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16. Abstract

The purpose of this study is to develop specifications for using glass cullet in roadway construction. Glass cullet results from collecting and crushing post consumer glass containers. Using glass cullet in roadway construction avoids expensive sorting to prevent color contamination and presents an opportunity to use glass cullet as a construction aggregate and reduce landfill requirements. A number of other states and organizations have investigated the use of glass cullet in various aspects of construction. Specifications for using glass cullet for roadway construction in the state of Texas are being developed in three phases: (1) Literature review and identification of available sources and suppliers; (2) Laboratory testing; and (3) Specification development. This report covers Phase 1, literature review and identification of available sources and suppliers.

Findings from the literature review reveal a number of states have investigated the use of glass cullet in roadway construction and several have developed applicable specifications. An extensive study was performed by the Clean Washington Center and their report served as a primary source of information for the study reported herein. Specifications for other states can be used as guidelines for developing specifications for the state of Texas. Only a limited number of suppliers were located in Texas. Samples from Texas suppliers were evaluated in limited laboratory testing and the samples were found to match well with glass cullet evaluated by the Clean Washington Center. The glass cullet samples obtained from Texas suppliers were found to be free of lead, a potentially toxic substance. No hazardous materials were found in the samples. Recommendations are presented for further laboratory testing and completion of the specifications.

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USE OF GLASS CULLET IN ROADWAY CONSTRUCTION
Phase I. Literature Review and Identification of Sources and Suppliers

by

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Research Report Number 0-1331-1

conducted for the

Texas Department of Transportation

by the

College of Engineering
Texas Tech University

March, 1995

IMPLEMENTATION

This project will yield several products useful to the department, including: draft specifications for the use of glass cullet in transportation construction projects and a report providing an overview of glass cullet in roadway projects. Additionally, an assessment of glass cullet sources and suppliers in Texas will be provided. Procedures for enhancing the performance of glass cullet in roadway construction are likely.

FEDERAL/DEPARTMENT CREDIT

Prepared in cooperation with the Texas Department of Transportation, the Texas Natural Resource Conservation Commission, and the U.S. Department of Transportation, Federal Highway Administration.

DISCLAIMER

The contents of this report reflect the views of the authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of the U.S. Department of Transportation, Federal Highway Administration, Texas Natural Resources Conservation Commission, or the Texas Department of Transportation. This report does not constitute a standard, specification, or regulation.

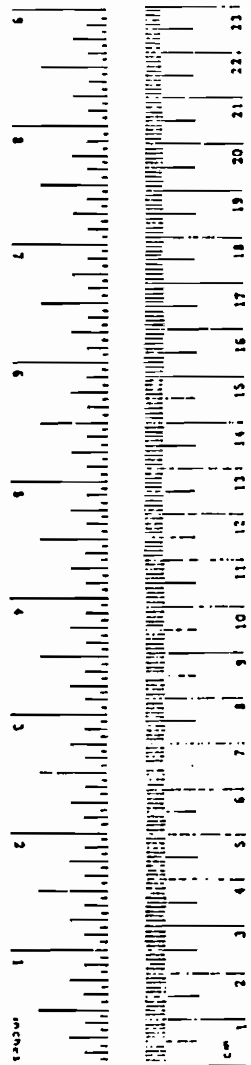
There was no invention or discovery conceived or first actually reduced to practice in the course of or under this contract, including any art, method, process, machine, manufacture, design or composition of matter, or any new useful improvement thereof, or any variety of plant, which is or may be patentable under the patent laws of the United States of America or any foreign country.

Not intended for construction, bidding, or permit purposes.

METRIC CONVERSION FACTORS

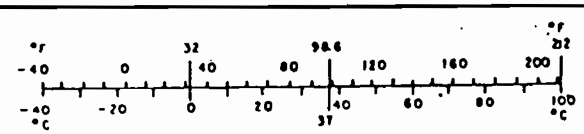
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
	AREA			
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
	MASS (weight)			
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
	VOLUME			
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
	TEMPERATURE (exact)			
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
	AREA			
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
	MASS (weight)			
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
	VOLUME			
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
	TEMPERATURE (exact)			
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



METRIC CONVERSION FACTORS

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SUMMARY

The purpose of this study is to develop specifications for using glass cullet in roadway construction. Glass cullet results from collecting and crushing post consumer glass containers. Using glass cullet in roadway construction avoids expensive sorting to prevent color contamination and presents an opportunity to use glass cullet as a construction aggregate and reduce landfill requirements. A number of other states and organizations have investigated the use of glass cullet in various aspects of construction. Specifications for using glass cullet for roadway construction in the state of Texas are being developed in three phases: (1) Literature review and identification of available sources and suppliers; (2) Laboratory testing; and (3) Specification development. This report covers Phase 1, literature review and identification of available sources and suppliers.

Findings from the literature review reveal a number of states have investigated the use of glass cullet in roadway construction and several have developed applicable specifications. An extensive study was performed by the Clean Washington Center and their report served as a primary source of information for the study reported herein. Specifications for other states can be used as guidelines for developing specifications for the state of Texas. Only a limited number of suppliers were located in Texas. Samples from Texas suppliers were evaluated in limited laboratory testing and the samples were found to match well with glass cullet evaluated by the Clean Washington Center. The glass cullet samples obtained from Texas suppliers were found to be free of lead, a potentially toxic substance. No hazardous materials were found in the samples. Recommendations are presented for further laboratory testing and completion of the specifications.

INTRODUCTION

The success of recycling collection programs has resulted in an oversupply of broken glass, or *cullet*, in many parts of the country (1). Glass cullet is regarded as oversupplied because currently there is only one well established market for glass cullet—the glass container industry. Use of glass cullet in glass production batches is limited by a number of factors including the following:

1. *Color contamination.* Glass cullet competes with virgin batch in the glass container industry at $60 per ton (2). Using cullet also conserves energy and energy costs in glass making. However, supplying cullet to furnace-ready specifications requires expensive color sorting to avoid color contamination of the batch. Estimated costs of sorting the glass cullet are a substantial fraction of the supply costs.

2. *Transportation costs.* Cullet, because of its relatively high density, is expensive to transport long distances. Transportation costs often outweigh the market price of cullet as container batch.

A number of organizations have investigated the use of glass cullet in roadway construction (1, 2, 3, 4, 5, 6). Of the reports reviewed, the work by Miller and Collins (4), and Larsen (5) are very helpful in describing technical opportunities and difficulties in using glass cullet as a construction aggregate. Miller and Collins (4) investigated several waste materials as candidates for aggregates in a variety of construction roles. Larsen (5) concentrated his efforts on glass cullet in pavement construction. Larsen noted poor adhesion between bitumen and glass aggregate and cautioned against the use of glass aggregate in hot-mix asphaltic concrete. Furthermore, Larsen reported the glass aggregate tended to break when subjected to studded tires (typically not a problem in Texas), which resulted in pavement raveling. Larsen also reported difficulties with skid resistance and suggested glass aggregates only be used in low speed areas.

The Clean Washington Center conducted an investigation of glass as a construction aggregate to open new markets for cullet. This investigation, sponsored by several states and industries, was performed by the Seattle office of Dames & Moore. States funding the investigation included Arizona, California, Minnesota, New York, and Oregon. Industries sponsoring the investigation were Browning-Ferris Industries, and Waste Management of North America. The Clean Washington Center judges the study to represent the most exhaustive investigation of construction applications for cullet to date (1). The four areas of concentration within the study are briefly presented below:

1. *Engineering Performance.* Cullet properties were compared to those of natural aggregate. From an engineering standpoint, cullet appears to be an excellent supplement or replacement for gravel in many construction applications.

2. *Environmental Impact.* Cullet was tested for harmful contaminants and their potential to leach over time. No appreciable environmental impact could be detected.

3. *Safety and Handling.* Since glass contains amorphous silica rather than crystalline silica, it does not pose the health risks associated with natural sand. While bottle cullet normally does not cause skin cuts, routine handling precautions are recommended.

4. *Economic Evaluation.* A number of factors such as collection, processing and transportation affect the costs of using cullet. In many cases, depending on local conditions, glass can be competitive in price or less expensive than utilizing conventional aggregates.

The Glass Feedstock Evaluation Project (2) is a comprehensive study and presents an excellent assessment of the use of glass cullet as construction aggregate in the U.S. Items covered in the study include market conditions, sample selection and testing, environmental suitability evaluation, engineering suitability evaluation, an evaluation of equipment needed to process and handle the glass cullet, economic modeling, and safety hazards. The Clean Washington Center endorsed glass cullet as follows (1):

> Both laboratory analysis and equipment evaluation point to the technical and economic viability of using cullet as a construction aggregate feedstock. Cullet is strong, clean, safe, and economical. Its benefits from an engineering standpoint include permeability, good compaction characteristics, and compatibility with conventional construction equipment. Many states, counties, municipalities and private contractors, in fact, have already approved cullet for use as construction aggregate and are conducting field trials.

Numerous specifications or supplemental specifications include provisions for glass cullet as a construction aggregate (2). A partial list is presented below:

California

- Amendment to 25-1.02A (Class 1, 2 or 3 Aggregate Subbases)
- Amendment to 26-1.02B (Class 2 Aggregate Base)
- Amendment to 26-1.02C (Class 3 Aggregate Base)
- Amendment to provisions in Section 26, Aggregate Base

Connecticut

- 1.01.01 Reclaimed Waste (definition)
- 2.02 Roadway Excavation, Formation of Embankment and
- Disposal of Surplus Material

National Standard Plumbing Code

- Chapter 13 Storm Drains

New Hampshire

- 304.2.1 Materials
- 304.2.3 Processed Glass Aggregate Gradation
- 304.2.4 Processed Glass Aggregate/Base Course Blends
- 304.3.1 Construction Requirements--General
- 304.3.5 Material Testing

Pennsylvania

- Waste Glass as Pipe Backfill
- Waste Glass as Embankment Material

Washington

- Part 9-03 Aggregates
- 9-03.21 Recycled Material (Allows up to 15 percent glass in most aggregates listed in Part 9-03. Permits only 10 percent of the material greater than 6 mm (1/4 inch) sieve size, based upon visual examination and weight)

The possibility of using glass cullet in roadway construction offers an attractive alternative to aggregate in parts of the state where aggregate sources are scarce and glass cullet is economically priced. The purpose of this study is to review available literature to determine the feasibility of glass cullet as an economical alternative to aggregate in roadway construction and to identify sources and suppliers of glass cullet in Texas. A final objective is to develop specifications for using glass cullet in roadway construction. Laboratory testing is planned as necessary for specification development. This report covers Phase I of the study and concentrates on the literature review and identification of available sources and suppliers.

PROBLEM STATEMENT

Post-consumer glass containers are collected as part of many Texas communities' recycling efforts. However, there are a number of obstacles to recycling glass into new containers, among these are

- a limited number of Texas reprocessing facilities,
- mixed glass breakage and color contamination,
- low glass value, and
- high transportation costs.

Using glass cullet in roadway construction and maintenance projects is worthy of investigation. Development of Texas Department of Transportation specifications for this project would also allow Texas municipal and county transportation entities to use glass cullet generated by their communities in roadway applications.

OBJECTIVES

The primary objective of this study is to identify sound engineering and environmental uses of glass cullet in roadway construction and maintenance projects and to develop specifications for each successful use of glass cullet evaluated, based on current TxDOT specifications. Development of specifications is the principal goal of the research, and all activities within the research program are aimed at supporting this goal.

Specifications for using glass cullet in roadway construction will be developed through the following phases:

Phase I. *Literature Review and Identification of Available Sources and Suppliers.* Literature will be compiled and reviewed to prepare a clear, concise summary report on using glass cullet in roadway construction. The summary report will include:

- a recommendation as to which glass cullet uses appear to be the most feasible and promising,
- an examination of potential disadvantages or obstacles to these uses,
- an evaluation of the potential effects on future recyclability, and
- an economic analysis comparing the use of glass cullet with currently utilized materials for the selected applications.

The summary report will also include a description of available sources and suppliers in the state of Texas. Source and supplier information is needed for the economic analysis.

Phase II. *Laboratory Testing.*
Laboratory testing will be accomplished to provide information not available from the literature search or to assure the accuracy of information found. Testing will focus on those problem areas identified by other researchers as were described in the proposal for this project. Potential problems include poor adhesion properties, effects of the addition of hydrated lime to improve performance, poor skid resistance, and other characteristics of glass cullet when used as a coarse aggregate. Additional laboratory testing will be used to assess the effectiveness of various polymer matrix materials and coupling agents to enhance the performance of glass cullet as aggregate for roadway construction and/or repair. Small scale tests will be conducted using glass cullet as aggregate in patching materials to repair pavement damages or install small sections of pavement on streets at the Texas Tech campus.

Phase III. *Specification Development.*
Specifications will be developed for each successful use of glass cullet identified during the course of this study. The specifications will be designed to fit current specification formats and requirements.

Reported herein are the findings from Phase I, Literature Review and Identification of Available Sources and Suppliers. Future reports will cover other phases of the study.

TECHNICAL INFORMATION AVAILABLE FROM LITERATURE

Clean Washington Center Study

The Clean Washington Center operates under the Washington State Department of Trade and Economic Development and has done the most comprehensive study to date on the use of waste glass as a construction aggregate. Therefore, a comprehensive review of their work is presented in this report. This section evaluates the suitability of glass cullet as a construction aggregate in terms of its properties (6), engineering suitability (6), and environmental suitability (7). The study conducted by Dames and Moore, Inc. for the Clean Washington Center was based on three independent variables: (1) the maximum size of cullet, (2) debris level in the cullet, and (3) cullet content as a percentage of total aggregate. The maximum cullet sizes considered were 19 mm (3/4 inch) and 6 mm (1/4 inch). The measurement of properties of the glass cullet was based on debris levels of 5 percent for 19 mm (3/4 inch) cullet and 2-3 percent for 6 mm (1/4 inch) cullet. The cullet contents, as a percentage of total aggregate used, were 100 percent, 50 percent and 15 percent.

Properties of Glass Cullet.

Waste glass is being recycled for a number of uses including container glass and fiberglass manufacture. Both of these uses involve color sorting and cleaning the waste glass to meet the required standards. Waste glass used by the roadway construction industry does not have to be sorted by color and can be crushed immediately. However, the use of glass cullet in roadway construction would decrease costs associated with sorting and cleaning glass cullet, but would also result in the inclusion of a number of impurities within the glass cullet mix. These impurities would include paper from labels, plastics from bottle caps, cork from bottle corks, and metals from bottle tops. If these impurities were to be removed from recycled glass, the cost of waste glass would be very high; therefore, any study on the feasibility of glass cullet use in construction would have to incorporate an allowable debris level as a study parameter. A maximum debris level can be specified for each application of glass cullet, and when the debris level exceeds the specified amount, conceivably, the excess debris will have a negative impact on the performance of the glass cullet in the application.

Several methods for quantifying physical contamination levels were identified in this study (7). The semi-quantitative visual method to obtain a percentage or index of contamination is based on the method proposed by the American Geological Institute (8). In the Clean Washington Center study, the debris contamination level of glass cullet was measured by weight, volume, and physical separation (7). These measurements were then correlated with results from the visual method, and the visual method was recommended as being satisfactory due to its convenience in a construction industry environment.

Classification Properties

The specific gravity tests conducted using ASTM C 127 for coarse aggregate and ASTM D 854 for fine aggregate revealed specific gravity of glass cullet ranging from 1.96 to 2.41 for coarse cullet and 2.49 to 2.52 for fine cullet. The specific gravity of crushed rock and gravelly sand ranged from 2.60 to 2.83. The tests also showed that the higher the level of debris, the lower the specific gravity. The difference in the specific gravities of the cullet and natural aggregate affect the relative density and the unit weight of the compacted samples. The relative density test indicated that cullet content has a major effect on the density of the cullet sample. The greater the cullet content, the lesser the value of relative density. The size of cullet has a minor effect on relative density.

Table 1 indicates the results from the compaction test. Gradation tests made on the compacted samples indicate that significant changes in gradation occur only when 100 percent cullet samples are subjected to heavy compaction. The degree of gradation change decreases with decreasing glass cullet content. Further, most of the gradation changes occur in the coarse and medium sizes. The degrees of gradation change are higher for higher levels of debris. The results of the gradation tests indicate the feasibility of using compaction methods for the field control of fill materials comprised of cullet. There is minimum breakage of cullet under normal working loads. This implies that cullet particles, like crushed rock, have adequate strength to behave like an elastic body which deforms under hydrostatic loads and displaces or rotates near shear planes.

Results of Los Angeles (L.A.) abrasion tests indicate that cullet is not as mechanically sound as crushed rock. The debris level also plays a part in the percent loss, with higher losses at higher debris levels.

Table 1. Change in Gradation with Different Compaction Procedures (6).

Max. Cullet Size	Cullet Content %	Size Fraction	Std. Proctor ASTM D 698		Mod. Proctor ASTM D 1557		Vibratory WSDOT 606	
			*B.C.	*A.C.	*B.C.	*A.C.	*B.C.	*A.C.
19 mm (3/4 in)	100	gravel	86.4	84.5	83.5	66.8	78.8	77.0
		sand	13.4	14.9	16.1	31.8	20.8	22.7
		fines	0.2	0.6	0.4	1.4	0.3	0.3
	15	gravel	33.1	34.1	57.2	51.1		
		sand	66.2	65.0	40.9	44.3		
		fines	0.7	0.9	1.9	4.6		
6 mm (1/4 in)	100	gravel	0.0	0.0	8.2	6.3		
		sand	99.4	98.7	90.8	91.7		
		fines	0.6	1.3	1.0	2.0		
	15	gravel	21.6	21.9	43.5	41.3		
		sand	77.6	76.9	54.2	53.7		
		fines	0.8	1.2	2.3	5.0		

*Note: B. C.=*Before Compaction*
A. C.=*After Compaction*

Engineering Properties

Tables 2 and 3 show results on how the compaction related properties of glass cullet aggregate mixes are influenced by the maximum size of glass cullet, cullet content in the mix, compaction method, and the type of conventional aggregate. It was observed from these results that the compacted density of cullet is affected largely by the cullet content and that density increases with decreasing cullet content. Additionally, the optimum moisture content increases slightly with decreasing cullet content. Higher densities are encountered at lower debris levels. The Proctor compaction curves are relatively flat (i.e., the compacted density is not sensitive to moisture content).

Table 2. Compaction Test Parameters for Gravelly Sand and Crushed Rock When Combined with Glass Cullet at Different Percentages (6).

Max. Cullet Size mm (in.)	Cullet %	Compaction Test	Gravelly Sand		Crushed Rock	
			Optimum Moisture percent	Max. Dry Density g/cm^3 (pcf)	Optimum Moisture percent	Max. Dry Density g/cm^3 (pcf)
19 (3/4)	15	Standard Proctor	5.7	2.09 (130.5)		
	50	Standard Proctor	6.0	1.99 (124.6)		
	100	Standard Proctor	5.5	1.59 (99.3)		
6 (1/4)	15	Standard Proctor	6.5	2.03 (126.5)		
	50	Standard Proctor	6.5	1.92 (119.5)		
	100	Standard Proctor	4.7	1.67 (104.4)		
19 (3/4)	15	Modified Proctor			6.0	2.22 (138.6)
	50	Modified Proctor			6.2	2.01 (125.3)
	100	Modified Proctor			7.5	1.78 (111.4)
6 (1/4)	15	Modified Proctor			5.5	2.22 (138.5)
	50	Modified Proctor			9.2	2.02 (126.0)
	100	Modified Proctor			5.6	1.78 (111.0)

Table 3. Compaction Test Parameters for Gravelly Sand and Crushed Rock Without Glass Cullet (6).

Description	Test method	Optimum Moisture percent	Max. Dry Density g/cm^3 (pcf)
Crushed Rock	Standard Proctor	7.2	2.27 (142)
Gravelly Sand	Modified Proctor	8.3	2.15 (134)

Results from the permeability tests done in accordance to the ASTM D 2434 (Table 4) show that permeability of cullet increases with increasing cullet content, cullet size and debris level but decreases with increasing degree of compaction. Indirect assessment of results of specific gravity, gradation, and durability indicate that cullet has intermediate filtration capacity.

Table 4. Results From the Constant Head Permeability Test (6).

Cullet Size mm (in)	Cullet Content %	Dry Density g/cm^3 (pcf)	Permeability (10^{-2} cm/sec)
19 (3/4 in)	100	1.44 (89.6)	26.0
	50	1.81 (113.2)	4.8
	15	1.91 (118.9)	3.1
6 (1/4 in)	100	1.52 (94.9)	6.0
	50	1.73 (108.1)	4.4
	15	1.85 (115.4)	2.6

Note: Approximate relative compaction is 90 percent of ASTM D698

Results from thermal conductivity tests done in accordance with the ASTM C 518 (Table 5) indicate that the thermal conductivities of cullet are lower than natural aggregate. Further, conductivity value decreases with increasing cullet content .

Table 5. Results from the Thermal Conductivity Test (6).

Max. Cullet Size mm (in.)	Type of Natural Aggregate	Cullet Content percent	Moisture Content, percent	Sample Density g/cm^3 (pcf)	Apparent Thermal Conductivity (W/m-K)
6 (1/4)	-	100	10.7	1.32 (82.5)	0.315
6 (1/4)	-	50	7.4	1.52 (95.1)	0.463
-	Natural Sand	0	6.6	1.72 (106.9)	0.638

Direct and triaxial shear test results indicate that the strength of cullet is the same as natural aggregate. Also, cullet content and debris level do not have appreciable effect within the test range. The addition of smaller size cullet to a natural aggregate reduces potential of plastic volumetric strain and tends to increase the bulk modulus.

California Bearing Ratio (CBR) tests conducted using the ASTM D 1883 procedure, reveal high CBR values for samples containing up to 15 percent cullet. Resistance R-Value tests performed on the basis of modification of AASHTO T-190 indicate that adding cullet to crushed rock will reduce the R-Value slightly, and this reduction will increase with increased cullet content. The modification involves using 15 to 25 blows of kneading compaction at 14224 g/cm^2 (100 psi) and 35560 g/cm^2 (250 psi) pressure, respectively, which are lower than those specified in the AASHTO T-190 method.

The resilient modulus was determined using a modified AASHTO T 294 test procedure. An internal load cell is used here instead of an external load cell. The addition of cullet to crushed rock will reduce the resilient modulus, and this reduction will increase with increasing cullet content. In order to address concerns regarding the use of cullet in roadway construction, the change of resilient modulus of the cullet samples over the first 1000 cycles was compared with that of crushed rock, and it was found that cullet, like crushed rock, does not show appreciable changes in the modulus value .

Engineering Suitability

This section deals with the suitability of glass cullet in various engineering applications (6).

Roadways. Roadway applications include the use of cullet in base course, subbase, subgrade, and embankments. Cullet is appropriate for use in all these applications, depending on cullet percentage. Table 6 lists recommended percentages, debris levels, and compaction levels for cullet use in roadway applications .

Table 6. Recommended Cullet Levels for Roadway Applications (6).

Roadway Application	Maximum Cullet Content percent	Maximum Debris Level percent	Minimum Compaction Level, percent
Base Course	15	5	95
Subbase	30	5	95
Embankments	30	5	90

Drainage. Drainage applications include retaining wall backfill, footing drain, drainage blankets, and French drains and the recommended usage of glass cullet is indicated in Table 7.

Table 7. Recommended Use of Glass Cullet in Drainage Applications (6).

Drainage Fill Applications	Max. Cullet Content, percent	Max. Debris Level, percent	Min. Compaction Level, percent
Retaining Walls	100	5	95
Foundation drainage	100	5	95
Drainage Blankets	100	5	90
French Drains	100	5	90

General Backfill. General Backfill applications include fills which support heavy stationary loads such as beneath footings; fluctuating loads, as beneath reciprocating pumps and compressors; and non-loaded conditions such as landscaping fill, or fill placed beneath pedestrian sidewalks. The recommended usage pattern for these applications is shown in Table 8.

Table 8. Recommended Use of Glass Cullet in General Backfill Applications (6).

General Backfill Applications	Max. Cullet Content, percent	Max. Debris Level, percent	Min. Compaction Level, percent
Stationary Loads	30	5	95
Fluctuating Loads	15	5	95
Non-Loaded conditions	100	10	85

Utilities. Utility applications involve the use of cullet for trench bedding and backfill and their recommended usage pattern is shown in Table 9.

Table 9. Recommended Use of Glass Cullet in General Backfill Applications (6).

Utility Trench Bedding and Backfill Applications	Max. Cullet Content, percent	Max. Debris Level, percent	Min. Compaction Level, percent
Water & Sewer Pipes	100	5	90
Electrical Conduits	100	5	90
Fiber Optic Lines	100	5	90

Environmental Suitability

The environmental testing program included three components(7). They are the organic and inorganic chemical characterization of feedstock and an assessment of potential for bacteria growth, an assessment of contaminant leachability over time, and an assessment of the incidence of lead and leachable lead contamination in different feedstock.

The total lead tests were performed on samples received from all the sources and a subset of the samples were analyzed for leachable lead. Chemical and contaminant leaching over time were conducted on three representative "high debris level" and "low debris level" samples. The chemical characterization tests assessed pH, priority pollutant total metals, semi-volatile organics and total organic carbon. Contaminant leaching over time were assessed by performing a sequential batch extraction using aqueous solution followed by the analysis of pH, biological oxygen demand, chemical oxygen demand, total organic carbon, and total metals.

No appreciable environmental impact was detected. All the cullet sources, but one, exhibited total and leachable lead concentrations below acceptable regulatory limits. The lead concentrations found in the anomalous sample was attributed to lead foil wrappers. Limited organic compounds were found in the high and low debris cullet samples and included samples of plastics, low concentration of food residues, and organics that occur naturally in nature. The evaluation of the contaminant leaching over time indicated that little or no potential exists for supporting bacteria growth and that metal concentrations did not appear to pose a risk to the environment.

Safety Analysis

Air samples for silica tests taken to assess potential airborne risks from crystalline silica (a known carcinogen) indicated concentrations of less than one percent (7). Cullet is an abrasive material, and irritation can be prevented with the use of protective clothing. Safety clothing used when working with natural aggregate can be worn while working with cullet.

Other Studies

The combination of glass with Portland cement concrete yields a highly unsatisfactory concrete because of alkali-silica reactions. Fly ash replacement of cement by the order of 25 to 30 percent by weight may be an effective means of ensuring normal growth and dimensional stability for both high and low alkali cements (9). Concrete made with glass and high alkali cement is generally unsatisfactory because of marked strength regression and excessive expansion. Severe stripping occurs when bituminous concrete and dense-graded aggregates and asphalt cement with no additives is exposed to water (10). Bituminous mixtures satisfying Marshall design criteria recommended by the Asphalt Institute can be designed using penetration grade asphalt and asphalt composed entirely of crushed glass (11).

Research done by the Connecticut DOT (5) recommends the use of glasphalt (asphalt concrete with glass as a part of the aggregate) only as a base course. Glasphalt was tested at eight different sites and the most common problems encountered were:

1. a need for delayed breakdown rolling,
2. development of surface raveling, and
3. difficulty in crushing glass.

Stripping between glass and asphalt occur in the presence of water due to loss of adhesion between asphalt and glass. In order to overcome this problem, hydrated lime was used as an antistripping agent with satisfactory results. The evaluation of degradation of glass from mechanical mixing, compaction, and testing revealed that degree of degradation was minor and unlikely to affect performance of an in-place pavement .

USE OF GLASS CULLET BY OTHER STATE DOT'S

Survey of State DOT's

As part of this literature survey, the following state DOT's were contacted to find out whether they have had experience with the use of glass cullet in roadway construction and if they have developed specifications for the use of glass cullet. The results from the survey are listed in Table 10 . In the subsequent paragraphs, the experiences of several states with glass cullet as well as their specifications are discussed in detail.

Table 10. Results from the Telephone Survey With Other State DOT's.

State	Work Done With Waste Glass ?	Does Specifications Exist ?	Remarks
Arizona	Yes	Do Not Know	
California	Yes	Yes	
Colorado	No	No	
Connecticut	Yes	Yes	
Florida	Yes	Yes	
Illinois	No	No	
Massachusetts	Yes	No	Used in a bike path at Amherst .
Michigan	No	No	
Minnesota	Yes	Yes	
New Hampshire	Yes	Yes	
New Jersey	Yes	Yes	
New York	Yes	Yes	
North Carolina	Yes	No	Used as backfill for pipes in median
Oregon	Yes	No	Under consideration for use at Portland Metrorail
Pennsylvania	Yes	Yes	
Virginia	Yes	Yes	
Washington	Yes	Yes	

Description of the Experiences of the DOT's From Other States

California State Department of Transportation

The California State Department of Transportation (CALTRANS) allows the use of glass in aggregate bases and subbases for up to 15 percent of the total aggregate mix, but they recommend aggregate base and subbase incorporating reclaimed glass shall not be placed in locations where surfacing will not be placed over the aggregate base and subbase. The grading specified for aggregate base shall conform to 38 mm (1-1/2 in). maximum or 19 mm (3/4 in) maximum grading.

Degradation (crushing of glass particles) when compacted, was primarily found to be in the fraction retained on the #4 sieve (10). CALTRANS also experienced problems with stripping when glass cullet was used in asphalt concrete. Studies on stripping with the Surface Abrasion Test revealed that the use of commercial additives, including dry lime, did not have a significant effect on the stripping of glass; whereas, when treated with the lime slurry the cullet performed quite well. During compaction it was noted that glass does not compact easily and is difficult to consolidate.

Connecticut State Department of Transportation

Connecticut DOT recommends the use of glass cullet as base course and embankment material (5). The glass shall conform to 9.5 mm (3/8 in) maximum grading. Based on a study undertaken by the them, Connecticut DOT determined that the angular particles produced from crushing glass are not detrimental to the stability of hot mix asphalt concrete mix. It was reported that there is loss of adhesion between asphalt and glass when hydrated lime is not used. When waste glass is used in Portland cement concrete, the mixture was found to be susceptible to alkali-silica reaction whereby the strength of the concrete is reduced when compared with the conventional aggregates.

Florida State Department of Transportation

Florida DOT recommends the use of crushed glass in asphalt concrete mixtures (13). However, the maximum quantity of crushed glass is limited to 15 percent of the total aggregate weight. Florida DOT also recommends that the asphalt binder used with mixtures containing recycled crushed glass shall contain 0.5 percent of the antistripping agent. The recommended test method for asphalt concrete mixtures containing recycled crushed glass is AASHTO T-283. It is also recommended that the minimum Tensile Strength Ratio (TSR) shall not be less than 80 percent. Florida DOT does not allow the use of recycled crushed glass in friction courses.

During their studies, Florida DOT observed that a glasphalt (asphalt with crushed glass as an aggregate component) mat cools at a slower rate than a conventional asphalt concrete mat. This decreased cooling rate is an advantage to paving in cool weather. Results of the tensile tests indicate that coarse glass mixtures are less affected by moisture conditioning than the control mixture. Fine glass mixtures, however, are quite susceptible to moisture damage.

Massachusetts State Department of Transportation

Massachusetts DOT has used glass in a bike path at Amherst, where 15 percent of graded crushed glass aggregate was used in the binder and top course. The mix obtained was rich and lime was added to prevent stripping. There are no further applications under consideration.

New Hampshire State Department of Transportation

New Hampshire DOT specifications suggest that Processed Glass Aggregate (PGA) shall be crushed and screened such that 100 percent of the material passes a 13 mm (1/2 in) screen, and not more than 1.5 percent of the material passing #4 sieve shall pass #200 sieve (14). It is recommended that the maximum quantity of PGA shall be 5 percent of the total dry weight of the mixture. PGA is also recommended for use

1. as road base,
2. as base material under sidewalks and parking lots,
3. as a percentage of aggregate in glasphalt,
4. wrapped in a geotextile sleeve for culverts and drainage trenches, and
5. as a daily landfill cover and a landfill closure material .

New Jersey State Department of Transportation

New Jersey DOT recommends using 10 percent crushed recycled container glass (CRCG), with 100 percent passing 9.5 mm (3/8 in) sieve, in bituminous stabilized base course (15). The maximum allowable debris level by weight retained on #4 sieve is 6.3 percent.

Studies conducted by New Jersey DOT showed that a 10 percent CRCG mixture of bituminous concrete without the anti-stripping agent will probably not be susceptible to significant moisture damage. Based on a criterion of a TSR value 80 percent and over, all tests showed acceptable values. However, the samples with an anti-stripping agent show higher values indicating less potential for moisture damage. Periodic visual surveys of the pavement surface condition indicated no deterioration of the pavement due to raveling, shoving, and cracking. However, some glass was observed on the shoulder of the pavement test sections (containing crushed glass) indicating a loss of surface glass.

New York State Department of Transportation

New York State DOT recommends that waste glass shall be crushed to a maximum particle size of 9.5 mm (3/8 in) and that it may contain up to a maximum of 5 percent debris by volume (16). This debris may be in the form of china, ceramics, paper, and other deleterious materials.

It is suggested that waste glass shall constitute no more than 30 percent by volume of the total soil mixture in embankments. Also waste glass is not recommended to be placed in contact with synthetic liners, geogrids, or geotextiles. Materials approved for base course shall consist of sand and gravel, blast furnace slag, stone, or blends of these materials with waste glass where the glass content does not exceed 30 percent by weight.

The crushed glass shall contain no more than 1 percent (by weight) of contaminants (debris) and shall meet the gradation of 100 percent passing the 9.5 mm (3/8 in) sieve and not more than 20 percent passing the #20 sieve. It is recommended that crushed glass may be included in the mixture up to a maximum of 5 percent of the total weight.

North Carolina State Department of Transportation
North Carolina DOT uses glass beads in the preparation of reflective paints. Glass was used in the backfill of pipes along medians of highways in Charlotte. It is reported that further work will be done if this experiment proves to be successful.

Oregon State Department of Transportation
Oregon DOT was one of the sponsors for the Clean Washington Center study. Even though they have not taken any steps to incorporate the use of glass cullet in specifications, they entertain proposals by contractors to use glass cullet, and evaluate these proposals on a case specific basis. One such proposal to use crushed glass in the construction of the Portland Metrorail is currently under consideration.

Pennsylvania State Department of Transportation
Pennsylvania DOT allows waste glass to be used up to 4 percent in Portland cement concrete and 10 percent for other uses (17). However, they do not permit the use of coarse aggregate containing waste glass in Portland cement concrete or bituminous concrete wearing courses. They recommend that up to 100 percent waste glass may be used for pipe bedding or pipe backfill provided that waste glass meets all coarse aggregate quality requirements.

Virginia State Department of Transportation
Virginia DOT approves the use of crushed recycled glass in the asphalt concrete mixtures used for surface, intermediate, and base courses (18). It is recommended that crushed glass shall contain no more than 5 percent by weight and that a maximum of 15 percent ± 3 percent by weight of the asphalt mixture shall be crushed glass. The crushed glass gradation shall be 100 percent passing the 9.5 mm (3/8 in) sieve and a maximum of 6 percent passing the #200 sieve. The asphalt mixture containing crushed glass shall produce a TSR of not less than 0.90 .

Washington State Department of Transportation
Washington State DOT recommends the use of reclaimed glass in the following applications (19):

1. Ballast and Shoulder Ballast
2. Crushed Surfacing Base Course and Aggregate for Gravel Base
3. Backfill for Foundations, Walls, Pipe Bedding and Drains, Sand Drains
4. Sand Drainage Blanket
5. Gravel Borrow
6. Bedding Material for Rigid and Flexible Pipes
7. Foundation Material

It is recommended no aggregate shall contain more than 15 percent glass, and no more than 10 percent of material retained on an individual sieve 6.4 mm (1/4 in) or larger shall be glass. Aggregate composed solely of glass is recommended for use as gravel backfill for walls, pipe bedding and sand drains, sand drainage blanket, gravel borrow, and bedding material for flexible pavements. It is also recommended that 100 percent of the glass shall pass 19 mm (3/4 in) sieve and not more than 5 percent by mass shall pass a #200 sieve. The maximum debris level in the crushed glass for these applications shall be 10 percent.

AVAILABILITY OF GLASS CULLET FROM TEXAS BASED SOURCES

Post-consumer glass containers are collected as a part of recycling efforts in many Texas urban areas. Recycling of waste glass to make new containers, however, faces several obstacles:

- availability of only a limited number of reprocessing facilities within the state
- mixed glass breakage
- color contamination
- low glass prices

The possibility of using glass cullet in roadway construction and maintenance projects is worthy of investigation. Development of Texas Department of Transportation specifications for this project would allow Texas municipal and county transportation entities to use glass cullet generated by their communities in roadway applications.

A survey of the major participants in the waste glass market within the state of Texas was conducted during the course of phase I of this research project. The survey population included major cities as well as other major collectors of waste glass in Texas. Currently, waste glass collected in the state of Texas is recycled to be used for several purposes. These include the manufacture of glass containers, plate glass, and fiberglass. In most of these applications, waste glass has to be sorted by color. Color sorting is sometimes done at the curbside of houses. In other cases, the sorting is done by the collectors themselves. If the sorting is done by the collectors, the cost of sorting can be significant (as much as $40 per ton).

It is envisaged at this point, that if waste glass cullet were to be used as a construction material, color sorting would not be necessary—driving down the price of glass cullet significantly. Based on the results of this survey, it appears that the market price of glass cullet will vary from one locality to another based on the market conditions of the particular locality.

Survey of Major Texas Cities

Table 11 indicates the results from the survey on waste glass among the major cities in Texas. Other than the major cities, there are a large number of small organizations involved in the collection of waste glass. Due to the large number involved, it was decided to contact only the major cities to get an assessment of their waste glass collection operations.

Table 11. Results from Survey of Major Texas Cities

City	Quantity Recycled	End Use	Market Price	Remarks
Dallas	1300 tons per year	Glass containers	$50/ton for clear and $35/ton for color. City provide transport.	City has 62 drop-off sites for waste glass. Waste glass is sold to **Allwaste** recycling in Houston.
Houston	2000 tons per year	Glass containers	$16/ton for glass of all colors. City does not provide transport.	Waste glass is collected curbside with aluminum and plastic, and then sorted at the city. Waste glass is sold to **Allwaste** recycling in Houston.
Austin	720 tons collected in January 1995.	Glass containers	$50/ton for clear, $40/ton for amber, and $15/ton for green.	Glass is sold to **Owens-Brockway** in Waco. through Acco Inc. which is a subsidiary of BFI waste systems.
San Antonio	120 tons per month	Fiberglass	$6/ton for clear, $0/ton for amber, and -$25 (a cost to the city) for green.	Collection area to increase from 60,000 to 240,000 houses in summer 1995. **Vista Fibers** also collect 80 tons from the suburbs of San Antonio.
El Paso	80 tons per month.	Fiberglass		City has no direct involvement in glass recycling. Glass is collected at Biggs army base.

Other Suppliers of Waste Glass in Texas

According to Allwaste Recycling of Houston—a major waste glass collector in the state of Texas and the U.S.—Texas collects approximately 100,000 tons of waste glass every year. This indicates that the contribution from the major urban areas to this total quantity is less than 10 percent of the total quantity. Allwaste personnel also indicate that most major cities in Texas recycle less than 10 percent of their own waste glass for recycling. They suggest the low landfill prices in Texas as one major reason for this low volume of glass recycling. The cost of landfill in Houston is reportedly in the range of $20/ton of waste as compared to $50 in Florida, $75 in California, and over $100 in New York/New Jersey. The quantities of waste glass recycled by some of the major cities in the country appear to be a good reflection of their landfill prices. The percent of waste glass recycled by New Jersey, Los Angeles, and Houston are approximately 60, 50, and 8 percent respectively.

Allwaste Recycling accounts for the major part of all waste glass collected for recycling in the state of Texas. A major portion of their collection in Texas comes from a large number of small scale organizations who deal in small quantities. Allwaste Recycling also has approximately a 30 percent market share of glass recycling in the country. Of the

100,000 tons of waste glass collected in Texas each year, about 70 percent comes from glass containers, and the 30 percent balance comes from plate glass manufacturers. Almost all the waste glass from glass containers is recycled back to glass container manufacture. Of the 30,000 tons of waste plate glass collected for recycling, about one half goes to the fiberglass industry, and the other half goes to make glass beads which are used to manufacture reflectors for the highway industry.

Another participant in the waste glass industry in Texas is BFI waste systems. They have waste container glass collection centers in Houston, Plano, San Antonio, Lubbock, Corpus Christi, Austin, and McAllen. Their total collection of waste glass is approximately 2,000 tons per month. The company representative indicated that their waste glass sector is not profitable.

ECONOMIC FEASIBILITY OF USING GLASS CULLET

In light of the collection, sorting, processing, and transportation obstacles associated with recycling into glass containers or fiberglass, the use of glass cullet as an aggregate material in the production of asphalt becomes extremely attractive. The cost of collecting glass for non-container markets will be lower compared to container markets because the stringent sorting and processing requirements associated with the glass container market will be largely reduced. Additionally, there are three types of costs which are often cited as being inadequately accounted for in regard to landfill tipping fees: depletion costs, opportunity costs and environmental damage.

Both Allwaste recycling and BFI waste systems indicate that if waste glass were to be used in highway construction, and if this use involved the use of color-mixed waste glass, the prices for waste glass would be much lower since color sorting will not be necessary. However, this advantage will be minimal in areas where color sorting mechanisms are already in place at the curbside. Sources at Allwaste Recycling indicated that based on the current market situation, a ton of color mixed waste glass can be purchased for $20 in Houston, $0 in Dallas, and -$25 in New York City. The cost cited for Houston is higher than for the other localities cited because in Houston, Allwaste has to compete with a glass company which is located very close to the city waste glass collection facility. In Dallas, waste glass is available in moderately large quantities, but there are no major markets in the vicinity. In the case of New York City, waste glass is available in large quantities, and since the landfill prices are high, the user can actually receive subsidies for collecting waste glass. A waste recycling company in El Paso (El Paso Recycling) indicated that they are not in the market for waste glass because the current market conditions dictate a price of $9 per ton, and it is not possible to provide waste glass at that price.

Therefore, the economic viability of waste glass recycling for highway construction depends upon the market situation in a given area. However, the highway professionals with experience using glass cullet and industry experts within the glass recycling industry contacted in this study indicated that if there is a market for glass cullet in the highway industry, it would be economically competitive with other materials in major metropolitan areas and their surrounding vicinities. These professionals also indicated that a market for color-mixed waste glass may significantly increase collection efforts aimed at waste glass recycling. With the current collection rate of less than 10 percent in the state, there is a significant amount of material currently going into landfills that could be collected for useful purposes.

Information Available from Previous Studies

Connecticut's Experience

Connecticut DOT arrived at its cost and availability considerations for glasphalt based on the following assumptions (5):

1. All glass received for production of glasphalt met gradation requirements.
2. Asphalt plant contractors did not bear the cost for hauling the glass from processing centers to batch plants.
3. The addition of 1 percent by weight hydrated of hydrated lime would be required in all glasphalt mixes to prevent loss of adhesion.
4. Bituminous producers modify their plants to include a mechanical dust feeding device and storage bin(s) for hydrated lime.

With these assumptions in mind, the net increase in cost of production of would be approximately $5.00 per ton. However, this increased cost may be less than the actual cost of dumping the material in landfills—considering that tipping fees typically fall in the range of $25-75/ ton.

In Connecticut, the current estimate of available waste glass (7500 tons per year) would allow glasphalt production representing 1 to 4 percent of the total annual bituminous production by Connecticut DOT, assuming the glass represents between 10 to 30 percent by weight of the mix. With the hypothetical case of one batch plant producing 10,000 tons of glasphalt per year, it is estimated that the glasphalt production would be approximately $5.00 per ton higher than conventional class 1 surface course material or class 4 material. Some savings would incur at the intermediate processing centers where the landfill fees of $25-75 per ton would not be paid for glass disposal.

New York's Experience

The New York State DOT specifications allow crushed glass to be used up to 5 percent of the weight of aggregate in binder mixes. It was reported that at a disposal cost of between $36 to $80 per ton, using up to 5 percent of crushed glass results in an annual disposal cost savings of $4.9 to $10.8 million (20).

Florida's Experience

In Florida, color sorted glass sells for $30 to $55 a ton; whereas, disposal of waste glass in landfills would cost as much as $33 per ton. It is expected that in the southeast Florida area where the solid disposal problem is acute and where a considerable amount of glass waste is generated, waste glass may be an economic alternative to commercial fine glass (13).

Economic Model Proposed by Clean Washington Center

The Clean Washington Center proposed a comprehensive economic model for the use of glass cullet in highway construction (21). In this model, they compared the economic aspects involved with three options for waste glass to be used: the landfill option, container glass option, and the aggregate option. Figure 1 indicates their Glass Feedstock Material Flow Model and Figure 2 indicates their Glass Feedstock Economic Model. Table 12 indicates the results from the economic analyses performed for the Seattle area in the state of Washington. It can be seen that even with the high landfill prices in the area ($72/ton), the aggregate option involves a revenue cost of about $20 per ton. However, from the standpoint of the waste management agency, it is the least costly option compared with $74/ton for the landfill option and $22.50 for the glass container manufacture option.

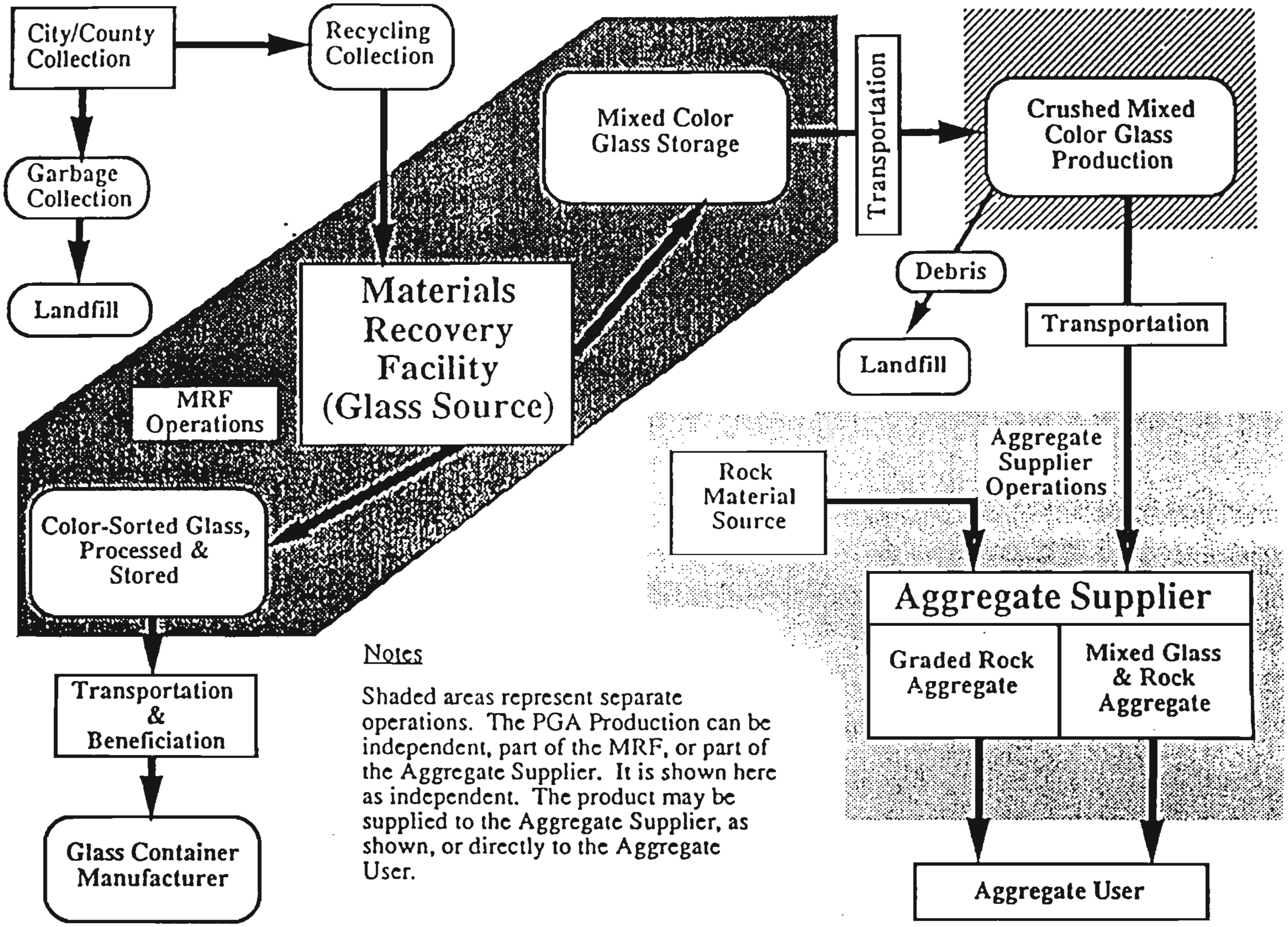

Figure 1. Glass Feedstock Material Flow Model (17)

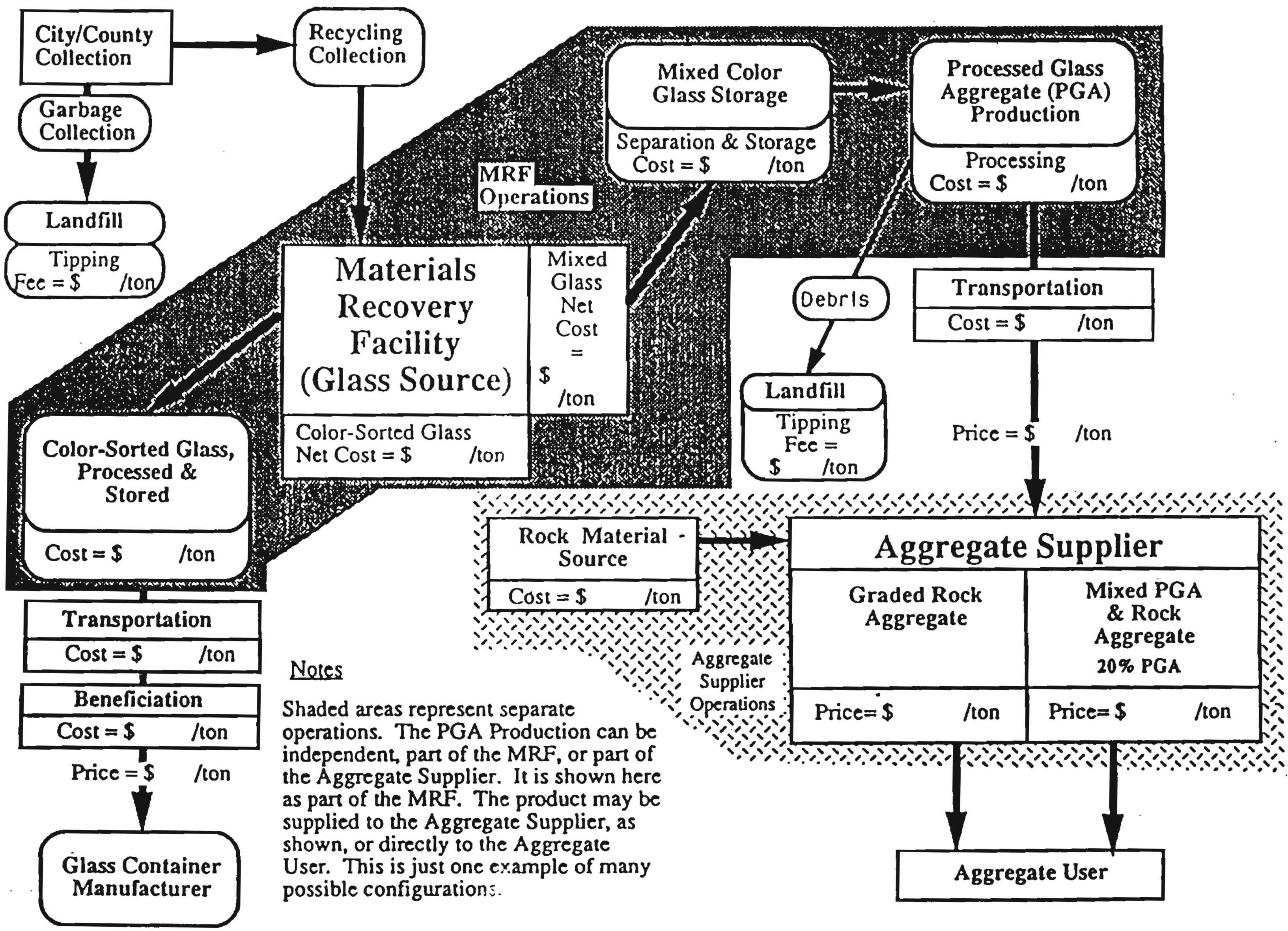

Figure 2. Glass Feedstock Economic Model (17)

Figure 3. Economic Decision Model

Landfill Option		Value	Revenue (Cost)/Ton	Revenue (Cost)/Year
Cost of unsorted glass	$/ton		$0.00	$0.00
Source of glass	(-)	MRF		
Quantity available	tons/year	1,000		
Transportation cost	$/ton-mil	($0.10)		
Distance to landfill	miles	20	($2.00)	($2,000)
Cost at landfill	$/ton		($72.00)	($72,000)
Annual Revenue (Cost)			($74.00)	($74,000)

Bottle Market Option		Value	Revenue (Cost)/Ton	Revenue (Cost)/Year
Cost of unsorted glass	$/ton		$0.00	$0.00
Source of glass	(-)	MRF		
Quantity available	tons/year	1,000		
Cost to separate and color sort	$/ton		($40.00)	($40,000)
Transportation cost	$/ton-mil	($0.10)		
Distance to market	miles	75	($7.50)	($7,500)
Price at market	$/ton		$25.00	$25,000
Annual Revenue (Cost)			($22.50)	($22,500)

Aggregate Option		Value	Revenue (Cost)/Ton	Revenue (Cost)/Year
Cost of unsorted glass	$/ton		$0.00	$0.00
Source of glass	(-)	MRF		
Quantity available	tons/year	1,000		
Glass separation	$/ton		($16.00)	($16,000)
Crusher capacity	tons/hr	10		
Crusher capital cost	$	($8,000)		
Equipment life	years	5		
Crusher labor cost	$/hr	($20)	($2.00)	($2,000)
Crusher maintenance cost	$/ton			
Debris disposal (landfill)	$/ton	($74)		
Debris level	%	3%	($2.22)	($2,220)
Processing & storage area	sqr feet	3,000		
Facility cost	$/ton-yr	($1.00)	($3.00)	($3,000)
Transportation cost	$/ton-mil	($0.10)		
Distance to user	miles	15	($1.50)	($1,500)
Price from user	$/ton		$5.00	$5,000
Annual Revenue (Cost)			($19.97)	($19,970)

If the aggregate option has the lowest operating costs, you still need to decide if the capital investment is worthwhile. We see that the aggregate option creates a net annual saving of $2,530, in return for an $8,000 investment. This investment can be viewed as a series of cash flows:

Year	0	1	2	3	4	5
Cash Flow	($8,000)	$2,530	$2,530	$2,530	$2,530	$2,530

Internal Rate of Return (IRR) 17.50%

SUMMARY OF FINDINGS

Clean Washington Center Study: Summary Of Performance and Feasibility of Glass Cullet Applications

This section gives a summary of the performance and feasibility of glass cullet use in various applications, as published by the Clean Washington Center (22, 23).

APPLICATION	PERFORMANCE & ENVIRONMENTAL EVALUATION	TECHNICAL FEASIBILITY	ECONOMIC FEASIBILITY
Aggregate Base Course	Cullet and cullet aggregate mixtures have good workability. Cullet abrasiveness may prematurely wear surfaces .	Yes	Yes
Asphalt Base Course	Asphalt does not adhere well to glass. Anti-stripping agent or hydrated lime prevents glass raveling . Less oxidation and stripping when used in base courses .	Yes	Unclear
Asphalt Surface Course	Cullet makes the road vulnerable to moisture distress . Cullet enhances nighttime visibility of road edge .	Yes	Yes
Embankments	Mix design for embankments is not sensitive to changes in glass content. Performance of cullet in embankments depends on loading conditions .	Yes	Yes
Backfill/Cleanfill (Aggregate free of clay, silt and organic debris .)	Cullet exhibits good compaction and permeability characteristics. Usage restricted when site is subject to heavy or fluctuating loads .	Yes	Yes

APPLICATION	PERFORMANCE & ENVIRONMENTAL EVALUATION	TECHNICAL FEASIBILITY	ECONOMIC FEASIBILITY
Utility Bedding and Backfill	The thermal conductivity of cullet is similar to natural aggregate. Cullet is easier to work with in wet conditions.	Yes	Yes
Controlled Density Fill (Highly pumpable mix of cement, water, fly ash, and lightweight aggregate.)	The likely exposure to moisture would promote silica- alkali reaction.	Unclear	Unclear
Drainage Aggregate (Aggregate fill used to quickly drain moisture out of area; also as filter or treat water from non- point sources .)	Particle angularity of cullet helps cullet remove solids and improve turbidity of water .	Yes	Yes
Drain Pipe Bedding and Backfill (Aggregate fill under, around, and on top of perforated drain pipes carrying ground water .)	Cullet compacts easily to required density. Thermal conductivity is similar to that of natural aggregate .	Yes	Yes
French Drains (Trenches filled with aggregate and covered with earth that act as underground water conduits .)	Cullet compacts easily to the required density . Permeability of crushed glass is equal to or better than the traditional 50/50 mix of pea gravel and sand .	Yes	Yes

APPLICATION	PERFORMANCE & ENVIRONMENTAL EVALUATION	TECHNICAL FEASIBILITY	ECONOMIC FEASIBILITY
Underdrains- (An underground water collection system using cullet wrapped in geotextile)	This type of underdrain is stronger than plastic pipe and suitable for a variety of uses .	Yes	Yes
Water Filter Medium(A Substitute for Sand in Water Filtration)	The cleanliness required in the filter medium will require tertiary washing prior to use .	Yes	Unclear
Electro-Magnetized Wastewater Filter Medium (bed of crushed glass used to clean municipal & hazardous waste)	System takes up less space than conventional systems and gives higher backwash rates. Water and chemical costs decreases since it is a non- chemical treatment .	Yes	Yes
Aqueduct Liner	Unknown	Unclear	Unclear
Glass Polymer Composite(GPC) Sewer Pipe (A glass-resin composite cast into sewer pipe)	GPC pipe has 2-4 times the strength of concrete pipe. It is highly resistant to acidic corrosion. It is not subject to abrupt failure, hydrostatic leaking and permeability problems of concrete .	Yes	Yes
Parking Lots and Driveways	Colored plate glass in driveways has an aesthetic appeal. The pavement tends to ravel, dislodging glass particles .	Yes	Yes

APPLICATION	PERFORMANCE & ENVIRONMENTAL EVALUATION	TECHNICAL FEASIBILITY	ECONOMIC FEASIBILITY
Termite Barrier (Glass aggregate is used as a physical barrier for termite infestation in structures)	Glass barrier is less hazardous compared to conventional chemical methods .	Yes	Unclear
Sandblasting (Glass fines used for surface finishing)	Abrasive nature of glass makes it a good candidate . Pulverizing glass to sand particle size is an energy intensive process .	Yes	Unclear
Lightweight Aggregate (A low density mix of glass, clay & other materials for lightweight concrete)	Expansion due to alkali-silica reactions is under ASTM limits over the short run. Cullet usage preserves virgin lightweight aggregate but process is energy intensive.	Unclear	Unclear
Pozzolan	Glass Cullet does not meet ASTM specifications for pozzolanic activity . Energy intensive and has higher costs than conventional products.	Unclear	Unclear
Traction Sand (Silica sand used in railroads to provide traction under wheels of trains .)	Unknown	Unclear	Unclear
Glasscrete (PCC containing glass aggregate .)	Alkali-Silica reaction causes reduction of concrete strength.	Unclear	No
Shotcrete	Alkali- silica reactions cause the deterioration of concrete.	No	No

Other Studies

The recommendations from other studies are varied. In general, the use of glass cullet in asphalt concrete is not considered as an attractive option due to problems associated with asphalt stripping under moist conditions. However, the use of antistripping agents is reported to alleviate this problem to a greater extent. The State of New Jersey recommends the use of glass cullet in asphalt stabilized bases with or without antistripping agents. They do not recommend glass cullet in surface courses of asphalt concrete due to the fact that some glass particles get loose from the asphalt concrete, creating a negative perception in the minds of the public.

The use of glass cullet in Portland cement concrete is not feasible due to the high levels of alkali-silica reactivity associated with it. The problem is considered to be particularly acute with fine material of the cullet. It is reported in some studies that the alkali-silica reactivity of Portland cement concrete with cullet is about 20 times as much as that of conventional siliceous gravel aggregate.

Existing Specifications

Existing specifications of other DOT's indicate uses for glass cullet in a variety of applications. These range from applications in asphalt concrete to drainage to backfill. Based on the available information, it is the belief of this research team that from an engineering standpoint, the material is suitable for a wide variety of uses. The economic feasibility would vary depending on the locality and the availability of the glass in large quantities.

Scope of the Remaining Part of the Study

Based on the literature survey conducted, it is felt that the technical information pertaining to the suitability of crushed glass in roadway construction is currently available. Also, there are a number of uses for in roadway construction for which glass cullet can be applied effectively. A comprehensive study in this regard was done by the Clean Washington Center, and additional studies for the duration of project 1331 may not be needed. However, since the sources of glass cullet for Texas are different from those used in the Clean Washington Center study, it is the opinion of the research team that tests need to be performed to assess the debris level of the cullet as well as to examine how this level of debris may affect engineering properties. Therefore, the following testing program is envisaged for the remainder of the project, prior to the final specifications development. The test factorial for engineering properties is indicated in Table 13. An 'x' indicates the tests to be performed under the test factorial. The tests to be performed are for shear strength, permeability, compaction, and gradation. The variables to be incorporated into the test program are the debris level in the cullet and the glass cullet content used in the mix.

Table 12. Test Factorial for Engineering Property Tests.

Cullet Content (%)	Debris Level (%)	Shear Strength Test	Permeability Test	Compaction Test	Gradation Test
5	0	x		x	x
5	5	x		x	x
5	10	x		x	x
10	0	x			
10	5	x			
10	10	x			
20	0	x		x	x
20	5	x		x	x
20	10	x		x	x
50	0		x		
50	5		x		
50	10		x		
100	0		x	x	x
100	5		x	x	x
100	10		x	x	x

EVALUATION OF GLASS CULLET FROM TEXAS BASED SOURCES

Glass cullet samples from Texas based suppliers were evaluated on three different levels:

1. availability
2. physical-chemical properties
3. comparisons with glass cullet studies conducted in other states

The results of the evaluation are described in the following paragraphs.

In summary, only one Texas supplier, Allwaste Recycling, Inc., had commercial quantities of glass cullet available. Two specific products were offered by Allwaste: a coarse, crushed product and a finer, screened product. Neither product contained leachable chemicals or heavy metals which would restrict their use for roadway applications. Only the coarse product offered by Allwaste matched the screen size distribution reported in a study performed by Dames and Moore, Inc. for the Washington State DOT. Also, based on micro-photographs, the glass cullet products from Allwaste can be described as multifaceted shards and plates. Such shapes are not conducive to high packing factors or to load bearing and stress transfer should the cullet be used to replace sand or gravel in road applications.

Availability

Only one State of Texas supplier was found for commercial quantities of glass cullet: Allwaste Recycling, Inc. Allwaste has two major processing centers, located in Houston and Dallas. The company reportedly plans to open other plants in major Texas cities as regional supply centers. Two other glass recyclers were identified. Owens Corning, a major producer of glass products, has closed its facility in Waco, Texas. BFI, a national solid waste handler, collects and stores waste glass but does not have crushing and screening capabilities, nor do they offer any recycled glass products at this time.

Allwaste Recycling offered two products: a coarse grade of crushed glass and a finer, screened product. The latter, listed as #12 cullet, consists of grain sizes typical of sand, (80% by weight was found between 10 and 40 U.S. sieve numbers) and is available only from the company's out of state processors. The former coarse grade product is listed as "Minus 5/8 Sieve." This product is similar in screen size to glass recycled products tested by the Washington State DOT. However, the sample of this coarse product that was received for testing also contained plastics, paper, and dirt debris. Concern was expressed that these extraneous materials might compromise the use of the cullet as a replacement for sand or gravel in roadway applications. Hence, some preliminary physical-chemical tests were performed on the two Allwaste products.

Physical-Chemical Properties

Both of the glass cullet samples from Allwaste were subjected to leaching extraction and microscopic evaluation. These tests were performed in order to better state specifications for the products should TxDOT choose to use the glass cullet.

Leach Tests

Randomly selected samples of both products were leached with dichloroethylene for several hours with reflux. The leachate was then injected in a GC/MS to determine if hazardous extractables were present in either sample. The attached table indicates that the finer cullet product had fewer extractables, but that neither sample contained anything that would be considered harmful to the environment. Other literature sources had reported concerns about the possibility that the recycled glass cullet could contain chemical contamination.

Microscopic Tests

Random samples of the two glass cullet samples were also selected for microscopic examination. Two such tests were performed: an optical scan of the products and a scan by electron diffraction x-ray analysis (EDXA). The optical scan was used to assess the general size and shape of the cullet particles, while EDXA was used to determine if heavy metals were associated with the cullet. Examples of both the optical tests and the EDXA tests are shown in Figures A and B. The optical assessment indicates that the cullet consists of multifaceted glass shards and plate shaped pieces. Fibrous debris from paper and plastics associated with the glass cullet are also visible. The EDXA studies are supposed to indicate which atomic species, i.e., metallic species, are present in the glass cullet. As expected, silica (Si) and oxygen (O) are present, as are sodium (Na), calcium (Ca), and aluminum (Al). The latter three atoms are natural silicate impurities in glass. The clear, green, and amber colored glasses which make up the cullet were individually checked for heavy metals. In all cases, no lead, arsenic, or similar toxic or hazardous metals were found. This indicates that for these glass cullet samples, recycled glass cullet is relatively free of such contamination.

Comparisons With Other Studies

Although as many as ten other states and several large cities have investigated the use of recycled glass cullet for roadway purposes, only the state of Washington provided a comprehensive evaluation of glass cullet use and its characteristics for their purposes. The simplest comparison involves a simple screen size or grain size distribution of the glass cullet products available. The attached figure shows the size distributions of the two Allwaste samples as compared to samples prepared for the Washington State DOT by a consulting firm. It is to be noted that the fine Allwaste #12 cullet sample has a size distribution typical of sand. The coarser Minus 5/8 Sieve sample from Allwaste is somewhat similar to the gravel-sand sized glass cullet tested by Washington State. Hence, it is probably safe to assume that the recycled glass cullet available in Texas is very similar, if not identical, to the recycled glass cullet being used by other state departments of transportation. This is an important assumption, since it implies that the limitations observed by others in the use of recycled glass cullet will apply to proposed uses in Texas. Hence, potential applications for use in Texas can be more sharply focused, while other suggested uses can be discarded as already being demonstrated as being impractical. Based on the reports in the literature from other states, it is apparent that the use of recycled glass cullet for roadway construction will have several limitations and should require use specifications.

95-RE 53 Seive #12 fine Glass
55x

Figure 4. Multi-Faceted Glass Particle

95-RE 50 ≤ #200 ROUGH
55x

Figure 5. Fine Glass Schards with Paper Fibers in the Debris

QUALITATIVE ELEMENT IDENTIFICATION

SAMPLE ID:95RE50 #200 ROUGH 125-93

POSSIBLE IDENTIFICATION
SI KA OR RB LA?
NB LA OR AU LA MA
CA KA KB
O KA
NA KA
K KA OR IN LA?
AL KA OR BR LA?

PEAK LISTING

	ENERGY	AREA	EL. AND LINE
1	0.511	10834	O KA
2	1.035	9601	NA KA
3	1.451	688	AL KA OR BR LA?
4	1.736	95710	SI KA OR RB LA?
5	2.145	18415	AU MA
6	3.309	2114	K KA OR IN LA?
7	3.685	17764	CA KA
8	4.013	2064	CA KB
9	9.685	5541	AU LA

Figure 6. EDXA Analysis of Glass Cullet

Si	**Silica**
Ca	**Calcium**
O	**Oxygen**
Na	**Sodium**
K	**Potassium**
Al	**Aluminum**

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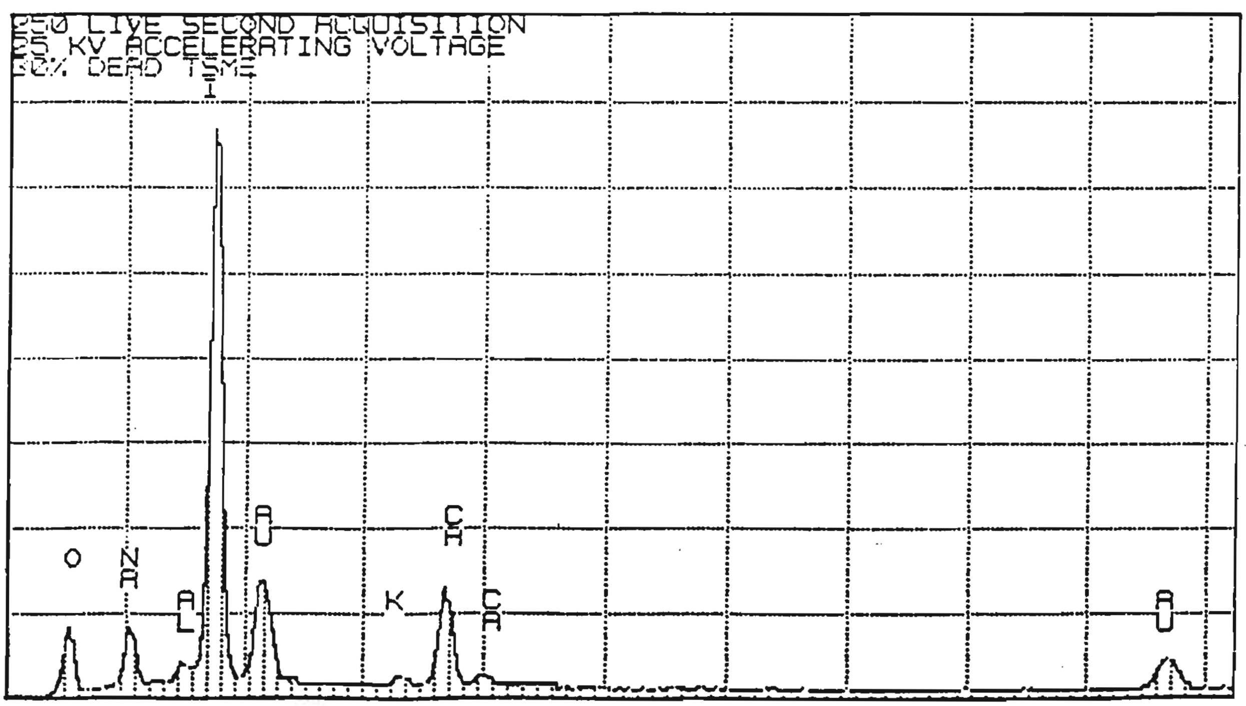

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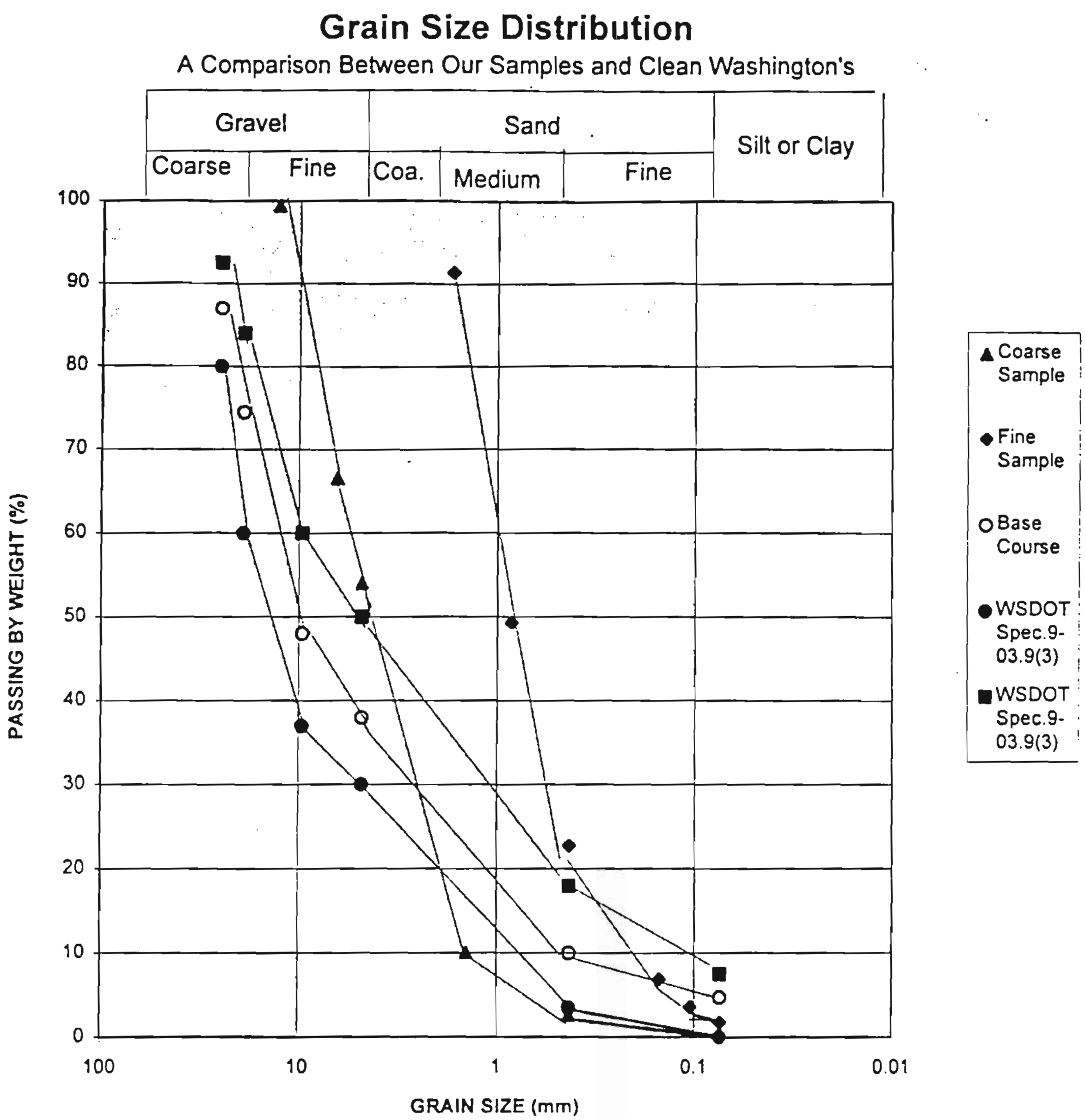
250 95RE50 #200 ROUGH 125-93



SYMBOL	DESCRIPTION	% GRAVEL	% SAND	% FINES
○	Base Course	61.80	33.50	4.70
●	WSDOT Spec.9-03.9(3)	70.00	30.00	0.00
■	WSDOT Spec.9-03.9(3)	50.00	42.50	7.50
▲	Our Coarse Sample	45.99	45.40	0.59
◆	Our Fine Sample	—	98.31	1.69

Figure 7. Grain Size Distribution Chart

Table 13. Electron Diffraction X-Ray Analysis - Sample 1 (Fine Cullet)

Sample 1: Glass 1: Fine Cullet		
Possible Hydrocarbons Present:		
NAME	**MOL. WT.**	**FORMULA**
Hahnfett	9999	
Tricosenyl Formate	366	C24H46O2
Hentriacontane	436	C31H64
Triacontane	422	C30H62
Pentadecane	212	C26H32

**Note: The chromatography was poor for this sample and the compounds did not separate completely. There are other compounds that were unable to be identified.

Table 14. Electron Diffraction X-Ray Analysis - Sample 2 (Rough Cullet)

Sample: Glass 2: Rough Cullet		
Possible Hydrocarbons Present:		
NAME	**MOL. WT.**	**FORMULA**
Hahnfett	9999	
1-(ethenyloxy)-Hexadecane	268	C18H36O
Tetradecane	198	C14H30
Tritetracontane	605	C43H88
Hexacosane	366	C26H54
Hexatriacontane	507	C36H74
Tetracosane	338	C24H50
Octacosane	394	C28H58
1-chloro-Octadecane	288	C18H37Cl
(Z,Z)-9, 12-Octadecadienioc acid	280	C18H32O2
(Z)-9, 17-Octadecadienal	264	C18H32O

CONCLUSIONS AND RECOMMENDATIONS

A literature review was completed on the use of glass cullet in roadway construction. Furthermore, available sources and suppliers in Texas were identified, and samples from Texas suppliers were compared with samples used in investigations by other states. Specific conclusions from the study include the following:

- A number of states have investigated the use of glass cullet in roadway construction, and several have developed applicable specifications that can be used as guidelines for developing TxDOT specifications.

- Glass cullet samples from Texas suppliers were similar to samples used in other studies. However, no lead or hazardous materials were found in samples from the Texas suppliers.

- The number of glass cullet suppliers in Texas is very limited.

Recommendations resulting from the study are given below:

- A laboratory test plan was outlined and should be performed in the next phase of research.

- Specification development should continue using specifications from other states as guidelines for TxDOT specifications.

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3. Breakspere, R.J., "New Developments in Waste Glass Utilization", Conservation and Recycling, Vol. 3, 1980, pp. 233-248.

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22. Clean Washington Center, Glass Market Information System Application Summary Reports, December 1993.

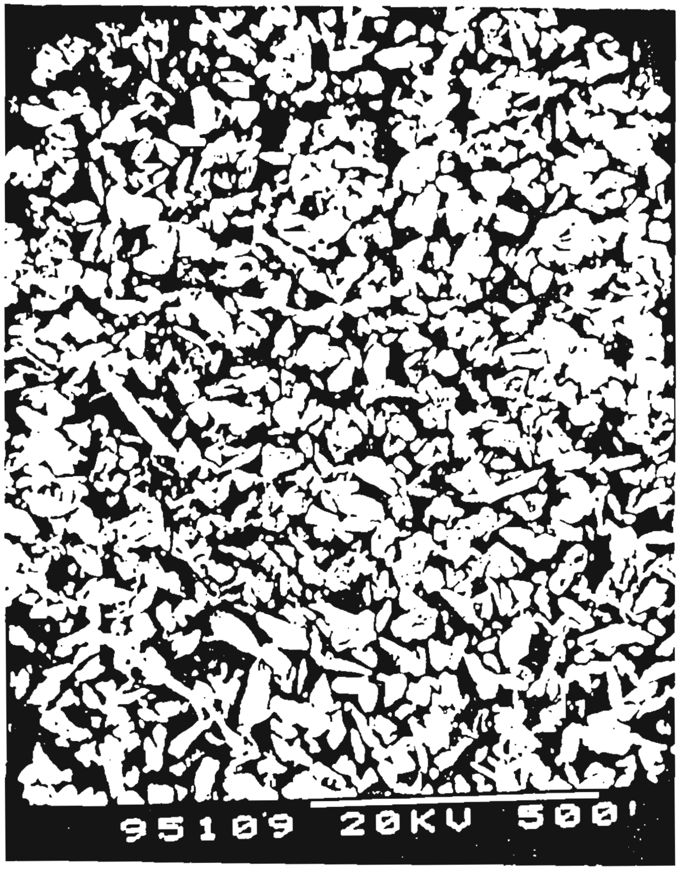
23. Clean Washington Center, Glass Feedstock Evaluation Project - Task 1, Report Testing Program Design, March 1993.

Personnel Contacted for the Survey

City of Dallas:	Carlos Rozello, Recycling Coordinator
City of Houston:	Gary Readore, Recycling Coordinator
City of Austin:	Allan Watts, Recycling Division
City of San Antonio:	Edna , City Recycling Coordinator
City of El Paso:	Richard Raco, Recycling Division
BFI Waste Systems:	Bob Kovich, Marketing Manager, Houston
Allwaste Recycling:	Curt Bucey, Marketing Representative
North Carolina DOT	Mr. Azimi, Materials Laboratory
Oregon DOT	Elizabeth Hunt
Massachusetts DOT	Material Research Laboratory

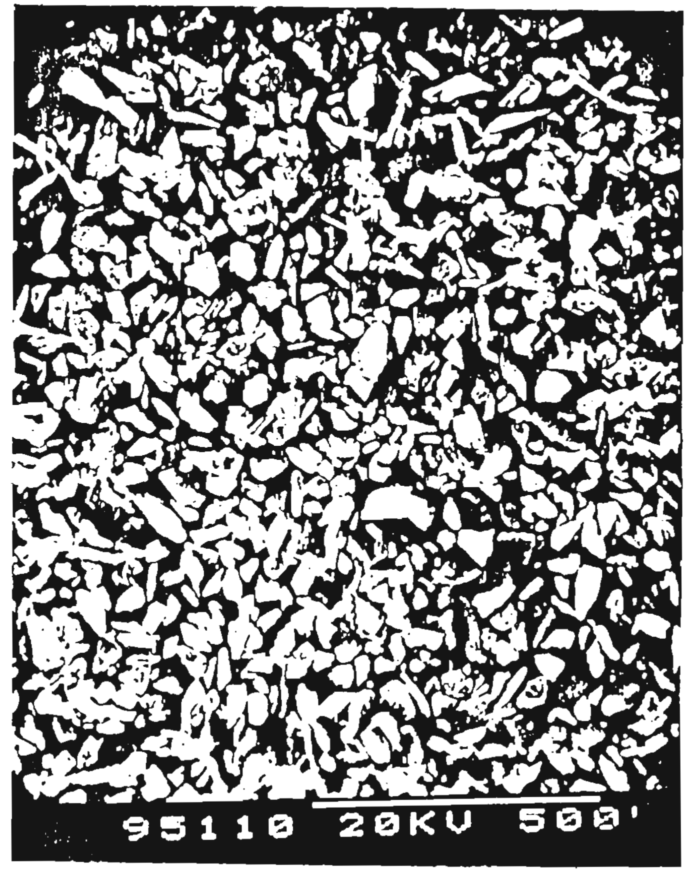
APPENDIX

Additional Data



95-RE51 <#200 FINE

55X



95-RE51 <#200 FINE

55X

95-RE 53 Seive #12 FINE glASS
55x

95-RE 50 ≤ #200 ROUGH
55x

ALITATIVE ELEMENT IDENTIFICATION

PLE ID:95RE51 #200 FINE 125-95

IBLE IDENTIFICATION

SI KA OR RB LA?
NB LA OR AU LA MA
CA KA KB
NA KA
O KA
K KA OR IN LA?
AL KA OR BR LA?

PEAK LISTING

	ENERGY	AREA	EL. AND LINE
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2	1.034	7280	NA KA
3	1.446	278	AL KA OR BR LA?
4	1.736	82701	SI KA OR RB LA?
5	2.146	22424	AU MA
6	3.317	616	K KA OR IN LA?
7	3.686	14527	CA KA
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9	[illegible]	5969	AU LA

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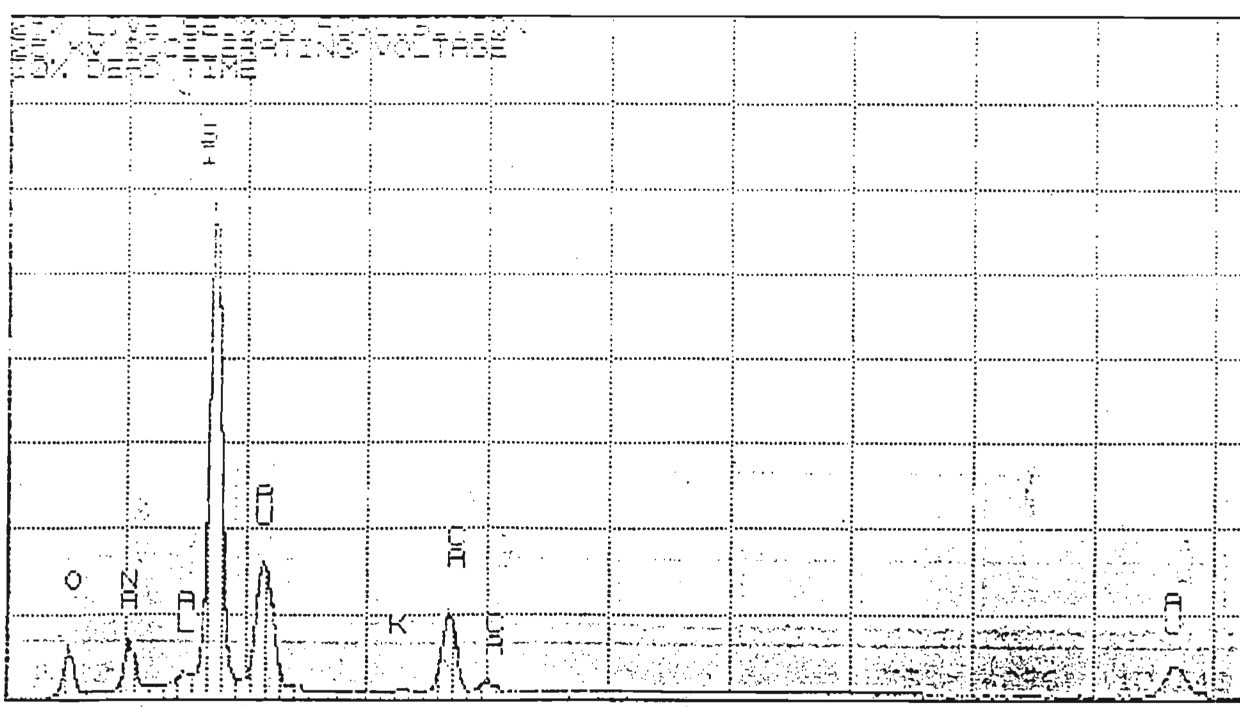

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252 95RE51 #200 FINE 125-95

QUALITATIVE ELEMENT IDENTIFICATION

SAMPLE ID:95RE52 #20 ROUGH CLEAR 125-99

MATERIAL IDENTIFICATION
SI KA
AU LA LB MA
CA KA KB
O KA
NA KA
AL KA

PEAK LISTING

	ENERGY	AREA	EL. AND LINE
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2	1.037	5143	NA KA
3	1.453	583	AL KA
4	1.7[illegible]	42[illegible]	SI KA
5	2.14[illegible]	[illegible]	AU MA
6	[illegible]	[illegible]	CA KA
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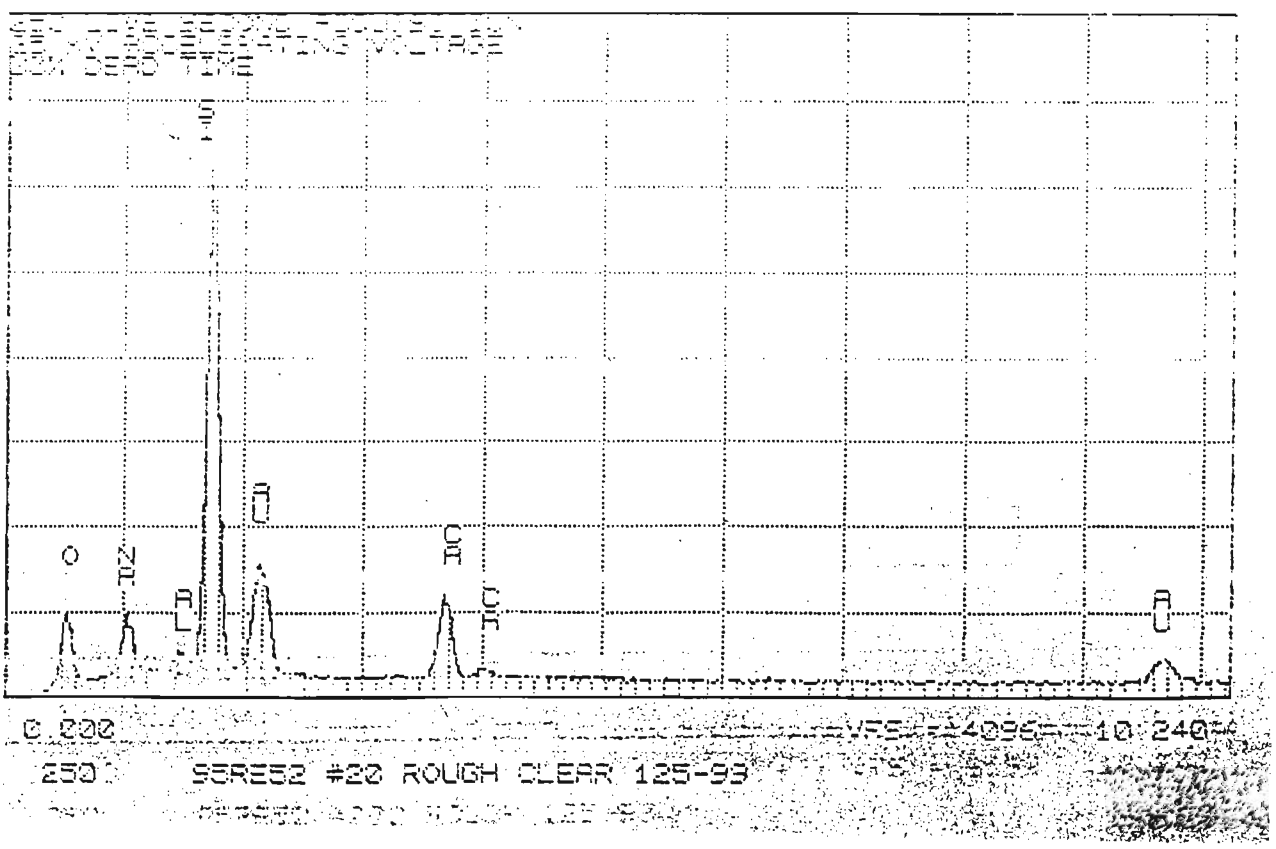

ITATIVE ELEMENT IDENTIFICATION

ID:95RE50 #200 ROUGH 125-93

BLE IDENTIFICATION
KA OR RB LA?
LA OR AU LA MA
KA KB
KA
KA
KA OR IN LA?
KA OR BR LA?

PEAK LISTING

ENERGY	AREA	EL. AND LINE
0.511	10834	O KA
1.035	9601	NA KA
1.451	628	AL KA OR BR LA?
1.736	95710	SI KA OR RB LA?
2.145	18415	AU MA
3.309	2114	K KA OR IN LA?
3.685	17764	CA KA
4.012	2064	CA KB
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