a specified level. If this level has not been reached, further compaction or other adjustments will be required in the field. If the compaction criterion has been reached or exceeded, the fill is said to be acceptable and engineering performance characteristics such as strength and compressibility are ensured. Field density tests are typically performed using a nuclear densometer. For granular materials such as cullet and gravel, the test accuracy may suffer from the presence of voids inside of the materials. In addition, the presence of hydrocarbon-containing organic content such as labels in cullet fill may be erroneously read as moisture by the instrument.

Because nuclear densometer testing during the Glass Feedstock Evaluation was inconclusive, additional field testing was conducted by the CWC after completion of the study. This testing compared density measurements obtained using a nuclear densometer with those obtained using a sand cone. The latter is a physical test that determines the density of the compacted material by measuring its volume and weight.

The nuclear densometer tests included the backscatter mode (ASTM 2922) which measures the density near the surface, and direct transmission mode (ASTM 5195) with the source probe extending to depths of 6 to 12 inches. The CWC study concluded that nuclear densometers can be used for the testing of cullet aggregate. No correction to the density measurements is required and the test procedures can be the same as those used for natural materials. The test frequency is recommended to be the same as for natural material at one test per lift per 2,500 square feet of fill, but not less than one per lift.

In-field testing and project experience suggests the following test procedures.

1. Cullet aggregate is typically compacted by vibratory compaction equipment. The vibration can cause the finer particles to migrate toward the bottom of each lift. As a result, the void space reduces and density increases in the bottom portion of the lift. Such uneven distributions of particle sizes and non-uniform density profiles can wrongly indicate a poorly graded material. Hence, the backscatter mode of the nuclear density test should be avoided as this test mode measures the density in the upper portion of the lift. It is recommended that the test be performed using the direct transmission mode with the test probe extending the full depth of the lift.

2. To get the most accurate overall reading, it is recommended that four measurements be obtained at each test location with the nuclear densometer rotated 90 degrees between measurements.

The average of the measurements should be used for record purposes. This procedure reduces the effect of non-homogeneity on the density measurement.

3. The surface of cullet aggregate is typically uneven and highly permeable. Such surface conditions will normally reduce the density measurement of a nuclear densometer because the instrument will be supported on the highest peak. To avoid this effect, a thin layer of sand should be used to fill the voids and even the surface prior to measurement.

4. A parallel check on the accuracy of the density measurements by a nuclear densometer can be performed using physical tests such as the sand cone method (ASTM D1556) or rubber balloon method (ASTM D2167).

5. The moisture measurement may be affected by the non-homogeneity of the compacted fill and the organic content in the cullet debris. If necessary, a moisture compensation should be included in the densometer operation. Details of such compensations are presented in the CWC's *Moisture Content Measurement of Glass Aggregate Using a Nuclear Densometer Best Practice (No. BP-GL-4012).*

Nuclear densometers are the most popular tool to test the density of fill materials. The procedure is quick and easy to perform, and the test results are available at the completion of the test. Hence, the quality of the fill can be evaluated immediately and adjustment to the placement or compaction procedures can be made without delay to the fill operation. Ultimately, this simple test method allows the quality of fill to be controlled effectively and efficiently.

Additional information about the use of nuclear densometers with glass cullet aggregate can be found in the CWC's *Best Practices in Glass Recycling*, #'s 4011 and 4012)

Visual Debris Classification

Visual inspection is a common procedure for the initial assessment of the acceptability of construction aggregate. The inspection is usually performed at storage sites prior to any laboratory testing of the material. Sometimes, visual inspection is performed as a field screening procedure. In some cases, the acceptability of the material for a particular application may be based solely on the results of the field visual inspection.

There is little background for standardized visual inspection procedures for recycled glass. A simple method has been used to obtain a percentage level of debris content of a glass cullet sample. Typical debris includes metal caps, plastic, paper, and any other non-glass materials (see Part 1 of Section 3 for more information about typical debris levels of cullet). The method is based on the Percent Composition Charts developed by American Geological Institute (Comparison Chart for Estimating Percentage Composition, AGI Data Sheets 23.1 and 23.2). These charts, shown on page 56, show the estimated percentage of composition of debris in a sample from 1 to 50%.

The method uses a test pan of eight to ten inches in diameter and one to two inches in depth. One to three pounds of glass cullet is placed and leveled in the test pan. The test pan is then placed next to the standard charts and an estimated percentage is selected based on the comparison of the composition shown on the charts and the debris present on the test pan. It is important to disregard the aggregate and compare only the contaminants with the charts. The results can be recorded quantitatively using percentages, or qualitatively using terms such as low for 1 to 3%, medium for 3 to 15%, and high for over 15%. Inter-medium terms such as low to medium, and medium to high can also be considered.

The visual inspection and classification test should be used for sub-samples retrieved from various portions of the glass storage. The number of tests should be based on the quantity and homogeneity of the bulk material. In general, at least one test should be conducted for every 50 cubic yards of material. The test results for all sub-samples should be reported.

The visual inspection is based on the two-dimensional view of debris. Since the debris (e.g., paper, plastic, metal) in recycled glass typically lays flat (platey), the visual inspection method will generally produce results higher than the debris content measured by physical tests such as the measurement of percent debris by weight or volume. A comparison of the visual inspection and the physical test results can be found in the Engineering Suitability Evaluation volume of the full Glass Feedstock Evaluation.

In-field Verification: The results of the CWC Glass Feedstock Evaluation volume and weight testing are summarized in Table 12, following page. Loss of ignition test results are also listed. The volume and weight testing confirmed the debris levels as determined by visual classification. The visual classification produced a greater quantitative variation between the high and low debris levels than did the volume and weight testing. This is because most of the debris is platey in nature (labels and caps). A platey material (one which has a length and width but a very small thickness), will be readily measured using the visual method, which quantifies the cullet debris in a two-dimensional view.

The volume and weight methods however, are affected by all three dimensions of the debris in equal proportion. As a result, the platey nature of the debris is reflected in the lower percentage results of these two methods. Among the volume and weight tests, the smallest variation between high and low debris feedstocks was obtained from the weight method, and in general, the greatest was obtained from the dry method by volume.

Table 12
Debris Content by Various Methods

Sample	Debris Content Visual Method (%)	Debris Content Weight Method (%)	Debris Content Dry Volume Method (%)	Debris Content Wet Volume Method (%)	Loss of Ash Content[1.] (%)	Ignition Organic Matter[2.] (%)
OR-01	10	1.0	4.0	1.2	NA[3.]	NA
OR-05	15	2.9	7.7	3.5	99.9	0.1
CA-14	15	6.5	7.2	10.3	99.4	0.6
MN-04	1	0.2	0.5	0.5	100	0
MN-08	1	0.6	0.8	1.1	99.7	0.3
WA-10	1	0.3	0.8	0.6	99.8	0.1
WA-09	2	0.5	NA	0.8	NA	NA

Notes
1. Material remaining after ignition (cullet and inorganic debris)
2. Organic material lost during ignition
3. Not Analyzed

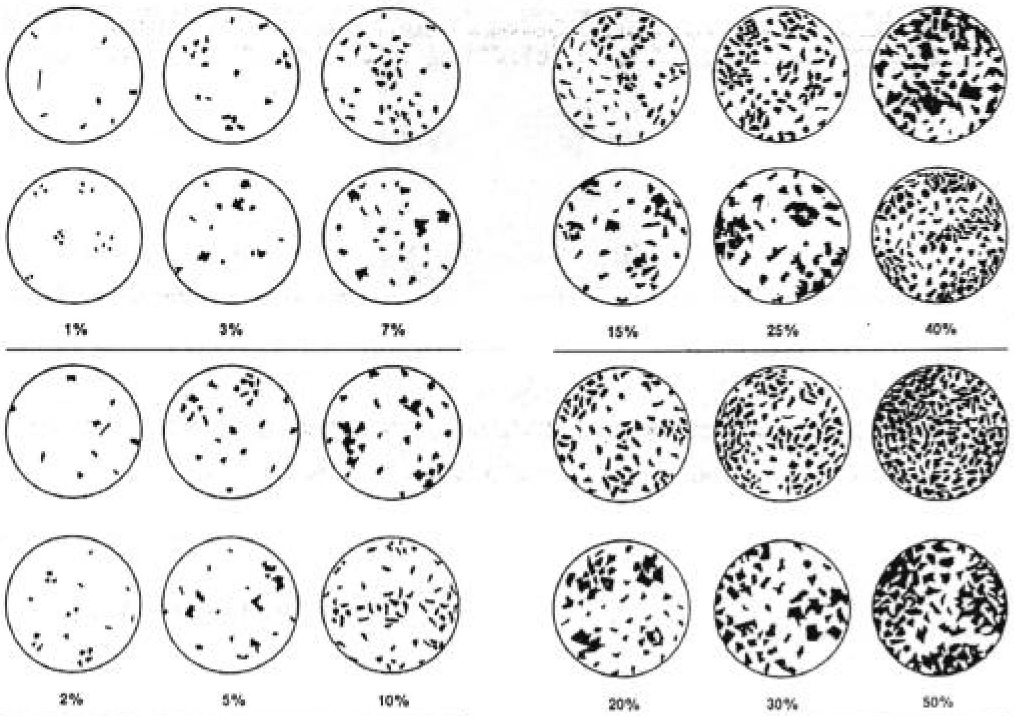
It should be clearly understood that the percentages produced by the visual classification method are neither mass nor volume percentages. Rather, they are parameter-less indicators of the relative level of contamination in a glass sample.

AGI DATA SHEET 15.1

AGI DATA SHEET 15.2

Comparison Chart for Estimating Percentage Composition

Prepared by Richard D. Terry and George V. Chilingar, Allan Hancock Foundation, Los Angeles. Reprinted from *Journal of Sedimentary Petrography*, v. 25, n. 3, p. 229–234, Sept. 1955.



ESTIMATING PERCENTAGE CONTMINATION

25854-001-016

DAMES & MOORE

Glass Feedstock Evaluation Project

FIGURE 2.2

8

4. Conclusions for Construction Aggregate Users

The significance of the geotechnical and engineering property testing conducted during the CWC Glass Feedstock Evaluation, the FDOT study, and related studies is summarized below for construction aggregate users.

Specific Gravity
& Relative Density: The cullet samples have a lower specific gravity than natural aggregate. The lower specific gravity resulted in lower maximum and minimum index densities. The density difference between a 15% and 100% cullet sample can be as high as 30%. The presence of debris in the cullet reduced the specific gravity. This reduction is also reflected in the unit weight of the compacted samples.

Durability: Cullet is not as mechanically sound as crushed rock. The L.A. Abrasion loss for the 1/4 inch minus cullet is about 30%, and that for the 3/4 inch minus cullet is about 42%. Although these losses are at least two times greater than that of the crushed rock, they are relatively close to the normal limiting values for roadway aggregate. It is believed that aggregate mixed with 50% cullet, even with a cullet size of 3/4 inch minus, will meet the abrasion limit for roadway aggregate.

Compactability: In general, the compaction curves of the cullet samples are relatively flat meaning that the compacted density is not sensitive to the moisture content. This insensitivity to moisture content means that the material can be placed and compacted during wet weather, keeping construction downtime to a minimum.

The maximum density values obtained from the impact (Modified Proctor) compaction and vibratory (WSDOT 606) compaction tests are about equivalent. Other than the 100%, 3/4 inch minus cullet material, both compaction methods produced little or no gradation change. The similarity in density values implies the feasibility of using either method for the field control of the cullet-added fill materials. On the other hand, if a fill materials comprising 100% cullet is to be compacted by heavy field compaction equipment, the WSDOT or vibratory type of compaction method should be used for the purpose of density control.

Confined compression testing up to pressures of 210 psi (1470 kPa) proved that very little degradation would occur for waste glass subjected to high static stresses in a confined zone. However, field compaction equipment may crush the grains near the surface where low confining pressures exist. This problem should be addressed during additional field testing.

Gradation: Significant gradation change occurred only when 100% cullet samples were subjected to heavy impact compaction. All other test conditions produce little or no gradation change. These results imply the feasibility of using all three compaction methods for the field control of the fill materials comprised of cullet. In addition, since these compaction methods mimic the compaction effort of the field equipment, the minimal gradation change would also imply minimal difference in the engineering properties of the laboratory compacted samples and those of the insitu fill material. This would tend to validate engineering designs which are based on properties derived from laboratory testing.

The hydrostatic compression and triaxial shear loading produced little gradation change, implying minimal breakage of the cullet under normal working loads.

Particle Shape: All cullet particles tested were angular. About 20% to 30% of the 3/4 inch minus cullet but only 1% of the 1/4 inch minus cullet had a flat or platey shape. However, both sizes of cullet had a low percentage of flat and elongated particles. These shapes indicate that the 3/4 inch minus cullet has a potential to cut, puncture, or wedge into the moving parts of the normal construction equipment. On the other hand, similar problems are not likely for the 1/4 inch minus cullet. The low percentage of the flat and elongated particles means a low percentage of needle-sharped particle, implying a low potential of puncturing problems.

Permeability: Based on the traditional classification system presented in Table 5, all the cullet samples tested exhibit medium to high permeability. These permeabilities correspond to those of a medium sand and gravel which are commonly used as filter materials.

Shear Strength: Both direct shear and triaxial shear test results indicate that the strength of cullet is about the same as natural aggregate. In addition, cullet content and debris level do not appear to have an appreciable effect on the strength within the ranges tested. The addition of 1/4 inch minus cullet to a natural aggregate tends to increase the bulk modulus and reduce the potential of plastic volumetric strain. This beneficial stiffening effect is because the aggregate-cullet mixture is more well-graded than natural aggregate only.

CBR:

High CBR values (above 90) were obtained for samples containing 15% cullet of either size. For samples containing 50% cullet, the CBR depends on the compaction method used in the sample preparation. Samples prepared using the impact compaction method (Modified Proctor) exhibit high CBR values (above 70) regardless the cullet size. Samples with 1/4 inch minus cullet, prepared using the vibratory compaction method have a high CBR (over 90), but samples with 3/4 inch minus cullet, prepared using the vibratory compaction method exhibit a medium to high CBR value (over 40).

The test results indicate that cullet exhibits good to excellent CBR values. Additionally, for materials which contain over 15% cullet, the compaction method used in sample preparation should mimic the field compaction to ensure accurate field confirmation.

Resistance R Value:

High R-Values (above 73) were obtained for samples containing up to 50% cullet of either size. The results indicate that the cullet-added crushed rock, with a cullet content up to 50%, possess adequate strength for both base and subbase aggregate.

Resilient Modulus
(Cyclic Triaxial):

Relatively high resilient moduli (above 29 ksi at a bulk stress of 25 psi) were obtained for samples containing up to 50% cullet of either size. The results indicate that the cullet-added crushed rock, even for a cullet content of 50%, would have a resilient modulus appropriate for a typical pavement design.

Safety:

Glass aggregate dust typically contains less than 1% crystalline silica by weight and is not considered hazardous by federal standards. This places cullet in the category of "nuisance dust" with a Permissible Exposure Limit (PEL) of 10 mg/m3.

Glass cullet dust can be a skin and eye irritant. Cullet dust is abrasive due to the high angularity of its particle shapes, and appears to be more irritating than dust from natural aggregates or soils. However, experience from construction sites indicates that cullet dust, and the irritations associated with the dust, can be easily prevented using simple measures. The following safety precautions are based on the CWC Glass Feedstock Evaluation test results and the field experience of construction site personnel:

a) All personnel should know that direct skin contact with glass cullet should be avoided. To protect against possible cuts or penetration injuries, site personnel working with cullet should wear long sleeves, pants, gloves, work boots, hard-hats, ear protection, and eye protection. Shirt sleeves and pant legs can be taped for additional protection. Site personnel should also be instructed not to sit, kneel, or lay on cullet surfaces, or work surfaces containing cullet. Furthermore, working surfaces should be kept clean of cullet particles by sweeping.

b) Construction personnel should be made aware of the potential inhalation hazard and skin and eye irritation from cullet dust. To minimize exposure of glass dust to skin, ears, and eyes, site personnel should use the same protective gear listed above for protection against cuts and penetrative wounds. To protect against dust inhalation, workers can also wear disposable nuisance dust masks. Samples of the glass should be brought to the meeting so personnel know what to expect.

   Although all personnel should have knowledge of dust control measures, responsibilities should be clearly assigned. Minimizing cullet dust hazards should begin with a dust control program. As with any aggregate, the need for dust control is most obvious during dry weather. Since glass has a specific gravity less than that of natural aggregate, the fines from cullet aggregate may be more prone to becoming airborne. On construction sites, cullet dust can be generated when the cullet is delivered and end-dumped from trucks. Handling and stockpiling of cullet aggregate on-site can also create a dust cloud. Site personnel involved in handling or stockpiling cullet should monitor for potential cullet dusting, and be prepared to implement dust control measures.

   Wet suppression using a garden hose is the most common and effective measure of dust control. Since cullet aggregates are generally free-draining, the application of water to cullet generally does not adversely impact its compaction characteristics. However, if the glass aggregate contains more than 10% fines (particles smaller than No. 200 sieve in size) the material may become moisture-sensitive. This situation should be handled by qualified geotechnical engineering personnel.

Water can be applied to the cullet aggregate in the truck bed before dumping. To avoid ponding of surface water, the stockpile should be built at locations with positive drainage away from the stockpile area. During the dry summer months, the stockpile can be sprinkled with water whenever the surface is dry and fine particles can become airborne and transported by wind.

c) Cullet may draw the attention of curious onlookers or passers-by. For maximum safety, take measures to minimize public access to areas where cullet is being used or stockpiled. These areas should be surrounded by cautionary tape, and cullet stockpiles should be placed in low visibility or minimum access areas.

d) The advantages and disadvantages of using cullet as a construction aggregate and the merit of cullet fill should be discussed with the owner, engineers, general contractor, contractor's earthwork sub-contractor, labor foremen, and laborers before the material is delivered. Samples of the cullet aggregate should be available so that all know what to expect. The awareness of the rationale for using a new construction material at all levels of the crew tends to mitigate concern, and to facilitate the cost-effective use of the material.

In-Field Testing of Density and Moisture Content Using a Nuclear Densometer:

The CWC Glass Feedstock Evaluation study concluded that nuclear densometers can be used for the testing of cullet aggregate. No correction to the density measurements is required and the test procedures can be the same as those used for natural materials. The test frequency is recommended to be the same as for natural material at one test per lift per 2,500 square feet of fill, but not less than one per lift. Test procedures are subject to the modifications listed in the "Field Testing" section.

3. Physical and Chemical Properties, and Environmental Suitability

This section of the Toolkit presents physical, chemical, and environmental properties of glass cullet or glass cullet leachate, as applicable to its use as cullet aggregate.

1. Physical Properties

Typical Debris Content

Table 13 presents typical debris content levels and type of debris for different collection and sorting categories, based on the visual classification results of the CWC Glass Feedstock Evaluation. In general, the types of debris observed in cullet include paper, foil, and plastic labels; plastic and metal caps; cork; paper bags; wood debris; food residue, and grass. Debris at levels of 10 percent or greater in either of two size classifications (1/4" minus and 3/4" minus) are defined as high debris level. Debris levels of greater than three percent and less than ten percent are defined as medium debris levels. Debris levels of less than three percent are defined as low debris levels.

Table 13
Typical Debris Content Levels for Collection and Sorting Categories

Collection and Sorting Category	Typical Debris Level	Type of Debris
Redemption	High	Paper and plastic labels, plastic, corks
Blue bags with commingled bottles, cans, and paper (two sources)	High	Paper wads, corks, food residue, paper labels, metal caps, grass, plastic foodwrap, tin, plastic and wood debris
unattended dropboxes or barrels (two sources)	High	Paper labels, metal caps, brown paper bags, foil labels
curbside commingled glass (color sorted at curb)	High	Plastic caps, paper and plastic labels, newsprint
curbside commingled with other containers (negative sort)	High	Paper and plastic labels, plastic and metal caps

Table 13
Typical Debris Content Levels for Collection and Sorting Categories·

Collection and Sorting Category·	Typical Debris Level	Type of Debris
containers (negative sort)		caps
curbside commingled glass only - not color sorted	High	Paper labels, metal caps, plastic labels
curbside commingled glass only, positive sort (two sources)	Medium	Paper labels, plastic caps, corks, metallic bottle seals, metal caps
attended dropbox	Medium	Paper/plastic labels, paper, corks, plastic caps
deposit (two sources)	Medium	Metal and plastic caps, paper and plastic labels
curbside commingled with other containers, positive sort (two sources)	Medium	Paper/plastic labels, metals caps, plastic caps, wet paper
curbside commingled with other containers, mixed sort	Medium	Paper/foil labels, plastic caps
curbside commingled glass only, negative sort	Medium	Metal and plastic jar and bottle lids, plastic and paper labels, plastic food bottles, tin can lids
curbside - source separated by consumer	Low	Paper labels, plastic caps
curbside commingled glass only, positive sort	Low	
curbside commingled glass only, negative sort	Low	
curbside commingled glass only, mixed fraction	Low	Paper labels, plastic/metal caps
curbside commingled with other containers, positive sort	Low	Paper labels, metal caps
curbside commingled with other containers, negative sort	Low	Paper/plastic labels, plastic caps
curbside commingled with other containers, mixed fraction	Low	Paper labels, plastic caps
deposit collection	Low	
furnace ready cullet - beneficiated	Low	Paper labels

The most common types of debris observed in the low debris level sources were similar to the high debris level: labels (paper and plastic) and bottle caps (metal and plastic).

Two collection schemes were positively associated with high debris levels - blue bag collection systems and unattended drop boxes. The highest percent of debris in the 1/4 minus and 3/4 minus sampled during the CWC Glass Feedstock Evaluation were obtained from an unattended dropbox/barrel. The most common types of debris observed in the high debris level sources were labels (paper and plastic) and bottle caps (metal and plastic). Mechanically-facilitated sorting/cleaning is associated with lower debris levels. Also, commingled glass only collection schemes appear to produce no cleaner a material than commingled container collection provided.

2. Chemical Properties

Biochemical Oxygen Demand (BOD)

BOD testing is essentially a bioassay procedure involving the measurement of oxygen consumed by living organisms (mainly bacteria) while utilizing the organic matter present in a waste, under conditions similar to those that occur in nature.

The FDOT study used the Thomas graphical method (Sawyer, 1978) to evaluate BOD versus time data. Three leachate samples were collected from a 2 ft. (60 cm) column at 36 minute time intervals generating three - 250 ml samples. The average rate constant was 0.08. The ultimate BOD of the three samples was approximately 600 mg/l, 400 mg/l, and 375 mg/l. The average BOD5 was 60% of the ultimate BOD. This percentage can be used to convert any of the five day BOD's reported in the study to ultimate BOD's. Column leaching tests BOD5 values for one of the FDOT samples had initial concentrations of 435, 1470 and 2880 mg/l at leaching times of 14, 22, and 33 hours, and final BOD5 concentrations of 6.6, 10.8 and 49.5 mg/l, at these times, respectively, for the 2, 4 and 6 foot (60, 120 and 180 cm) columns. Another of the FDOT samples had 479, 235 and 855 mg/l initial BOD5 concentrations at leaching times of 14, 34, and 53 hours, and final concentrations of 12, 12, and 6 mg/l at these times for the for the 2, 4 and 6 foot (60, 120 and 180 cm) columns. The FDOT results indicate that the later waste glass sample leachate was considerably less contaminated than the first, although it still exhibited pollutant levels greater than raw domestic waste water.

Total Phosphorus

Total phosphorus (TP) concentrations in samples taken for the FDOT study ranged from 0.4 to 2.0 mg/l, and 1.4 to 2.8 mg/l, for the first samples; and final samples had concentrations of 0.03 to 0.14 mg/l and 0.17 to 0.31 mg/l, respectively. Typical TP concentrations in raw domestic waste water are 8 mg/l and treated waste water are 1 mg/l. The study found that both waste glass sources had leachate concentrations similar to treated wastewater. Once waste glass is processed to remove the other contaminants, the phosphorus is not expected to be a problem.

Total Kjeldahl Nitrogen (TKN)

During the FDOT study, TKN analyses were performed on two leachate samples from two glass samples. TKN concentrations for the first glass sample for 2, 4, and 6 ft (60, 120 and 180 cm) columns were 32, 114 and 345 mg/l initially and 2, 1 and 7 mg/l in the final sample. The second glass sample had TKN concentrations of 37, 55, and 67mg/l initially and 1, <1, and 2 mg/l in the final sample for the 60, 120 and 180 cm) columns. The TKN typical value for raw domestic waste water is 40 mg/l and for treated domestic waste water 5 mg/l. Therefore, TKN for glass cullet would be high initially and acceptable after some time when exposed to rainfall.

Solids

The FDOT study tested glass samples for Total Dissolved Solids, Total Suspended Solids, and Fixed and Volatile Solids. Since a filter was used to hold the glass sample in place, low suspended solid concentrations were expected. No or negligible suspended solids concentrations were measured. The dissolved solids concentrations were so low that they were difficult to measure. A low level of solids was observed on the filter at the bottom of the column. The solids levels are not expected to create any environmental concerns.

Semi-Volatile Organics

The semi-volatile organic results from the CWC Glass Feedstock Evaluation indicated the presence of phthalates and relatively low levels of polycyclic aromatic hydrocarbons (PAHs), benzene derivatives, and phenols in one or more samples. Phthalate compounds were found in all high and low debris samples and ranged in concentrations from 38 parts per billion (ppb) to 16,000 ppb and accounted for the highest concentrations of semi-volatile organic contamination detected. Phthalates are components of plastics products.

The high debris feedstock samples contained higher concentrations of semi-volatile organic compounds than the low debris samples. Phthalates and TICs such as organic acids and derivatives and cyclic, straight chain, and branched hydrocarbons were detected in high debris samples, at estimated concentrations ranging from 130 ppb to 6,700 ppb.

The largest number of semi-volatile organic compounds were found in a high debris sample. This sample was collected from a "blue bag" collection scheme, and contained debris that generally is removed and disposed of in a landfill. The sample contained phthalates, PAHs, phenols and benzene derivatives and TICs such as organic acids and derivatives and cyclic, straight chain, and branched hydrocarbons at concentrations ranging from 370 ppb to 19,000 ppb. This sample contained a wide array of visually classified debris such as food residues, grass, plastic food wrap, and corks as compared to the debris observed in other samples. PAHs are generally associated with petroleum products, phenols are common industrial chemicals, and azobenzene is used in the manufacture of dyes and rubber accelerators, as a fumigant and acaricide (Verschueren 1983). Information from the recycling collector revealed that plastic bottles previously containing oil are collected in this system, a possible source of the PAH contamination. <u>It is recommended that cullet from blue bag sources be analyzed on an individual basis prior to their consideration as aggregate feedstock.</u>

In addition to phthalates, low concentrations of phenol and 1,4-dichlorobenzene were found in some of the low debris level samples collected for the CWC Glass Feedstock Evaluation. 1,4-Dichlorobenzene is a common component of moth repellents, air deodorizers, soil fumigants and pesticides (Verschueren 1983). TICs detected in the low debris samples were similar to the TICs detected in the high debris samples.

Regulatory limits for organic compounds vary across the country and are generally based on site specific information and local and state regulations. Although organic regulatory limits are not available for direct comparison of organics found in the cullet samples, the organics do not appear to represent levels of concern.

pH and Total Organic Carbon

The pH levels of the high and low debris-content feedstock samples collected for the CWC Glass Feedstock Evaluation were similar and ranged between 9.9 and 10.4 Standard Units (SU), with the exception of one sample, which exhibited an emulsion layer that may have interfered with pH measurements (6.9 and 7.0 SU). The pH levels of the cullet were similar to levels that are found naturally in geologic materials. The federal regulatory limit that designates a solid material as hazardous waste contains a pH less than or equal to 2.0 or greater than or equal to 12.5. The potential pH of effluent was evaluated in a contaminant cullet testing over time program.

The TOC levels found in the high and low debris samples were generally similar and ranged between 0.059 to 0.69 percent. A high debris sample and a low debris sample contained the highest TOC concentrations, 0.69 and 0.29 percent, respectively. TOC levels found in the cullet samples are similar to naturally occurring soils which may range from 0.04 percent to 0.8 percent.

Priority Pollutant Metals

The concentrations of total metals detected in the CWC Glass Feedstock Evaluation were similar for both the high and low debris samples taken (Table 13, following page). Available published values for ranges of metals naturally occurring in granite, a common source of road construction aggregate, are also provided in Table 13 for comparison to the glass feedstock results (Connor & Shacklette, 1975). Three metals, chromium, copper, and zinc were detected at low concentrations in both the high and low debris samples. Nickel was detected only in one high debris level sample. Selenium was detected only in two low debris level samples. Lead concentrations are discussed in the next section. In general, the cullet metal concentrations were at or below the metal concentrations typically found in background levels of granite.

Table 14

Chemical Characterization Glass Feedstock Samples Clean Washington Center

		HIGH DEBRIS LEVEL									
		AZ-01 Brown Glass; Dropbox/Barrels - Unattended			OR-05 Brown Glass; Curbside-Commingled Glass Only, Color Sorted at Curb			CA-14 Mixed Colors; Blue Bags - Commingled Bottles/Cans/ Paper			Concentration Range
Analysis		A	B	D%	A	B	D%	A	B	D%	
Phthalates (ug/kg)											
Di-n-Butylphthalate		5200	ND	-	ND	ND	-	3200	3500	-9	ND - 5200
Butylbenzyl Phthalate		87	51	71	38	ND	-	9400	6100	54	ND - 9400
Bis(2-Ethylhexyl)Phthalate		2300	3000	-23	290	130	123	3500	1700	106	290 - 3500
Dimethyl Phthalate		ND	ND	-	ND	ND	-	190	ND	-	ND - 190
Diethyl Phthalate		ND	ND	-	ND	ND	-	16000	1600	900	ND - 16000
Di-n-Octyl Phthalate		ND	ND	-	ND	ND	-	140	ND	-	ND - 140
Polycylic Aromatic Hydrocarbons (ug/kg)											
Naphthalene		ND	ND	-	ND	ND	-	110	100	10	ND - 110
Pyrene		ND	ND	-	ND	ND	-	110	85	29	ND - 110
Fluoranthene		ND	ND	-	ND	ND	-	59 J	44 J	34	ND - 59J
Phenanthrene		ND	ND	-	ND	ND	-	180	140	29	ND - 180
Benzene Derivatives (ug/kg)											
1,4 - Dichlorobenzene		ND	ND	-	ND	ND	-	ND	ND	-	ND
Azobenzene		ND	ND	-	ND	ND	-	ND	74	-	ND - 74
Phenols (ug/kg)											
Phenol		ND	ND	-	ND	ND	-	ND	ND	-	ND
4-Chloro-3-Methylphenol		ND	ND	-	ND	ND	-	280	110 J	155	ND - 280
Pentachlorophenol		ND	ND	-	ND	ND	-	600 J	200 J	200	ND - 600J
4-Nitrophenol		ND	ND	-	ND	ND	-	370 J	ND	-	ND - 370J
pH (Standard Units)		10.4	10.5	-1	10.5	10.4	1	6.9[1]	7[1]	1	6.9 - 10.5
Total Organic Carbon (%)		0.085	0.11	-23	0.059	0.13	-55	0.69	0.56	23	0.059 - 0.69
Total Metals (mg/kg)	Natural Background Range, Granite[2]										
Antimony	NA	ND	ND	-	ND	ND	-	ND	ND	-	ND
Arsenic	ND - 19	ND	ND	-	ND	ND	-	ND	ND	-	ND
Beryllium	ND - 3	ND	ND	-	ND	ND	-	ND	ND	-	ND
Cadmium	NA	ND	ND	-	ND	ND	-	ND	ND	-	ND
Chromium	ND - 7	1.1	1.1	0	1.6	1.6	0	1.7	2.0	-15	1.1 - 2.0
Cobalt	ND - 7	ND	ND	-	ND	ND	-	ND	ND	-	ND
Copper	ND - 10	14	12	17	18	17	6	18	83	-78	12- 83
Mercury	ND - 0.7	ND	ND	-	ND	ND	-	ND	ND	-	ND
Nickel	ND - 7	ND	ND	-	ND	ND	-	2.4	2.4	0	ND - 2.4
Selenium	ND - 0.4	ND	ND	-	ND	ND	-	ND	ND	-	ND
Silver	NA	ND	ND	-	ND	ND	-	ND	ND	-	ND
Thallium	NA	ND	ND	-	ND	ND	-	ND	ND	-	ND
Zinc	15 - 310	8.2	6.5	26	10	8.8	14	21	28	-25	6.5 - 28

Notes:

1 - Sample had an emulsion layer which, when combined with water may have interfered with the pH value.
2 - Connor and Shacklette, 1975.
NA - Not Applicable / Not Available.
ND - Not Detected.
J - Estimated Value.

D% - $\frac{A-B}{B}*100$

Table 14

Chemical Characterization
Glass Feedstock Samples
Clean Washington Center

		LOW DEBRIS LEVEL									
		MN-04 Mixed Colors; Curbside - Source Separated by Consumer			MN-08 Mixed Colors; Curbside - Commingled Glass Only - Facility Sorted - Mixed Cullet Fraction			WA-10 Mixed Colors; Curbside - Commingled with Other (Plastics, Cans) - Negative Sort			Concentration Range
Analysis		A	B	D %	A	B	D %	A	B	D %	
Phthalates (ug/kg)											
Di-n-Butylphthalate		ND	ND	-	4100	3100	32	ND	ND	-	ND - 4100
Butylbenzyl Phthalate		63	94	-33	360	320	13	270	69	291	63 - 360
Bis(2-Ethylhexyl)Phthalate		1400	690	103	2600	1900	37	210	350	-40	210 - 2600
Dimethyl Phthalate		ND	ND	-	ND	ND	-	ND	ND	-	ND
Diethyl Phthalate		ND	ND	-	80	71	13	ND	ND	-	ND - 80
Di-n-Octyl Phthalate		ND	ND	-	ND	ND	-	ND	ND	-	ND
Polycylic Aromatic Hydrocarbons (ug/kg)											
Naphthalene		ND	ND	-	ND	ND	-	ND	ND	-	ND
Pyrene		ND	ND	-	ND	ND	-	ND	ND	-	ND
Fluoranthene		ND	ND	-	ND	ND	-	ND	ND	-	ND
Phenanthrene		ND	ND	-	ND	ND	-	ND	ND	-	ND
Benzene Derivatives (ug/kg)											
1,4 - Dichlorobenzene		ND	ND	-	ND	ND	-	ND	74	-	ND - 74
Azobenzene		ND	ND	-	ND	ND	-	ND	ND	-	ND
Phenols (ug/kg)											
Phenol		ND	ND	-	98	ND	-	ND	ND	-	ND - 98
4-Chloro-3-Methylphenol		ND	ND	-	ND	ND	-	ND	ND	-	ND
Pentachlorophenol		ND	ND	-	ND	ND	-	ND	ND	-	ND
4-Nitrophenol		ND	ND	-	ND	ND	-	ND	ND	-	ND
pH (Standard Units)		10.2	10.2	0	9.9	9.9	0	10.4	10.4	0	9.9 - 10.4
Total Organic Carbon (%)		0.070	0.086	-19	0.26	0.26	0	0.077	0.066	17	0.066 - 0.26
Total Metals (mg/kg)	**Natural Background Range, Granite [1]**										
Antimony	NA	ND	ND	-	ND	ND	-	ND	ND	-	ND
Arsenic	ND - 19	ND	ND	-	ND	ND	-	ND	ND	-	ND
Beryllium	ND - 3	ND	ND	-	ND	ND	-	ND	ND	-	ND
Cadmium	NA	ND	ND	-	2.7	ND	-	ND	ND	-	ND - 2.7
Chromium	ND - 7	1.6	1.8	-11	1.7	2.0	-15	6.4	11	-42	1.6 - 11
Cobalt	ND - 7	ND	ND	-	ND	ND	-	ND	ND	-	ND
Copper	ND - 10	30	29	3	25	28	-11	17	23	-26	17 - 30
Mercury	ND - 0.7	ND	ND	-	ND	ND	-	ND	ND	-	ND
Nickel	ND - 7	ND	ND	-	ND	ND	-	ND	2.0	-	ND - 2.0
Selenium	ND - 0.4	0.66	1.2	-45	0.62	ND	-	ND	ND	-	ND - 1.2
Silver	NA	ND	ND	-	ND	ND	-	ND	ND	-	ND
Thallium	NA	ND	ND	-	ND	ND	-	ND	ND	-	ND
Zinc	15 - 310	29	21	38	24	21	14	7.3	9.0	-19	7.3 - 29

Notes:

1 - Sample had an emulsion layer which, when combined with water may have interfered with the pH value.
2 - Connor and Shacklette, 1975.
NA - Not Applicable / Not Available.
ND - Not Detected.
J - Estimated Value.

$$D\% - \frac{A-B}{B} * 100$$

3. Environmental Suitability

During the CWC's Glass Feedstock Evaluation and the FDOT "Waste Glass" study, two potential environmental issues of interest were associated with the use of glass as construction aggregate: the biological impacts from chemical properties, and the potential for lead contamination. A summary of tests conducted and the test findings for those two issues is provided below.

Biological Impacts From Chemical Properties

Both the CWC Glass Feedstock Evaluation and the FDOT Study evaluated the potential for contaminant leaching from glass feedstock over time. The purpose was to evaluate the potential for impacts to the biology of the leachate receiving environment. While the FDOT Study discussed storage requirements to assure complete biological degradation prior to placement, the CWC Glass Feedstock Evaluation found no potential for harmful contaminant leaching from glass. A summary of the studies' findings is described below.

The FDOT study determined the total mass of pollutants released for the waste glass sampled. Biochemical Oxygen Demand (BOD) and Total Phosphorus (TP) were used to compare leachate concentrations to the volume of liquid used to extract the pollutants. The study suggested that to provide usable quantities of cullet aggregate, storage facilities should accumulate waste glass for some time to assure biological degradation. Rainfall occurrences were described as sufficient to accomplish the suggested "clean-up" so that the leachate would exhibit pollutant concentrations similar to normal storm water.

To assess the potential for contaminant leaching over time, the CWC Glass Feedstock Evaluation conducted sequential batch extractions of one high debris and one low debris feedstock in accordance with Method ASTM 4793.

One high debris sample and one low debris sample, and duplicates of each, were selected and analyzed. Following sequential batch extractions, the aqueous samples generated were analyzed for biological oxygen demand (BOD), chemical oxygen demand (COD), TOC, pH, specific conductivity, priority pollutant metals, and cobalt.

The concentration trends of BOD, COD, TOC, pH, and specific conductivity in the high and low debris samples decreased in concentration over time and do not appear to be at concentrations of concern. The BOD and COD concentrations were generally not detected following the third sequential extraction and analysis. The pH of the cullet effluent monitored over a ten day period was within pH ranges found in naturally occurring surface waters which generally range from 6 to 10 SU.

Chromium, copper, nickel, and selenium, were detected once or inconsistently in the high and low debris sample. Lead concentrations in both high and low samples remained relatively consistent over time and zinc levels generally decreased in concentration over time. Metals levels appear to be generally within naturally occurring ranges typically found in metals in ground water and surface water.

Lead and Leachable Lead Contamination

The CWC's Glass Feedstock Evaluation assessed the incidence of lead and leachable lead contamination in different feedstocks. Total lead levels were evaluated on all of the cullet sources. Toxic Characteristic Leachate Procedures (TCLP) tests were conducted on a subset of these sources.

Total lead concentrations for 28 out of 29 sources were either undetected or detected at concentrations that are similar to naturally occurring lead concentrations found in granite. Only one source, from a beneficiation plant where cullet is processed to furnace-ready standards (WA-15), contained highly variable total lead concentrations in ten replicate samples analyzed (ranging from 29.4 ppm to 6635 ppm). The glass from this source is not considered a potential feedstock for construction aggregate because of its high beneficiation value. It was unclear whether the high lead incidence found in this source represented an anomaly or was in fact representative of cullets beneficiated in this plant.

All samples from potential construction aggregate feedstock sources, processed to aggregate gradations, showed total lead concentrations that were undetectable or at low concentrations similar to the levels found in natural granite. TCLP lead results for all cullet sources but one (WA-15 again), were undetected and below the federal regulatory limit of 5 mg/l.

Additional Lead Testing:

Additional lead tests were performed by the Clean Washington Center following completion of the Glass Feedstock Evaluation to obtain a larger statistical sampling on the incidence of lead contamination.

The testing was conducted because the original lead tests indicated that the elevated lead readings tended to show up as "spikes", that is, highly localized concentrations of lead, the testing was performed. This implied that the lead was not uniformly distributed throughout the piles, but rather occurred in discrete pieces, and that choosing a sample with a piece of lead was therefore a statistical "event." The additional testing seems to verify that supposition.

Total lead tests were performed on each of five discrete samples for ten of the 5-gallon bucket samples collected during the Glass Feedstock Evaluation project, for a total of fifty tests. Additionally, three TCLP tests were performed for a subset of four of the ten buckets, for a total of twelve TCLPs. The contents of the 5-gallon buckets had all been crushed to ¼" minus and contained all of the debris found in the original sampling from the glass piles (the original tests in the Glass Feedstock Evaluation had screened the samples to remove typical contaminants). The ten sources out of the original twenty-nine were chosen because of indications of the presence of lead during the previous project testing.

Lead Testing Results and Conclusions:

Table 15 presents the results for all of the TCLPs performed for glass piles from the Glass Feedstock Evaluation and subsequent testing by the Clean Washington Center. Table 16 presents the results from the total lead tests performed only during the additional testing by the Clean Washington Center.

Only one test for total lead, from sample WA-10, reported a result greater than 100mg/l, while 49 were below 60mg/l. These results supply strong evidence that, while lead is present, probably from pieces of lead foil wine neck wraps, the volume of lead tends to be swamped by the volume of glass in any method of weighed averages.

A statistical analysis based on the T-distribution gives a level of less than 30mg/l total lead for a one-sided 95% confidence interval.

The dilution factor relating total lead tests to TCLPs is 20:1. Therefore, a result of 100mg/l in a total lead test should correlate to equal to or less than 5mg/l in a leaching procedure. The TCLP is the standard procedure for regulatory determination of hazardous waste. 5mg/l is the minimum value of a TCLP for dangerous waste classification by the Washington State Department of Ecology.

For the additional TCLP tests run, in one instance, from bucket WA-11, a result of 11mg/l was detected. All other results were below 0.5mg/l. A 95% one-sided confidence interval for all TCLPs run during the project results in an inference of less than 5mg/l.

Two possible lessons can be derived from these results:

1. Anyone choosing to enter the glass processing business should probably undertake a regular program of total lead testing—in some cases, it may be required. For example, the Washington State Department of Transportation, in its specifications for glass aggregate, specifies that suppliers of glass aggregate mus quarterly perform, firve total lead tests on random grab samples from stockpiles of glass aggregate. Total lead tests are much less expensive than TCLPs, and may serve as an historical record of good stewardship of the material. Glass aggregate users should inquire of suppliers the source of glass (does it include wine bottles?) and if the supplier has a lead testing program in place.
2. These results also support efforts at educating the public to remove and dispose of wine bottle neck wraps with solid waste rather than with recyclables.

Table 15
Statistical Analysis of TCLP Lead

Description of Data	i	TCLP Lead Data & Calculations		
		Xi (mg/kg)	A (xi-xavg.)	A^2
9/9/92 NW Recycling - Green	1	14.70	11.72	137.358
9/9/92 NW Recycling - Clear	2	3.60	0.62	0.384
9/9/92 NW Recycling - Brown*	3	0.50	(2.48)	6.150
9/9/92 Skagit River Steel - Clear	4	0.50	(2.48)	6.150
9/9/92 Skagit River Steel - Green	5	10.50	7.52	56.550
9/9/92 Skagit River Steel - Brown*	6	0.50	(2.48)	6.150
10/15/92 Clean WA Center – Kent Highlands Mixed Glass Before Debris Screening	7	0.21	(2.77)	7.673
Same as above	8	0.36	(2.62)	6.864
Same as above	9	0.13	(2.85)	8.123
Same as above	10	0.11	(2.87)	8.237
Same as above	11	0.07	(2.91)	8.468
Same as above	12	0.28	(2.70)	7.290
Same as above	13	0.07	(2.91)	8.468
Same as above	14	0.27	(2.71)	7.344
Same as above	15	0.28	(2.70)	7.290
Same as above	16	0.22	(2.76)	7.618
Same as above	17	18.0	15.02	225.600
Same as above	18	11.0	8.02	64.320
11/19/92 City of Seattle – Kent Highlands Mixed Glass After Debris Screening	19	1.40	(1.58)	2.496
Same as above	20	1.30	(1.68)	2.822
Same as above	21	2.20	(0.78)	0.608
Same as above	22	0.24	(2.74)	7.508
Same as above	23	0.15	(2.83)	8.009
Same as above	24	0.46	(2.52)	6.350
Same as above	25	3.70	0.72	0.518
Same as above	26	0.53	(2.45)	6.003
Same as above	27	0.17	(2.81)	7.896
Same as above	28	0.13	(2.85)	8.123
6/14/93 CWC - WM-10, Flint, high debris*	29	0.10	(2.88)	8.294
6/14/93 CWC - MN-08, Mixed, low debris*	30	0.10	(2.88)	8.294
6/14/93 CWC - WN-04, Green, low debris*	31	0.10	(2.88)	8.294
6/14/93 CWC - WA-09, Green, low debris*	32	0.10	(2.88)	8.294
6/14/93 CWC - WA-15, Furnace ready	33	42.20	39.22	1538.208
6/14/93 CWC - WM-15, Furnace ready dup.	34	21.20	18.22	331.968
6/14/93 CWC - BFI-06, Amber, Med. debris*	35	0.10	(2.88)	8.294
6/14/93 CWC - CA-09, Amber, Med. debris*	36	0.10	(2.88)	8.294
6/14/93 CWC - OR-10A, Flint, Med. debris*	37	0.10	(2.88)	8.294
6/14/93 CWC - WM-09, Green, Med. debris*	38	0.10	(2.88)	8.294
7/29/93 CWC - WM-14a, Green, high debris	39	0.08	(2.90)	8.410
7/29/93 CWC - WM-14b, Green, high debris*	40	0.05	(2.93)	8.585
7/29/93 CWC - WM-14c, Green, high debris*	41	0.05	(2.93)	8.585
7/29/93 CWC - OR-14a, Flint, Med. Debris	42	0.26	(2.72)	7.398
7/29/93 CWC - OR-14b, Flint, Med. Debris	43	0.40	(2.58)	6.656
7/29/93 CWC - OR-14c, Flint, Med. Debris	44	0.27	(2.71)	7.344
7/29/93 CWC - BFI-07a, Flint, Med. debris	45	0.07	(2.91)	8.468
7/29/93 CWC - BFI-07b, Flint, Med. Debris*	46	0.05	(2.93)	8.585
7/29/93 CWC - BFI-07c, Flint, Med. debris	47	0.06	(2.92)	8.526
7/29/93 CWC – WA-14a, Mixed, low debris	48	0.43	(2.55)	6.503
7/29/93 CWC – WA-14b, Mixed, low debris	49	11.0	8.02	64.320
7/29/93 CWC – WA-14c, Mixed, low debris	50	0.27	(2.71)	7.344

Sum Xi: 148.77 Sum dif sq: 2,717.631

Avg. Xi: 2.98

Standard Deviation from Mean: S=(sum dif sq/n-1)^1/2: 7.447

Upper Confidence Interval (UCI) Calculations

One-tailed 90% UCI T statistic (Ts), Ts=1.3, for n-1=49

One-tailed 95% UCI T statistic (Ts), Ts=1.667, for n-1=49

90% UCI is Avg Xi + Ts(S/(n)^1/2 — 90% UCI: 4.349

95% UCI is Avg Xi + Ts(S/(n)^1/2 — 95% UCI: 4.746

Table 16
Statistical Analysis of Total Lead Content

Client ID	TCLP Lead Data & Calculations		
	Xi (mg/kg)	A (xi-xavg.)	A^2
AZ-2a	1.20	(21.17)	448.17
AZ-2b	1.40	(20.97)	439.74
AZ-2c	0.70	(21.67)	469.59
AZ-2d	1.70	(20.67)	427.25
AZ-2e	3.10	(19.27)	371.33
BFI-07a	20.00	(2.37)	5.62
BFI-07b	6.80	(15.57)	242.42
BFI-07c	10.00	(12.37)	153.02
BFI-07d	37.00	14.63	214.04
BFI-07e	5.40	(16.97)	287.98
MN-8a	44.00	21.63	467.86
MN-8b	17.00	(5.37)	28.84
MN-8c	24.00	1.63	2.66
MN-8d	55.00	32.63	1,064.72
MN-8e	12.00	(10.37)	107.54
OR-12a	44.00	21.63	467.86
OR-12b	58.00	35.63	1,269.50
OR-12c	16.00	(6.37)	40.58
OR-12d	44.00	21.63	467.86
OR-12e	28.00	5.63	31.70
OR-1a	28.00	5.63	31.70
OR-1b	12.00	(10.37)	107.54
OR-1c	23.00	0.63	0.40
OR-1d	76.00	53.63	2,876.18
OR-1e	10.00	(12.37)	153.02
WA-11a	25.00	2.63	6.92
WA-11b	14.00	(8.37)	70.06

Table 16
Statistical Analysis of Total Lead Content

Client ID	TCLP Lead Data & Calculations		
	Xi (mg/kg)	A (xi-xavg.)	A^2
WA-11c	18.00	(4.37)	19.10
WA-11d	10.00	(12.37)	153.02
WA-11e	14.00	(8.37)	70.06
WA-10a	8.60	(13.77)	189.61
WA-10b	26.00	3.63	13.18
WA-10c	18.00	(4.37)	19.10
WA-10d	190.00	167.63	28,099.82
WA-10e	14.00	(8.37)	70.06
WM-10a	40.00	17.63	310.82
WM-10b	4.10	(18.27)	333.79
WM-10c	21.00	(1.37)	1.88
WM-10d	23.00	0.63	0.40
WM-10e	15.00	(7.37)	54.32
WM-11a	8.10	(14.27)	203.63
WM-11b	15.00	(7.37)	54.32
WM-11c	12.00	(10.37)	107.54
WM-11d	6.90	(15.47)	239.32
WM-11e	18.00	(4.37)	19.10
WM-14a	8.50	(13.87)	192.38
WM-14b	4.80	(17.57)	308.70
WM-14c	9.20	(13.17)	173.45
WM-14d	11.00	(11.37)	129.28
WM-14e	5.80	(16.57)	274.56

Sum Xi: 1,118.30 Sum dif sq: 41,291.45

Avg. Xi: 22.37

Standard Deviation from Mean: S=(sum dif sq/n-1)^1/2: 29.03

Upper Confidence Interval (UCI) Calculations

One-tailed 90% UCI T statistic (Ts), Ts=1.3, for n-1=49

One-tailed 95% UCI T statistic (Ts), Ts=1.667, for n-1=49

90% UCI is Avg Xi + Ts(S/(n)^1/2 — 90% UCI: 27.70

95% UCI is Avg Xi + Ts(S/(n)^1/2 — 95% UCI: 29.25

4. Conclusions for Construction Aggregate Users

The significance of the physical and chemical properties testing, and environmental suitability evaluation conducted during the CWC Glass Feedstock Evaluation, the FDOT study, and related studies is summarized below for construction aggregate users.

Debris Content: When sourcing material for use in aggregate applications, ask potential suppliers how the glass feedstock was collected. Two collection schemes were positively associated with high debris levels - blue bag collection systems and unattended drop boxes. The highest percent of debris sampled during the CWC Glass Feedstock Evaluation were obtained from an unattended dropbox/barrel. The most common types of debris observed in the high debris level sources were labels (paper and plastic) and bottle caps (metal and plastic). Mechanically-facilitated sorting/cleaning is associated with lower debris levels. Also, commingled glass only collection schemes appear to produce no cleaner a material than commingled container collection provided.

Chemical Properties: The chemical properties of glass and glass cullet leachate are all within ranges that imply that they do not pose any problems for construction aggregate users. The CWC Glass Feedstcok Evaluation found that the concentration trends of BOD, COD, TOC, pH, and specific conductivity decreased in concentration over time and do not appear to be at concentrations of concern. Suspended and dissolved solids concentrations were so low that they were difficult to measure, and are not expected to create any environmental concerns. The cullet metal concentrations found in the studies were at or below the metal concentrations typically found in background levels of granite. One area that deserves slightly more robust attention is described below.

Semi-Volatile Organics. The semi-volatile organic results from the CWC Glass Feedstock Evaluation indicated the presence of phthalates and relatively low levels of polycyclic aromatic hydrocarbons (PAHs). Regulatory limits for organic compounds vary across the country and are generally based on site specific information and local and state regulations. Although organic regulatory limits are not available for direct comparison of organics found in the cullet samples, the organics do not appear to represent levels of concern.

Investigations revealed that plastic bottles previously containing oil were commingled with glass and other recyclables in the blue bag program sampled in the study. This is the most likely source of the polycyclic aromatic hydrocarbons (PAH) contamination. Other plastic products are the most likely source of phthalates.

Construction aggregate users should be aware that glass should not be commingled by the processor/supplier. Practical experience with most recycling programs is that commingling of glass with these types of plastics tends to be uncommon. As a measure of caution, glass aggregate users should include a “no hazardous waste” line item in specifications given to suppliers.

Environmental
Suitability:

Biological Impacts from Chemical Properties. Both the CWC Glass Feedstock Evaluation and the FDOT Study evaluated the potential for contaminant leaching from glass feedstock over time. While the FDOT Study discussed storage requirements to assure complete biological degradation prior to placement, the CWC Glass Feedstock Evaluation found no potential for harmful contaminant leaching from glass.

Lead. Test results supply strong evidence that, while lead is present, probably from pieces of lead foil wine neck wraps, the volume of lead tends to be swamped by the volume of glass in any method of weighed averages. A statiscial analysis based on the T-distribution of the CWC Glass Feedstock Study results gives a level of less than 30mg/l total lead for a one-sided 95% confidence interval. Since the dilution factor relating total lead tests to TCLPs is 20:1, a result of 100mg/l in a total lead test should correlate to equal to or less than 5mg/l (the federal regulatory limit for TCLP tests) in a leaching procedure.

Anyone choosing to enter the glass processing business should probably undertake a regular program of total lead testing—in some cases, it may be required. For example, the Washington State Department of Transportation, in its specifications for glass aggregate, specifies that suppliers of glass aggregate mus quarterly perform, firve total lead tests on random grab samples from stockpiles of glass aggregate. Total lead tests are much less expensive than TCLPs, and may serve as an historical record of good stewardship of the material.

4. Processing Equipment Guidelines

1. Equipment Properties

In order to select glass processing equipment, the objectives of the potential purchaser should be determined. This may include capital budget, minimum production capacity, portability, etc. References from existing owners should also be obtained. Once the field is narrowed to several models it would be helpful to visit an actual installation of the piece of equipment being considered. Another alternative is to retain an engineer experienced in materials handling. Such a professional should be able to design a system which meets the needs of the client.

2. Conclusions for Construction Aggregate Users

The following guidelines and recommendations are provided for potential purchasers of glass processing equipment:

Training and Maintenance

The equipment should be relatively easy to operate and maintain. Training to operate and maintain the equipment should be provided by the manufacturer. Replacement parts and technical assistance should be readily available. The equipment should be protected under a strong warranty to cover unforeseen breakdowns during the first year or so of operation. The equipment should be safe to operate. Guards should be provided to protect workers from flying glass, rotating shafts, belts, pulleys, and other moving parts.

Product Quality

Because cullet gradation and debris level are very important factors with regard to engineering performance, the crushing system should have a screening system to control particle size and debris level. This system may be a vibrating screen, a rotating trommel, or an angled screen. Although not all of the manufacturers offer screens or trommels as an option, many of them probably have the ability to fabricate such a device.

Adjustable Crushing Mechanism

The ability to adjust the gradation of the cullet is a desirable option. By controlling gradation, a cullet supplier might target the glass product to specific applications. Also, without adjustability there may be too much oversized material. Although the oversize material can be collected on a screen and recirculated through the crusher, this is an inefficient way to produce cullet. Thus, it is preferable that the crusher produces cullet close to the size desired. In this way, the majority of the cullet passes through the screen and most of the debris is retained. Crusher adjustability can take several forms. There may be an external adjustment which changes clearances through which cullet must pass. The crushing mechanism speed may be varied with adjustable belts and pulleys or gears and chains. Also, different mechanism configurations may be installed which yield different cullet gradations.

Wearing Surfaces

Cullet is a very abrasive material. It is therefore desirable that all wearing surfaces - particularly those of the crushing mechanism - be constructed of abrasion-resistant materials. Alternatively, wearing surfaces should be designed such that they may easily be replaced or resurfaced by depositional welding. Additionally, food residue and label glue render cullet to be quite sticky. As a result, cullet tends to adhere to conveyor and drive belts. This will abrade the belts and can clog the drive mechanism. Designs that prevent cullet from sticking to belts or continuously remove the cullet will result in lower maintenance costs.

Auxiliary Equipment

Auxiliary equipment may be desired to further automate or expedite production of cullet. Hoppers should be wider and have move volume than the largest loader bucket to be used to feed it. Otherwise, bottles will overflow the hopper and drop to the floor. Inlet conveyors should be large enough to transport bottles from the inlet hopper location to the elevation of the crusher. The feed rate of the inlet conveyor should not exceed the capacity of either the crusher or the outlet conveyor (if any). Trommels or vibrating screens should be appropriately designed to work in conjunction with the other components of the system. The use of auxiliary equipment also affects the overall dimensions of the glass crushing system. It is important to consider height, length, and width restrictions before purchasing the equipment. Equipment should easily pass through existing doorways, and under any overhead wires or structures.

System Portability

System portability may be an important requirement. Such systems should be easily loaded or even mounted onto a truck or trailer. Additionally, it is possible to transport partially disassembled systems designed for quick assembly at a site. Systems which are not designed to be portable may be fairly tall structures. These should be well-anchored in seismically-active areas to reduce the risk of overturning during an earthquake.

Power Requirements

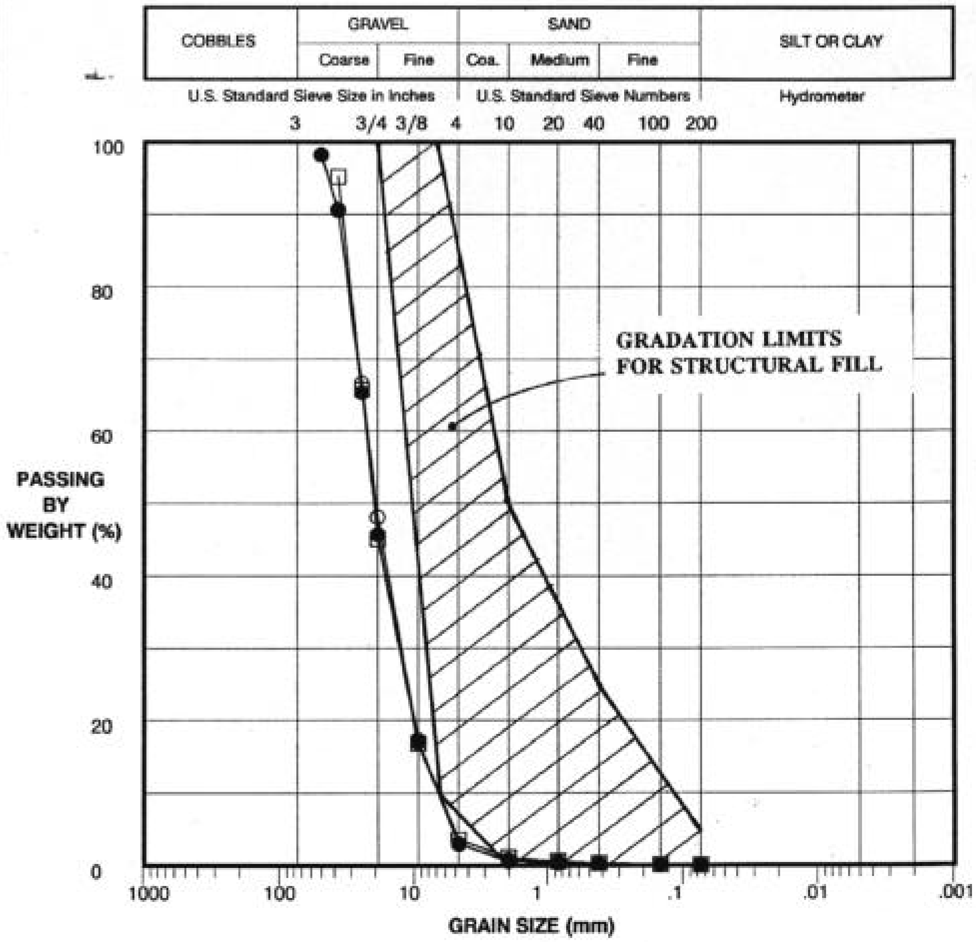
Power requirements for the crushing system should be assessed. Some systems have multiple electric motors, each requiring a separate circuit and on/off switch. All switches should be large and easy to throw in case of an emergency. At very remote installations, or with portable systems, a generator may be desired to make the system more self-contained.

Costs

Economic analysis indicates that the largest expenses relative to glass processing are, in order

1. Labor
2. Equipment depreciation
3. Facility costs
4. Maintenance
5. Raw Material (including transportation costs)
6. All Other

The following graphs illustrate the importance of equipment selection to minimize labor costs. In graph 1, the oversize material will need to be either disposed as solid waste, or recirculated through the quipment, adding labor costs. Contrast this with graph 2, where all the material meets spcifications on one pass. Rescreening material also has the effect of concentrating contaminants.



GRAIN SIZE DISTRIBUTION

SYMBOL	SAMPLE NO.	% GRAVEL	% SAND	% FINES
○	S-1-A	96.8	3.1	0.1
●	S-1-B	96.8	3.1	0.1
□	S-1-C	96.2	3.8	0.1

REMARKS: Sample composed of 100% cullet. Curves depict gradation of sample from different batches.
Crushing Equipment: Miller Manufacturing Company, Model GB-750

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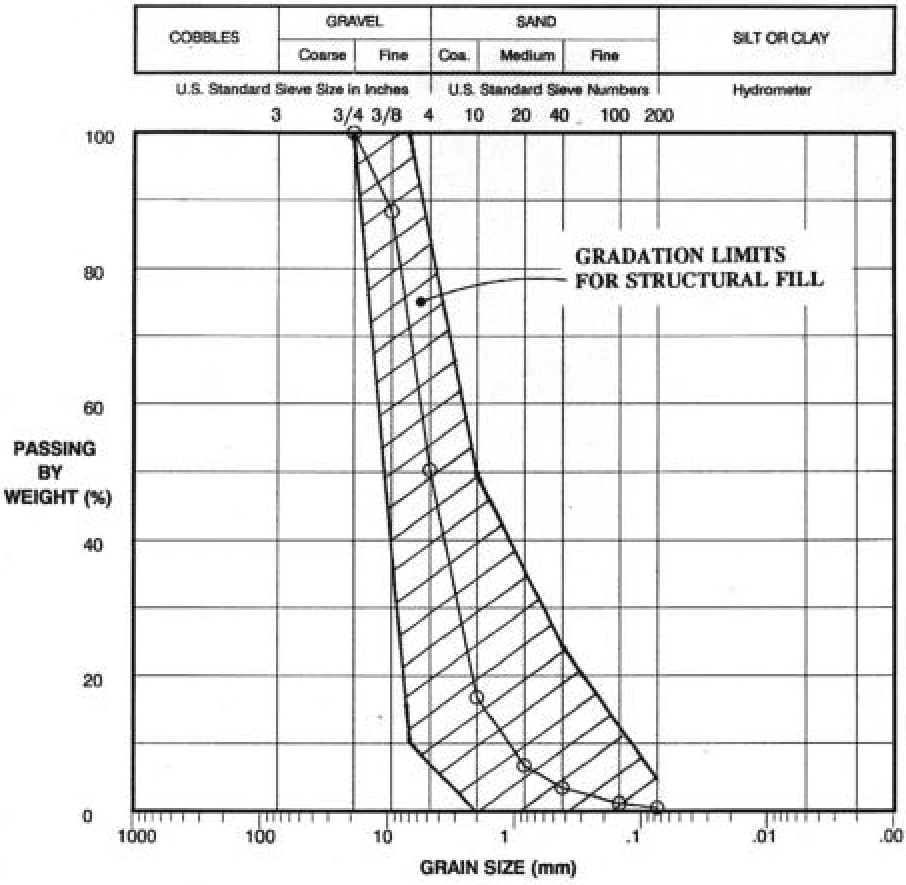
JOB NO.25854-001 Plate B-1



GRAIN SIZE DISTRIBUTION

SYMBOL	SAMPLE NO.	% GRAVEL	% SAND	% FINES
○	S-5-1	49.4	50.0	0.5

REMARKS: Sample composed of 100% cullet. Curves depict gradation of samples from different batches.
Crushing equipment: GEW Model A

07-06-1993 Glass Feedstock Evaluation **DAMES & MOORE**

JOB NO.25854-001 Plate B-9

5. General Guidelines and Specifications for the Use of Glass as a Construction Aggregate in Proven End-Use Applications

Glass cullet is used for a variety of construction applications, including general fill and backfill, roadway construction, utility bedding and backfill, drainage medium, and miscellaneous uses such as landfill cover, sandblasting, and underground storage tank backfill. Specifications for individual states are based on local variables such as aggregate sources and climate.

1. Summary of State Policies Regarding Glass Construction Aggregates

Washington State The Washington State Department of Transportation (WSDOT) permits the use of recycled glass as an additive up to 15% to unbound aggregate used for seventeen specific applications, including a number of fill and ballast uses. No more than 10% of the glass should be retained on a ¼-inch sieve.

WSDOT also provides specifications for construction aggregates composed entirely of cullet. These aggregates may be used for wall backfill, rigid and flexible pipe bedding, drainage backfill, drainage blankets, and gravel borrow. The cullet must be smaller than ¾inch, and should contain no more than 5 percent by weight of material finer than a No. 200 sieve. The maximum debris content, including all non-glass constituents, is 10% as identified by visual methods. In addition, the glass supplier must test the total lead content of the cullet on a quarterly basis according to EPA methods 3010/6010. The mean of these tests cannot exceed 80 parts per million lead.

Oregon The Oregon Department of Transportation (ODOT), in November 1996, began issuing Special Provisions with bid specifications allowing the use of up to 100% recycled glass in non-structural fill, drainage blanket, utility bedding and backfill, subsurface drains, and wearing surface drains. One hundred percent of the glass must pass a 1/2 inch sieve, with a maximum of 5% by weight finer than 200 mesh.

Maximum debris content is 5% or 10%, as specified per application, determined by visual classification.

California

The California Department of Transportation (CalTrans) has accepted cullet specifications for Class 1, 2, 3, and 4 base and Class 2 and 3 subbase roadway aggregate for the support of flexible and rigid pavements. These aggregates can consist entirely of cullet, or a mixture of cullet and other reclaimed materials, such as asphalt concrete, cement concrete, lean concrete base, and cement treated base. The different classes of base and subbase aggregate are distinguished by gradations. The size of the cullet used must follow the size criteria specified for those aggregate applications by CalTrans. Material used in these base and subbase aggregates must be free of organic material and other deleterious substances. Surfacing material must be placed over all aggregate bases and subbases containing glass cullet.

Connecticut

The State of Connecticut specifies that aggregate used for roadway embankments may contain up to 25% by weight of cullet smaller than one-inch. Aggregate containing cullet cannot be placed within five feet from the face of any slope.

New York

The New York State Department of Transportation (NYSDOT) allows aggregate for embankments to contain up to 30% by volume of glass cullet. In addition, roadway subbase material may contain up to 30% by weight of glass cullet. Cullet used for these applications must be smaller than 3/8-inch, and should contain no more than 5% by volume of ceramics and non-glass materials, based on visual inspection. Waste glass cannot be placed in contact with any synthetic liners, geogrids, or geotextile material.

New Hampshire

The New Hampshire Department of Transportation (NHDOT) allows glass cullet to replace 5% by weight of the dry aggregate used for roadway base course material. The material used to produce this cullet should consist primarily of recycled food and beverage glass containers. Small amounts of ceramics and plate glass are also permitted, although glass containing hazardous or toxic materials is not allowed. The cullet must be smaller than ½inch in size, and not more than 1½% of the material smaller than a No. 4 sieve should be smaller than a No. 200 sieve. NHDOT requires that all base course be tested for compliance with this gradation prior to placement. Post-placement visual inspection of the base course is also required. Base course containing cullet must be capped with non-cullet aggregate before the public is allowed to drive over the material.

2. End-Use Application Specifications

Potential applications of cullet and cullet-added materials are listed below. Care has been taken to provide recommendations which are felt to be conservative based on the test results of the CWC Glass Feedstock Evaluation and FDOT studies. Experience and time may well serve to expand the use of cullet in many applications.

Except where noted, the cullet described below includes both 1/4 inch and 3/4 inch minus gradations. Also, a maximum debris content of 5% is recommended for all applications except for nonstructural fill, such as those used for landscaping and daily landfill cover, where a debris content of 10% is acceptable. In general, specifications are based on criteria that are related to the engineering behavior of the in-place material. When the material is used in structural load applications, the behavior and properties must be especially well understood.

General Fill and Backfill Applications

Cullet can be used as fill material for general construction uses such as site grading, filling under slabs, backfilling beside foundations or behind retaining walls, and landscaping. Since the CWC Glass Feedstock Evaluation, 100% cullet fill has been used in many construction projects for fill and backfill projects. Based on recent case study (see Section 6) the cullet fill has performed satisfactorily. For fluctuating loading and heavy, stationary loading conditions, a maximum cullet content of 15% is recommended. However, no case history of such application is currently available.

Load-Supported Applications

Load-supporting backfill includes fills that support heavy stationary loads such as fill beneath footings and slabs, fluctuating loads such as those beneath reciprocating pumps, compressors or other machinery, and light-loaded conditions such as fill placed beneath pedestrian sidewalks.

Load-supporting fills must be strong, with minimal settlement potential under material self-weight and applied loads. The strength requirement can be achieved by compacting the material to a pre-determined density. The settlement potential can be minimized by controlling the gradation and deleterious debris content. Glass aggregate is a granular material which will deform elastically under load, but will return to the original volume when the load is removed. However, both organic and inorganic debris in the glass can effect the elasticity of the aggregate. No long-term deformation is expected if the debris is limited to less than 5% to 10% as determined by visual inspection.

Lateral Loads and Friction. Cullet fill will apply lateral loads including active, at-rest, and passive pressures to a retaining structure. The magnitude of these loads is a function of the strength and density of the fill. Since glass aggregate is non-cohesive, its strength can be represented by its internal friction angle which is typically 38 to 42 degrees. Glass aggregate is generally lighter than natural aggregate because the specific gravity values of glass cullet (about 2.0 to 2.5) are less than those of natural aggregate. The density of compacted fill typically ranges from 100 to 115 pcf.

Frictional resistance develops at the interface of fill particles and at the structure surface. In construction applications, the load-applying surfaces may include concrete, wood, steel, or plastic. Typically, the frictional resistance can be estimated using about 2/3 to 3/4 of the internal friction angle of the fill material. For critical structures, a laboratory direction shear test is recommended for the determination of the interface frictional resistance.

Fluctuating Loads. For fill under cyclic loading, both the strength and durability of the material are critical. The latter depends on gradation and material characteristics. The suitability of such fill can be evaluated using laboratory tests such as CBR (California Bearing Ratio), Resistance R Value, or Resilient Modulus tests. The resilient modulus can be determined by cyclic triaxial tests. However, this test requires special equipment and is not commonly conducted. In engineering practice, the resilient modulus is often obtained from other test values such as CBR. For data on several gradations and mixtures of glass aggregate see the full Glass Feedstock Evaluation.

Non-Loaded

Applications

Cullet can be used as landscaping or in non-loaded areas for general fill purposes. Model specifications for general fill and backfill applications are presented below.

Loading Conditions	Maximum Cullet Content (%)	Maximum Debris Content (%)	Minimum Compaction Level (%)
Heavy, Stationary Loads	30	5	95
Fluctuating Loads	15	5	95
Non-Loading	100	10	85
Light, Stationary Loads	100	10	95
Lateral Loads	100	10	95

Roadway Applications

Roadway applications include the use of cullet aggregate in base course, subbase, subgrade, and embankments. Cullet can be added to natural aggregate and the mixed material will have adequate strength and resistance to abrasion and traffic loads. Based on the CWC Glass Feedstock Evaluation test data, a 15% cullet content is recommended for base aggregate and a higher cullet content, up to 30%, is recommended for sub-base aggregate and for the construction of roadway embankments.

The gradation of 1/4 inch minus cullet corresponds to that of a medium to coarse sand. This cullet can be used as the filler material for some coarse natural aggregates. Due to the gradation change and the high angularity of the cullet, the addition of 1/4 inch minus cullet may enhance the engineering performance of natural aggregate and may even help some of the borderline aggregates meet gradation requirements.

The model specifications for roadway applications are presented below.

Applications	Maximum Cullet Content (%)	Maximum Debris Content (%)	Minimum Compaction Level (%)
Base Course	15	5	95
Subbase	30	5	95
Embankments	30	5	90

Utility

Applications

Cullet can be used as a backfill material for utility trenches, vaults, and other underground facilities. The thermal conductivity of the cullet material is similar to that of the natural aggregate. Hence, cullet material can replace natural aggregate for utility trenches where the heat transfer characteristics of the backfill is of concern. Cullet content up to 100% can be used for backfill up to the last two feet below the final grade. Depending on the loading conditions on the backfill area, the last two feet of the backfill can have cullet contents varying from 15% to 100%.

The specifications listed below apply to backfill which are not subjected to surcharge loading such as from a roadway or slab. If the trench backfill lies within five feet of a loading area, then the specifications provided in above *General Fill and Backfill* would apply.

Applications	Maximum Cullet Content (%)	Maximum Debris Content (%)	Minimum Compaction Level (%)
Water & Sewer Pipes	100	5	90
Electrical Conduit	100	5	90
Fiber Optic Lines	100	5	90

Drainage Applications

Drainage applications include retaining wall backfill, footing drains, drainage blankets, and french drains. In general, the permeability of the 1/4 minus cullet material is about the same as that of natural sand and the permeability of the 3/4 minus cullet material is about the same as that of natural gravel. Hence, fill material made of 100% cullet can be used for construction of drainage facilities such as drainage blankets, french drains, foundation drains, and behind retaining walls.

The cullet materials appear to have favorable characteristics for use as filtration media. Further study on the filtration capacity of cullet materials is recommended. Once its filtration capacity is confirmed, the cullet can be used in applications such as septic fields, leachate treatment and water purification.

The recommend gradation specifications are listed below.

Sieve Size	3/4”	1/4”	No. 10	No.40	No. 200
Percent Passing (by weight)	100	10-100	0-100	0-50	0-5

The recommended specifications on the cullet content, debris content and compaction level are listed below.

Applications	Maximum Cullet Content (%)	Maximum Debris Content (%)	Minimum Compaction Level (%)
Retaining Wall	100	5	95
Foundation Drain	100	5	95
Drainage Blanket	100	5	90
French Drain	100	5	90
Leachate Collection	100	5	90

Miscellaneous Applications

Cullet of both sizes could be used for daily landfill cover or underground storage tank backfill. In landfill applications, 100% cullet may be used. Backfill for underground storage tanks can consist of up to 100% cullet except for the last two feet which may have cullet contents ranging from 15% to 100%, depending on the loading condition of the backfill area. Additionally, the abrasive nature of cullet also makes it a candidate as a sand blasting medium.

The model specifications for such applications are presented below.

Applications	Maximum Cullet Content (%)	Maximum Debris Content (%)	Minimum Compaction Level (%)
Landfill Cover	100	10	90
UST Backfill	100	5	90

1. Case Studies (See Other Electronic Files)

2. Lessons Learned

The case histories detailed in Part 1 of this section provide valuable insight into the in-field performance of glass cullet aggregate. A number of advantages, and some disadvantages, are discovered with each use. A summary of these issues is provided below.

Drainage & Moisture Insensitivity

1. Excellent permeability creates a free-draining aggregate that works exceptionally well as a capillary break and as retaining wall backfill. (#1)

2. Moisture insensitivity of glass cullet aggregate allows placement in areas of standing water and stabilizes muddy slab subgrades. Moisture insensitivity also allows glass to be placed and compacted during wet weather, while showing greater "workability" than sand and gravel (#1,3, 6, 8)

3. Due to its free-draining nature, cullet can dry out quickly during periods of dry weather. Consequently, spraying with water or the use of heavier compaction equipment may be necessary to obtain the level of specified density.

Compaction

1. Compaction of glass cullet aggregate is similar to the compaction of natural aggregates and can be compacted to a "dense and non-yielding state" (#1, 8)

Handling & Placement

1. Handling and placement of glass cullet aggregate is in most cases no more difficult than natural aggregates (#1)

2. Glass cullet aggregate is lighter and easier to place using hand tools than conventional drain gravel. (#2, 5, 8)

3. Cullet can be stored in open stockpiles to facilitate drainage of resident moisture. (#4)

4. Some minor cuts to power cords, hand tools, small equipment tires, and site personnel have been reported. (#3, 5, 8)

5. Some dusting occurs during transportation/dumping of cullet (#3)

6. Truck or machine traffic over exposed cullet can cause deep ruts and create minor impasses. Alternating lifts between cullet and sand and gravel remedies the situation. (#6, 9)

7. Because of it's platy shape, cullet can be "sticky", particularly during wet weather. Cullet particles can adhere to construction equipment and then spread to adjacent areas. (#8)

Gradation Specifications

1. Cullet should be graded to a gradation that is similar to that of a fine to coarse sand, with 5 to 10 percent by weight smaller than a no. 200 sieve. This amount of fine grained material would help fill the voids in the cullet, resulting in higher densities, greater strength, and less compressibility. Additional fines would also help retain moisture during periods of dry weather. (#9)

Regulations

1. States with little of no knowledge of the use of glass as construction aggregates may require special permits and/or research into appropriate specifications to use in given applications. (#4)

Availability

1. Some glass cullet processors underestimate the demand for glass to be used as a construction aggregate and cannot meet contractor needs. (#3)