Using Recovered Glass as Construction Aggregate Feedstock

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The success of recycling collection programs has resulted in an oversupply of broken glass, or cullet, in many parts of the country. To open the construction aggregate market, a multistate and industry evaluation of glass as construction aggregate was conducted. The study defines the suitability of cullet as a construction aggregate in terms of its engineering performance, environmental impact, cost comparability with natural aggregates, and safety in handling. The analysis concludes that glass, as an aggregate, is strong, clean, safe, and economical. From an engineering standpoint, cullet appears to be an excellent supplement or replacement for natural aggregates in many construction applications. Comprehensive tests were performed for specific gravity, gradation, workability, durability, compaction, permeability, thermal conductivity, and shear strength. The effects of debris level, cullet content as a percentage of aggregate, and cullet size were also investigated. When cullet is compacted to a dense state, the material is rigid and strong. The test data indicate that under normal working stresses, the moduli and shear strength of the cullet samples are similar to those of natural aggregate. In the case of $^1/_4$-in. minus cullet, adding cullet to the natural aggregate can even increase the rigidity and strength. Compaction curves tend to become flatter as cullet content increases, implying that the maximum dry density is relatively insensitive with respect to moisture. From a construction standpoint, this means that the material can be compacted even in wet weather.

Construction aggregates promise to be a viable market option for glass recycling. The size of the construction aggregate market dwarfs the potentially available supply of recovered glass, and in most cases, the cost to recover and market glass as a construction aggregate is less than the cost to use it as landfill. As a unique material, glass can contribute to performance in many engineered applications.

To open this market for glass, a multistate and industry study (*1*), with participation and support from three state departments of transportation, undertook to demonstrate the technical and economic feasibility of using glass as construction aggregate feedstock. The purpose of the Glass Feedstock Evaluation Project was to provide the necessary information on cullet properties and processing so that engineers can specify the use of cullet as a construction aggregate with confidence and suppliers of recycled glass aggregate can invest in market development with minimal risk. The study defines the suitability of cullet as a construction aggregate in terms of its engineering performance, environmental impact, cost comparability with natural aggregates, and safety in handling. The analysis concludes that recovered glass used as aggregate is strong, clean, safe, and economical.

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GLASS RECYCLING IN 1993

The one well-established market for recovered glass, the glass container industry, is characterized by oversupply. The advent of community recycling programs in the late 1980s and early 1990s resulted in a tremendous surge in the supply of recovered glass. This growth in supply continues unabated as more communities join the ranks of recyclers and more people are drawn into existing recycling programs. For a community of 10,000, the supply can be roughly estimated at 250 tons per year, assuming 50 percent recovery at an annual consumption level of 80 lb of glass per person. Many communities recover upward of 70 percent of the available glass.

On the demand side, many glass plants are limited to a low percentage of cullet (crushed glass) in their batch for technical and economic reasons. This market also suffers supply-and-demand dislocations because of geographic concentration of glass plants, and transportation costs often outweigh the market price of cullet. Also, although cullet processed to furnace-ready standards brings up to $60 per ton, the costs to color-sort and remove such contaminants as ceramics and metals can exceed the cullet's present market value.

Because there is no need to color-sort glass for aggregate use and because the contaminant specifications are less stringent, the cost to supply to the construction aggregates market is far less than that of beneficiating glass to be remade into bottles. As a materials source for either the container or the construction aggregate markets, unprocessed cullet exhibits varying quality in terms of its nonglass content depending on how the glass is collected and sorted for recycling. A principal aim of the Glass Feedstock Evaluation Project was to assess the engineering performance and environmental suitability of glass in aggregate applications over the range of debris content levels that would reasonably be associated with the different collection and sorting techniques.

TECHNICAL APPROACH

For the study, glass sources were selected from around the country to represent the spectrum of glass collection and sorting systems—drop boxes, deposit collection, curbside commingled collection, and blue bag programs, among others. (In a commingled collection program, one or more recyclables are collected together and then later sorted; in a blue bag program, all recyclables are collected together.) Sample material was composited from stockpiles and ranged in size from whole bottles to fines. A laboratory jaw crusher was used to prepare the glass for environmental testing and debris-level classification. All debris was passed through with the glass. Debris was defined as any deleterious material that could affect the performance of engineered fill, generally, nonceramic materials. Types of debris observed in cullet samples included paper, foil, and plastic labels; plastic and metal caps; cork; paper bags; wood debris; food residue; and grass.

Twenty-nine sources were categorized for debris content level, and representative high and low debris-level sources were selected for engineering performance testing. In addition to debris content level, the study investigated two other key independent variables to determine their effect on engineering performance. These were the cullet content in the aggregate mix (15, 50, or 100 percent by weight) and the aggregate mix gradation ($^1/_4$ or $^3/_4$-in. minus). Affordable techniques are available to control both these variables: aggregate mixing equipment for cullet content and glass crushers for gradation. Two types of natural aggregate—a crushed rock and a gravelly sand—were selected for the mixed samples.

The applications of interest were all unbound aggregate applications. It was beyond the scope of the study to look at glass in composites such as glassphalt and glasscrete. A statistical analysis was conducted on the environmental data and on key engineering data to ensure that any variability in results was within the expected range at a high confidence level.

ENVIRONMENTAL SUITABILITY

No appreciable environmental impact could be detected. The testing program contained three components: organic and inorganic chemical characterization, including evaluation of the potential for bacterial growth; an assessment of contaminant leachability over time; and a determination of the incidence of lead and leachable lead.

Limited organic compounds were found, not at harmful levels, including plastic debris, low concentrations of food residues, and organics that occur naturally in the environment. One atypical blue bag collection source contained elevated levels of polycyclic aromatic hydrocarbons (PAHs), attributed to the inclusion in the collection program of recyclable plastic bottles that once contained oil products.

The incidence of lead contamination was found to be within acceptable limits. Lead foil wrappers used on wine bottles do cause highly localized peaks of lead concentration, but these concentrations statistically average to levels typical of many natural soils. All sources were examined to determine lead incidence, and for 10 of those indicating the presence of lead, multiple samples were analyzed (6 discrete samples from composited sources).

SAFETY ANALYSIS

Bulk samples showed crystalline silica concentrations of less than 1 percent, placing glass dust in the nuisance category according to federal regulations (20 CFR 1910.1000), and air samples taken during compaction testing showed total dust concentrations below 0.5 mg/m^3 compared with the permissible exposure limit of 10.0 mg/m^3. There is evidence for the carcinogenicity of crystalline silica, and dusts from materials containing greater than 1 percent crystalline silica are classified as toxic, as is silica sand. Silica in glass is in the amorphous form.

Cullet is an abrasive material, causing irritation when the skin comes in contact with very fine fragments. Bottle cullet crushed to $^3/_4$-in. minus does not normally present the skin cut or penetration hazards associated with larger glass bottle fragments, drinking glasses, and plate glass. Although there are no standard methods for recording the skin penetration hazard, it is noted that laboratory personnel experienced no lacerations while handling this material. The $^1/_4$-in. minus material was particularly benign from this standpoint. Recycling and glass industry personnel working with crushed cullet report no undue skin penetration hazards either. Routine handling precautions are recommended.

ENGINEERING SUITABILITY

From an engineering standpoint, cullet appears to be an excellent supplement or replacement for natural aggregates in many construction applications. Comprehensive tests were performed for specific gravity, gradation, workability, durability, compaction, permeability, thermal conductivity, and shear strength. The effects of debris level in the cullet (high and low debris), cullet content by weight (15, 50, and 100 percent), and size of cullet ($^1/_4$- and $^3/_4$-in. minus) were investigated.

Debris levels were determined using a visual method adapted from the American Geological Institute (AGI) (*2*). Accuracy of visual classification, which is easily employed in the field, was confirmed through quantifying the debris by weight and volume in six samples. Because of the platy nature of the debris, visual classification produces a greater quantitative difference between high and low debris levels than do volume- and weight-testing methods. Relatively high-debris and low-debris sources, with 5 percent and 1 percent debris levels, respectively, by visual classification, were selected for testing.

Principal findings of the engineering performance evaluation include the following:

- The data show that both $^1/_4$- and $^3/_4$-in. minus cullet are durable and mechanically sound. Cullet resistance to degradation is lower than that of natural aggregate. However, when cullet is mixed with natural aggregate, the resulting material will most likely have acceptable Los Angeles (L.A.) abrasion, *R*-value, and resilient modulus properties for use as roadway aggregate.
- Cullet compacted to a dense state is rigid and strong. These characteristics are attributed to the compactness of the bulk material, high shear strength of individual particles, and high interparticle frictional resistance. Under normal working stresses, the moduli and shear strength of the cullet samples are similar to those of natural aggregate. In the case of $^1/_4$-in. minus cullet, adding cullet to the natural aggregate can even increase the rigidity and strength.
- Cullet experiences very little gradation change under normal compaction and loading conditions. This gradation stability is due to the strength of the individual particles. The stable gradation translates to constant engineering properties, making it possible to base engineering designs on properties derived from laboratory tests.
- The cullet and cullet-aggregate mixtures have favorable compaction characteristics, which provide good workability of the material. In general, density of the compacted cullet samples is not sensitive to moisture content, an advantage in wet weather. Choosing the appropriate laboratory compaction method could be important, as is evident from the sensitivity of test data such as

California bearing ratio (CBR) values (presented below) to the compaction methods.

- Debris level does affect some engineering properties of the cullet, but on the basis of the test data, good engineering performance can be expected for cullet containing up to 5 percent (by visual classification) debris.

Individual test results and their significance are summarized in the following sections.

Specific Gravity

Fourteen specific gravity tests (ASTM D854) were conducted on the fraction of the samples finer than the standard U.S. No. 4 sieve. Fourteen bulk specific gravity tests (ASTM C127) were conducted on the fraction of the samples coarser than $^1/_4$ in. Specific gravities of coarse cullet samples ranged from 1.96 to 2.41 and of fine cullet samples from 2.49 to 2.52. Differences in the test procedures and in the debris levels of the samples contribute to the differences in range. The lowest specific gravity of 1.96 measured for the high-debris, $^3/_4$-in. minus cullet reflects its higher debris level.

Specific gravities of the natural aggregates used in the testing program—crushed rock and gravelly sand—ranged from 2.60 to 2.83. These values are typical and are higher than those of cullet. Specific gravities of the mixed samples were found between those of 100 percent cullet and 100 percent natural aggregate. The difference in the specific gravities between cullet and natural aggregate and between high-debris and low-debris cullet are believed to affect the relative density and unit weight of compacted samples.

Maximum and Minimum Index Densities

Thirteen maximum index density tests were conducted using the ASTM D4253 test procedure. Maximum index densities ranged from 1.46 to 1.75 g/cm^3 (90.9 to 109.3 pcf) for the 100 percent cullet samples, 1.96 to 2.08 g/cm^3 (122.6 to 130.0 pcf) for the 50 percent cullet samples, and 2.18 to 2.25 g/cm^3 (135.9 to 140.3 pcf) for the 15 percent cullet samples. Fourteen minimum index density tests were conducted using the ASTM D4254 test procedure. The test results indicate that the minimum index densities range from 1.23 to 1.43 g/cm^3 (76.8 to 89.5 pcf) for the 100 percent cullet samples, 1.64 to 1.70 g/cm^3 (102.3 to 105.9 pcf) for the 50 percent cullet samples, and 1.83 to 1.87 g/cm^3 (114.2 to 116.6 pcf) for the 15 percent cullet samples.

The data indicate that maximum index density is affected largely by the cullet content. The trend of increasing density with decreasing cullet content is also true for the minimum index density. The 100 percent, $^3/_4$-in. minus, high-debris cullet sample also had the lowest density. Size has a minor effect on density. The reasons for the slightly higher density of the $^3/_4$-in. minus cullet samples is unclear. One possible explanation is that the presence of larger particles provides a lubrication effect that facilitates particle movement, resulting in a higher density.

Gradation

A total of 55 sieve analyses were conducted to investigate the degree of gradation change before and after the compaction, hydrostatic compression, and triaxial shear tests. Significant gradation change occurred only when 100 percent, $^3/_4$-in. minus cullet samples were subjected to heavy impact compaction, that is, the Modified Proctor test procedure, as exemplified in Figure 1. Note that the material has less than 5 percent fines (particle size less than No. 200 sieve) before and after compaction. (The before-compaction test curve is typical of the $^3/_4$-in. minus samples.) All other test conditions produced little or no gradation change.

The gradation test results indicate the feasibility of using both impact and vibratory compaction methods for field control of fill materials composed of cullet. Since these compaction methods mimic the compactive effort of field equipment, minimal gradation change implies minimal difference in the properties of laboratory-compacted samples as compared with field-compacted cullet. The exception to this is 100 percent cullet subjected to heavy impact compaction, which would normally be used for fill materials subjected to dynamic or heavy stationary loads, conditions precluding the use of 100 percent cullet.

The gradation change caused by the hydrostatic compression and triaxial shear tests was small, implying minimal breakage of the cullet under normal working loads. In other words, the cullet, like crushed rock, has adequate strength to behave like an elastic rigid body that deforms under hydrostatic loads and displaces or rotates near shear planes.

Particle Shape

Particle shapes were visually examined using the ASTM D2488 test procedure. All cullet particles tested were angular. About 20 to 30 percent of the $^3/_4$-in. minus cullet, but only 1 percent of the $^1/_4$-in. minus cullet, had a flat or platy shape. Both sizes had a low percentage of flat and elongated particles. This suggests that $^3/_4$-in. minus cullet has a potential to cut, puncture, or wedge into the moving parts of construction equipment, but similar problems are unlikely for $^1/_4$-in. minus cullet because of the low percentage of flat and elongated particles.

Durability

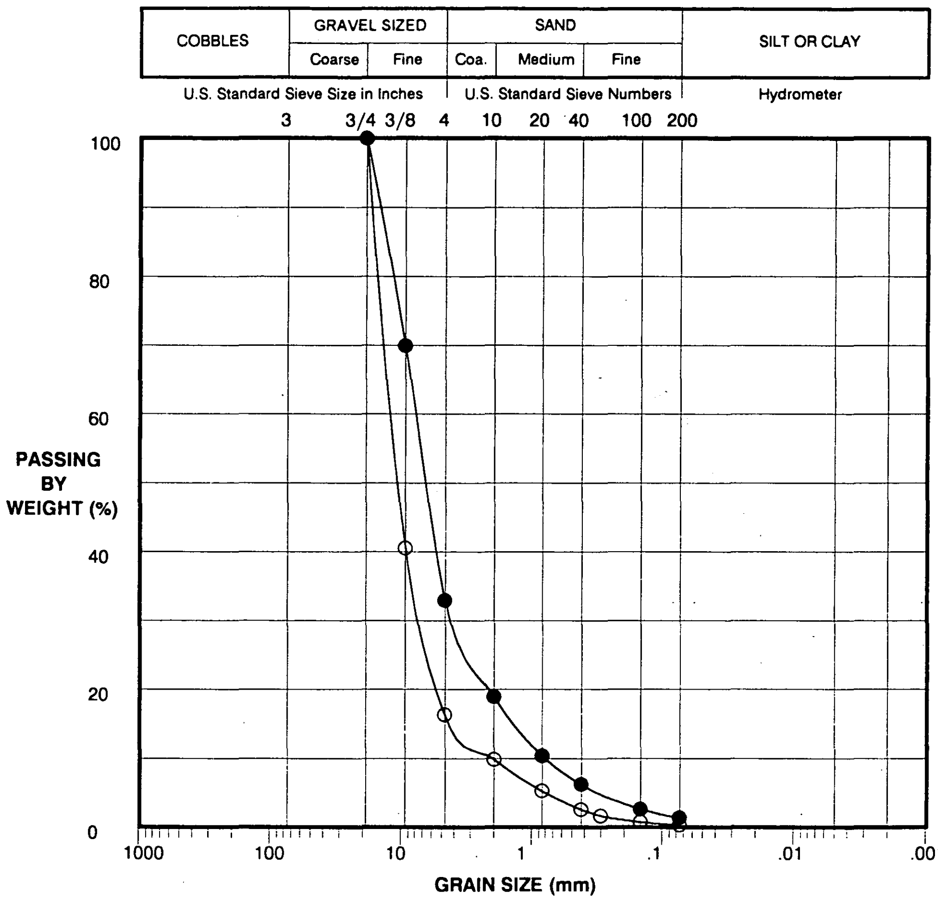
Durability was investigated by conducting the L.A. abrasion test on four samples. These included the 100 percent cullet content, $^1/_4$-in. minus, low-debris sample; 100 percent, $^3/_4$-in. minus, low-debris cullet sample; 100 percent, $^1/_4$-in. minus, high-debris cullet sample; and 100 percent crushed rock. The results were 29.9, 41.7, 30.9 and 13.6 percent, respectively. The percent loss of the 100 percent cullet samples represents the worse condition. It is reasonable to assume that the percent loss of mixed samples would lie somewhere between the percent loss of the two components.

These results indicate that cullet is not as sound mechanically as the crushed rock used in the program. The percent loss for $^1/_4$-in. minus cullet is about 30 percent and for $^3/_4$-in. minus cullet about 42 percent, losses at least two times that of the crushed rock. However, the values for 100 percent cullet are relatively close to the normal limiting values for roadway aggregate. For instance, the Washington State Department of Transportation (WSDOT) specifies a limiting value of 35 percent for a crushed surface course and 40 percent for ballast.

Compactability

Tests for compactability included 15 Standard Proctor compaction tests, 16 Modified Proctor compaction tests, and 15 WSDOT 606 vibratory compaction tests. Typical compaction curves are shown in Figures 2 to 4. In general, the Proctor compaction curves of the cullet samples are relatively flat. From a construction standpoint, this relative insensitivity to moisture content means that cullet can likely be placed during inclement weather.

Maximum density values obtained from the impact Modified Proctor and the vibratory WSDOT 606 tests are about equivalent. Both methods simulate the compaction efforts of heavy compaction field equipment. Since these methods produce little or no gradation change, the similarity in density values implies the feasibility of using either method for the field control of fill materials with cullet content. Again, this statement is not true for 100 percent cullet materials because of the gradation change induced by the Modified Proctor compaction method. For this reason, if 100 percent cullet is to be compacted by heavy field compaction equipment, a vibratory compaction method should be used.



GRAIN SIZE DISTRIBUTION

SYMBOL	DESCRIPTION	% GRAVEL	% SAND	% FINES
○	Before Compaction	83.5	16.1	0.4
●	After Compaction	66.8	31.8	1.4

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

FIGURE 1 Grain size distribution, 100 percent, high-debris, $^3/_4$-in. minus cullet.

Feasibility of Nuclear Density Gauge Testing

The feasibility of using a nuclear density gauge was evaluated. Gauge measurements, taken in the backscatter mode, were compared with known density and moisture content. A total of 24 tests were conducted on 100 percent glass and glass-aggregate blends. Test results were inconclusive, because the results showed a wide variation between the gauge and true measurements.

The data appear to indicate that moisture measurements are affected by the debris level of the cullet. The reason for this effect is unclear. The reasons for the wide variation in the density measurements is also unclear. However, two possible sources of errors were identified during the test—the nonuniform density of the test specimens and the laboratory wall effects.

Permeability

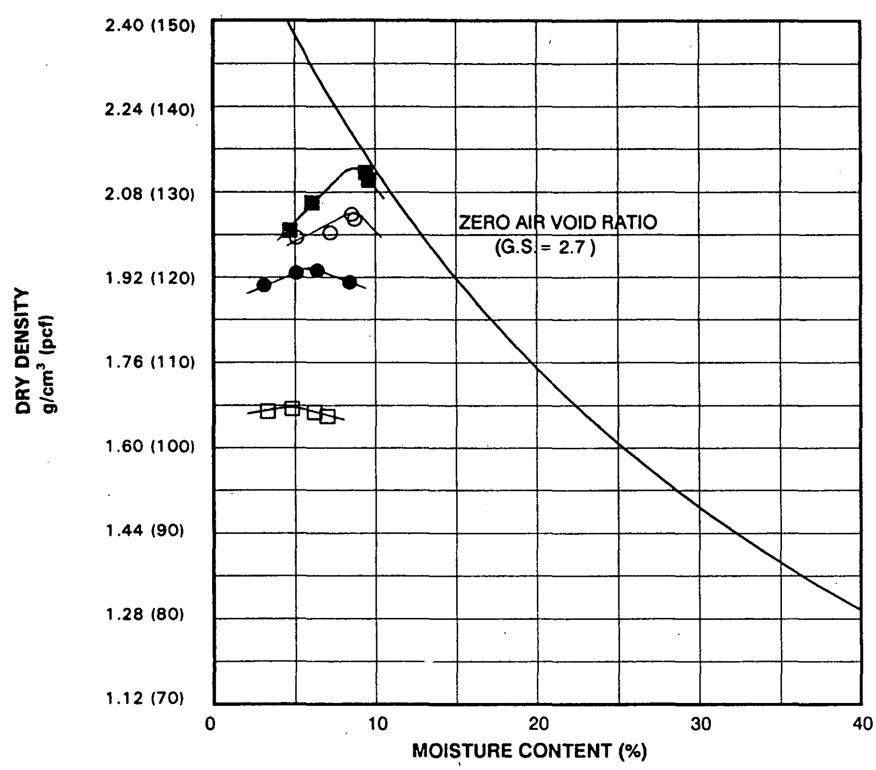
A total of 28 constant head permeability tests were conducted. In general, 100 percent cullet samples exhibited high permeabilities (>0.1 cm/sec), and 50 percent and 15 percent cullet content samples exhibited medium permeabilities (0.001 to 0.1 cm/sec). These permeabilities correspond to those of a gravel and medium sand, which are commonly used as filter materials. Permeability increases with increasing cullet content, cullet size, and debris level but decreases with increasing degree of compaction. This trend is consistent with permeabilities of the 100 percent gravelly sand compacted to the 90 and 95 percent compaction levels.

Thermal Conductivity

Four thermal conductivity tests were performed using the ASTM C518 test procedure. Results ranged from 0.260 to 0.638 W/(m · K), results close to values for natural aggregate. Conductivity decreased with increasing cullet content.

Shear Strength

The shear strength of the cullet samples was investigated by conducting seven sets of direct shear for 100 percent cullet and cullet-



SYMBOL	DESCRIPTION	TEST METHOD	OPTIMUM MOISTURE(%)	MAX. DRY DENSITY g/cm³ (pcf)
○	15% cullet & 85% gravelly sand	ASTM D698	8.6	2.03 (127.0)
●	50% cullet & 50% gravelly sand	ASTM D698	6.0	1.95 (121.4)
□	100% cullet	ASTM D698	5.0	1.68 (104.9)
■	100% gravelly sand	ASTM D698	8.8	2.12 (132.5)

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

FIGURE 2 Standard Proctor compaction test, low-debris, $^{1}/_{4}$-in. minus cullet.

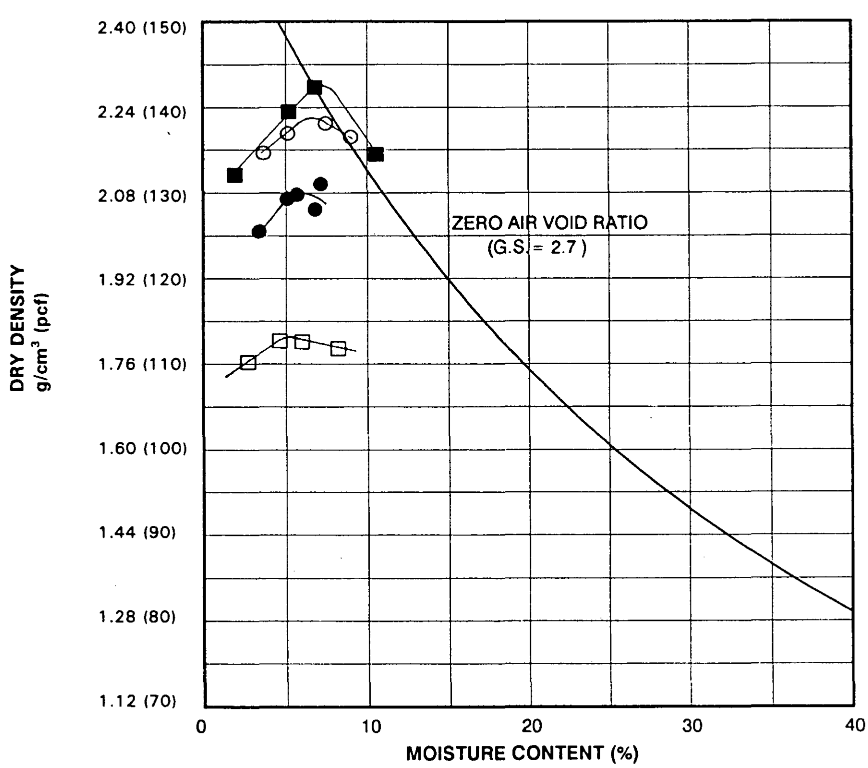
aggregate blends and five sets of triaxial shear tests on blends. In the direct shear tests the friction angles ranged from 49.4 to 53 degrees for cullet, where the friction angle of the gravelly sand sample was 51 degrees. The triaxial shear test results, presented in Table 1, gave friction angles from 42 to 46 degrees for cullet and a friction angle of 44 degrees for crushed rock. Cullet content and debris level do not appear to have an appreciable effect on the strength within the ranges tested.

In the triaxial shear results, the bulk modulus of $^1/_4$-in. minus cullet is slightly higher than that of the $^3/_4$-in. minus cullet, and the bulk modulus of the crushed rock lies between these. From the mechanics point of view, the $^1/_4$-in. minus samples are stiffer than the $^3/_4$-in. minus and 100 percent crushed rock samples. The better mechanical behavior can be explained by the better gradation of the $^1/_4$-in. minus cullet, which is indirectly validated by comparing the gradations of 100 percent crushed rock and $^1/_4$-in. minus and $^3/_4$-in. minus cullet. The $^1/_4$-in. minus cullet samples contained mostly sand-sized or "filler" particles, and the $^3/_4$-in. minus cullet and crushed rock samples contained mostly gravel-sized particles.

Resistance *R*-Value

Five *R*-value tests were performed using the WSDOT 611 test procedure, which is a modification of the AASHTO T-190 test method. The modification involves using 15 and 25 blows of kneading compaction at pressures of 690 and 1724 kPa (100 and 250 psi), respectively. These pressures are lower than those specified in the AASHTO T-190 method. The exudation pressure used in both test procedures is 2069 kPa (300 psi). Different exudation pressures may be used in other states; however, because of the granular nature of the test materials, it is believed that exudation pressure will not have a substantial effect on test results. No *R*-value tests were conducted on high-debris samples.

As seen from the results in Table 2, adding cullet to crushed rock reduces the *R*-value slightly, and this reduction increases slightly with increasing cullet content. *R*-value is commonly used to specify base or subbase 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 the California Department of Transportation



SYMBOL	DESCRIPTION	TEST METHOD	OPTIMUM MOISTURE(%)	MAX. DRY DENSITY g/cm³ (pcf)
○	15% cullet & 85% crushed rock	ASTM D1557	6.7	2.22 (138.5)
●	50% cullet & 50% crushed rock	ASTM D1557	6.5	2.08 (130.0)
□	100% cullet	ASTM D1557	5.2	1.81 (113.0)
■	100% crushed rock	ASTM D1557	7.2	2.23 (142.0)

REMARKS: Sample composed of cullet (low-debris, 1/4 inch minus) and crushed rock.

FIGURE 3 Modified Proctor compaction test, low-debris, $^1/_4$-in. minus cullet.

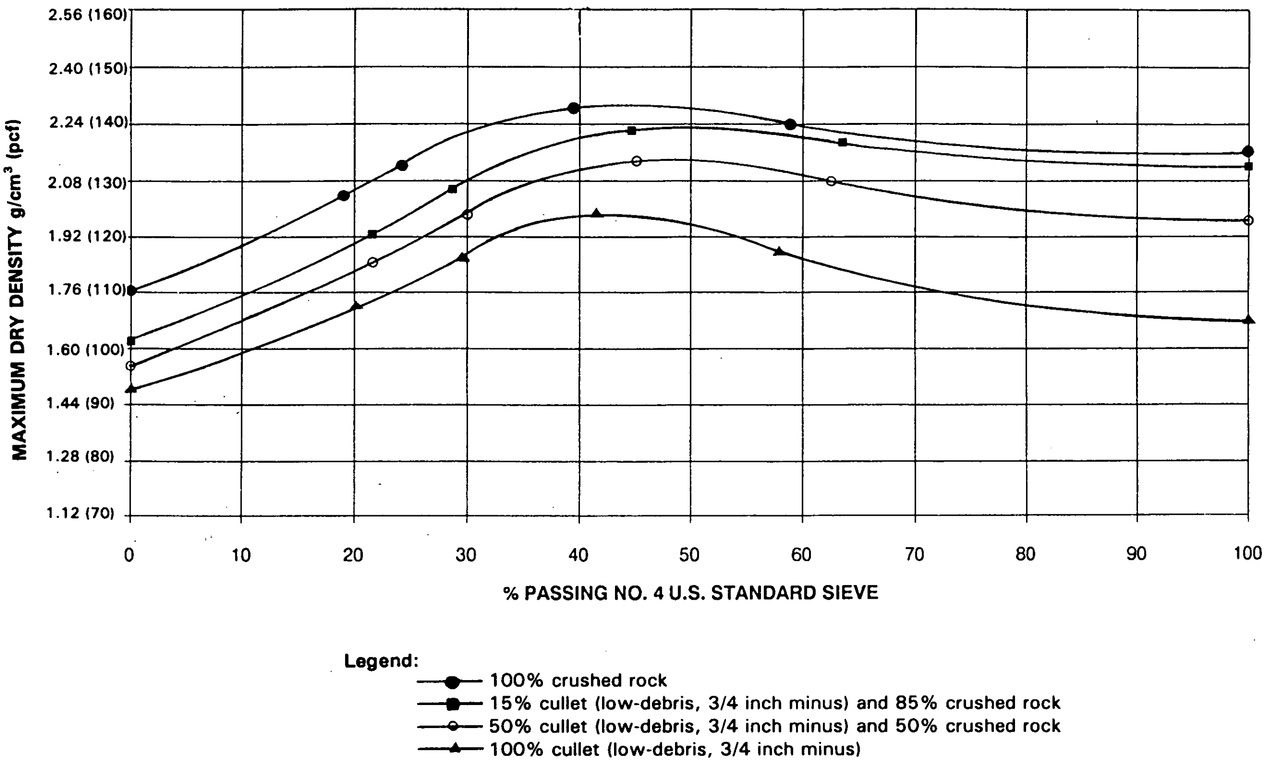


FIGURE 4 WSDOT 606 compaction test, low-debris, $^3/_4$-in. minus cullet.

TABLE 1 Triaxial Shear Test Results[a]

Sample Type	Cullet Content (%)	Cullet Gradation	Confining Pressure kPa (psi)	Bulk Modulus MPa (ksi)	Initial Tangent Modulus MPa (ksi)	Friction Angle (Degrees)
Low-debris sample	50	¼" minus	34.5 (5)	34.5 (5.0)	76.6 (11.1)	
Low-debris sample	50	¼" minus	68.9 (10)	31.7 (4.6)	125.5 (18.2)	43
Low-debris sample	50	¼" minus	103.4 (15)	35.1 (5.1)	109.0 (15.8)	
Low-debris sample	15	¼" minus	34.5 (5)	33.8 (4.9)	82.1 (11.9)	
Low-debris sample	15	¼" minus	68.9 (10)	31.7 (4.6)	91.1 (13.2)	46
Low-debris sample	15	¼" minus	137.8 (20)	35.1 (5.1)	81.4 (11.8)	
Low-debris sample	50	¾" minus	34.5 (5)	15.2 (2.2)	109.0 (15.8)	
Low-debris sample	50	¾" minus	68.9 (10)	23.4 (3.4)	81.4 (11.8)	42
Low-debris sample	50	¾" minus	137.8 (20)	26.9 (3.9)	148.4 (21.5)	
Low-debris sample	15	¾" minus	34.5 (5)	15.2 (2.2)	78.0 (11.3)	
Low-debris sample	15	¾" minus	68.9 (10)	23.4 (3.4)	109.0 (15.8)	44
Low-debris sample	15	¾" minus	137.8 (20)	24.8 (3.6)	163.5 (23.7)	
crushed rock	0	N/A[b]	34.5 (5)	28.9 (4.2)	65.6 (9.5)	
crushed rock	0	N/A[b]	68.9 (10)	28.9 (4.2)	161.5 (23.4)	44
crushed rock	0	N/A[b]	137.8 (20)	23.4 (3.4)	109.0 (15.8)	

Notes: a. All tests performed under consolidated and drained conditions. Samples were prepared closed to about 95% of the maximum dry density as determined by ASTM D 1557 test procedure.
b. Not Applicable.

TABLE 2 Resistance *R*-Value Test Results

Sample Type	Type of Natural Aggregate	Cullet Content (%)	Cullet Gradation	Resistance R Value
Low-debris sample	crushed rock	50	¼" minus	73
Low-debris sample	crushed rock	50	¾" minus	76
Low-debris sample	crushed rock	15	¼" minus	75
Low-debris sample	crushed rock	15	¾" minus	77
N/A	crushed rock	0	N/A	78

NOTES: All tests performed using the WSDOT 611 test procedure.

specifies a minimum *R*-value of 60 for Class 1 subbase 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 it is clear that the cullet-added crushed rock, with a cullet content up to 50 percent, possesses adequate strength for both base and subbase aggregate.

California Bearing Ratio

CBR values of specimens prepared using the impact compaction method are higher than those of specimens prepared using vibratory compaction, as seen from the Table 3 test results. The discrepancy increases as cullet content increases; values for 15 percent cullet content samples are about the same as those for crushed rock, regardless of the compaction method used.

Typical CBR values of a compacted granular material range from 40 to 80 (New York State Department of Transportation). All values of the cullet-added samples lie within this typical range. Also, adding 15 percent cullet to the crushed rock does not produce a noticeable difference in the CBR value. However, as the cullet content increases to 50 percent, an obvious reduction occurs. For those samples prepared using the impact compactor, the reduction was about 25 percent when the cullet content increased from 15 to 50 percent. A much higher reduction, about 50 percent, was noted for samples prepared using the vibratory compactor. These results underscore the importance of choosing the correct specimen preparation method for materials with cullet content over 15 percent.

Resilient Modulus (Cyclic Triaxial)

Five resilient modulus tests were performed using a modified AASHTO T294 test procedure. In the modified procedure, an internal load cell was used instead of an external load cell as specified in the AASHTO standard.

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 206.7 MPa (30 ksi) at a bulk stress of 172 kPa (25 psi). For a granular natural aggregate, the typical value is 206.7 MPa (30 ksi) at a bulk stress of 172 kPa (5 psi). From Table 2, it can be seen that even the 50 percent cullet sample would have a resilient modulus value appropriate for use in a typical pavement design. Adding cullet to crushed rock will reduce the resilient modulus, and the reduction increases with increasing cullet content. Note that the low modulus value in Table 4 for the 15 percent, $^3/_4$-in. minus cullet sample is likely caused by the puncturing of the membrane during the test.

One concern regarding the use of cullet mixes in roadway construction is the ability of cullet to withstand repeated traffic loads without breakdown. To help address this concern, the change in resilient modulus of the cullet samples over the first 1,000 cycles may be compared with that of the crushed rock. This comparison is shown in Figure 5. The cullet samples, like crushed rock, do 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 1,000 cycles. This stress level is typical of a subbase material under medium to heavy traffic loads and is much lower than the level at which crushing or breaking of the crushed rock particles would occur. In effect, cyclical load-

TABLE 3 California Bearing Ratio Test Results[a]

Sample Type	Type of Natural Aggregate	Cullet Content (%)	Cullet Gradation	Dry Density g/cm³ (pcf)	CBR VALUE [b]
Low-debris sample	crushed rock	50	¼" minus	1.98 (123.7)	70
Low-debris sample	crushed rock	50	¾" minus	2.01 (125.2)	95
Low-debris sample	crushed rock	15	¼" minus	2.13 (133.2)	110
Low-debris sample	crushed rock	15	¾" minus	2.12 (132.3)	115
Low-debris sample	crushed rock	50	¼" minus	1.93 (120.3)	42
Low-debris sample	crushed rock	50	¾" minus	1.99 (124.5)	44
Low-debris sample	crushed rock	15	¼" minus	2.13 (133.1)	109
Low-debris sample	crushed rock	15	¾" minus	2.12 (132.3)	90
N/A [d]	crushed rock	0	N/A [c]	12.24 (139.6)	105

Notes: a. All tests performed using the ASTM D 1883 test procedure.
b. Values correspond to 0.1 inches penetration.
c. Not Applicable

TABLE 4 Resilient Modulus (Cyclic Triaxial) Test Results[a]

Sample Type	Type of Natural Aggregate	Cullet Content (%)	Cullet Size	Dry Density g/cm³(pcf)	Resilient Modulus MPa (ksi)[b]
Low-debris sample	crushed rock	50	¼" minus	1.91 (119.2)	212.2 (30.8)
Low-debris sample	crushed rock	50	¾" minus	1.95 (121.8)	217.0 (31.5)
Low-debris sample	crushed rock	15	¼" minus	2.19 (137.1)	238.4 (34.6)
Low-debris sample	crushed rock	15	¾" minus	2.06 (128.5)	136.4 (19.8)[c]
N/A	crushed rock	0	N/A	2.10 (131.1)	277.0 (40.2)

Notes: a. All tests performed using modified AASHTO T 292-91 I test procedure.
b. At bulk stress of 25 psi.
c. Membrane likely punctured during test.

ing of cullet, like crushed rock, did not result in any appreciable crushing.

APPLICATIONS AND MODEL SPECIFICATIONS

Model specifications for using cullet in aggregate applications were developed. Every effort was made to provide specifications that are conservative in light of the study findings. Maximum cullet content, maximum debris levels, minimum compaction levels, and gradation are presented in Table 5 for specific applications.

Debris is defined as any deleterious material that affects the performance of the engineered fill. The percentage of debris is quantified using the AGI comparison charts for estimating percentage composition (*2*).

Cullet should be placed in level loose lifts not exceeding 8 in. and compacted to the specified minimum dry density. The maximum dry density of cullet-aggregate mixtures should be determined by using the Modified Proctor test as described by ASTM D1557. The maximum dry density of 100 percent cullet fills should be determined by using the Standard Proctor test as described by ASTM D698. A minimum of one density test per 1,000 ft² of fill but not less than one test per lift should be performed. The nuclear gauge method should be field-verified by the engineer before its use.

EQUIPMENT EVALUATION

Crushing systems are currently available that appear well suited for production of construction-quality cullet. This phase of the study consisted of first surveying mill manufacturers and then monitoring performance tests of six promising candidates. Equipment feature recommendations were developed to help potential processors make purchasing decisions, highlights of which follow.

Because cullet gradation and debris level are important factors with regard to engineering performance, the crushing system

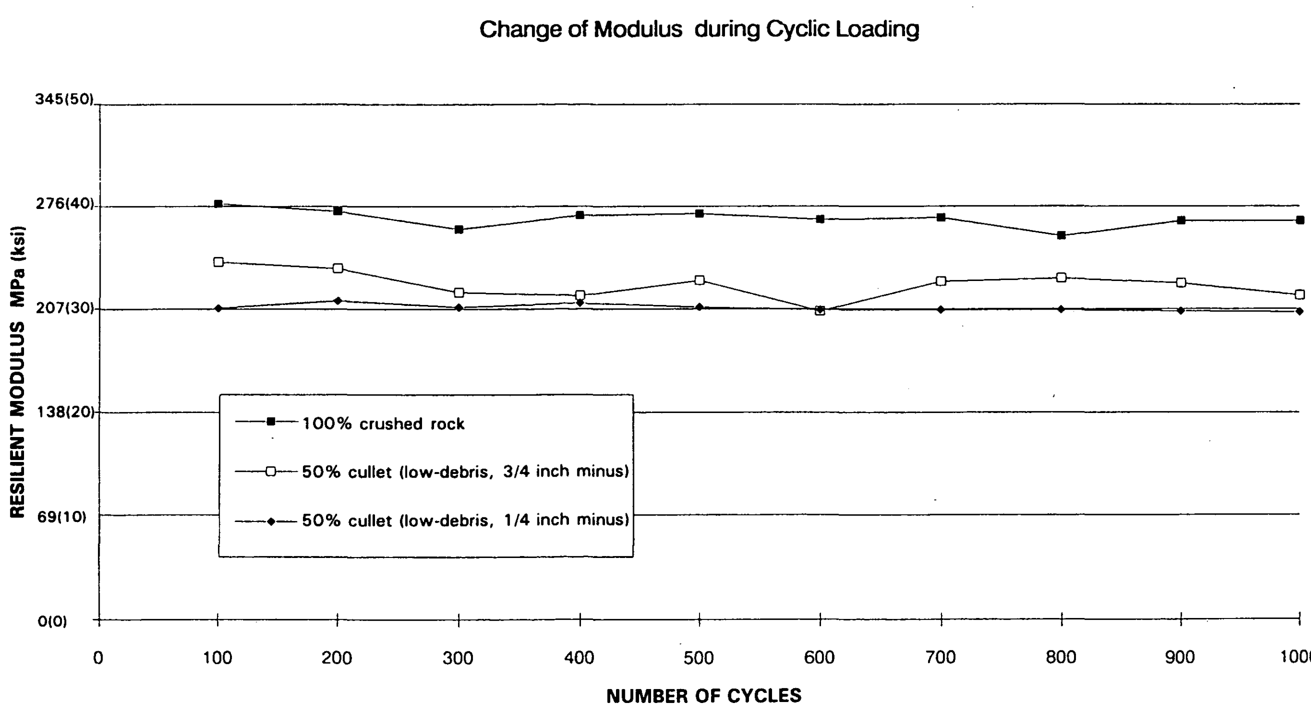


FIGURE 5 Resilient modulus test.

should have a screening system to control particle size and debris level. Ability to adjust the gradation is also a desirable feature option. By controlling gradation, a cullet supplier might target the glass product to specific applications. Cullet is also very abrasive, so wearing surfaces, particularly those of the crushing mechanism, should be constructed of abrasion-resistant material or, alternatively, wearing surfaces should be designed so that they may easily be replaced or resurfaced by depositional welding.

ECONOMICS OF CULLET AS AGGREGATE FEEDSTOCK

An economic model developed during the project identifies essential criteria and parameters for glass aggregate production and points to substantial economic incentives for cullet suppliers, aggregate suppliers, and aggregate buyers alike.

Although cullet used as aggregate feedstock does not command the high prices of the glass bottle market, neither does it require such high processing costs. Processing glass for aggregate feedstock costs from $5 to $9 per ton on the basis of the amortized equipment costs of the equipment evaluated and labor estimates. Sorting glass for the bottle market can run four to five times as much and processing color-sorted cullet to furnace-ready standards adds another $20 per ton. Because construction aggregate markets are primarily local, many recyclers will realize a substantial savings on transportation. Also, recycling costs less than landfilling—the savings of this avoided cost allows recyclers to supply cullet to aggregate processors or contractors at prices near the cost of transporting it, that is, in the $2 to $3 range as collection and processing costs are covered by recycling collection fees. For aggregate processors and purchasers, using cullet can therefore result in a significant cost savings on both a per-ton and per-project basis.

MARKET CONSIDERATIONS

The principal aim of the Glass Feedstock Evaluation Project was to open the way for glass cullet to be used in the construction aggregate market. The evaluation points to the technical and economic viability of using cullet as construction aggregate feedstock. From an engineering standpoint, cullet appears to be an excellent supplement or replacement for natural aggregates in many construction applications. Cullet was tested for harmful contaminants and their potential to leach over time. No appreciable environmental impact could be detected. Cullet can be safely used in construction using routine handling precautions. In many cases, depending on local conditions, glass can be competitive in price or less expensive than utilizing conventional aggregate. In summary, cullet is strong, clean, safe, and economical.

Although technical information is invaluable to opening markets, it is important to remember that there are other important market factors to consider in establishing a local market. Successful local markets are built on networks of suppliers, end users, and processors. Also important is targeting cullet at those applications that make the most sense locally. Factors such as what natural aggregates are locally available, how cullet might supplement or complement the natural aggregate supply, how much cullet might be supplied, what local specifications and environmental regulations apply, and the size of the demand for a given application should be reviewed. Transaction costs should be minimized.

Many jurisdictions around the country have specifications in place that prohibit the use of cullet. These specifications can now be updated on the basis of the information provided from this project. Finally, demonstration projects are also necessary to create local demand for glass cullet as aggregate. Demonstration projects provide local engineers with a chance to gain familiarity with glass and the way it behaves. Well-documented projects will add to the base of knowledge of using glass as a construction aggregate.

ACKNOWLEDGMENTS

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TABLE 5 Application Specifications

Structural Fill

Gradation: Sieve Size	Gradation: Percent Passing By Weight	Use	Max. Cullet Content (%)	Max. Debris Level (%)	Min. Compaction Level (%)
3/4"	100	Base Course	15	5	95
1/4"	10-100	Subbase	30	5	95
No. 10	0-50	Embankments	30	5	90
No. 40	0-25	Static Structural Loads	30	5	95
No. 200	0-5	Fluctuating Loads	15	5	95
		Nonstructural Fill	100	10	85
		Utility Bedding & Backfill	100	5	90

Drainage Fill

Gradation: Sieve Size	Gradation: Percent Passing By Weight	Use	Max. Cullet Content (%)	Max. Debris Level (%)	Min. Compaction Level (%)
3/4"	100	Retaining Walls	100	5	95
1/4"	10-100	Foundation Drainage	100	5	95
No. 10	0-100	Drainage Blankets	100	5	90
No. 40	0-50	French Drains	100	5	90
No. 200	0-5				

ment of Trade and Economic Development. The Clean Washington Center is the state's lead agency for the market development of recyclable materials. The study was cosponsored by the states of Arizona, California, Minnesota, New York, and Oregon, and by Browning-Ferris Industries and Waste Management of North America. The California, Oregon, and Washington departments of transportation participated in report reviews, and the Washington Department of Transportation Materials Lab performed portions of the engineering performance testing. Research was conducted by the Seattle office of Dames & Moore.

To order the Glass Feedstock Evaluation Project reports, please contact the Clean Washington Center at (206) 587-5520.

REFERENCES

1. Dames and Moore. *Glass Feedstock Evaluation Project: Reports for Tasks 1 through 5.* Clean Washington Center, Washington State Department of Trade and Economic Development, Seattle, 1993.
2. *AGI Data Sheets 15.1 and 15.2: Comparison Chart for Estimating Percentage Composition.* American Geological Institute, Alexandria, Va., 1982.