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USE OF DOMESTIC WASTE GLASS FOR URBAN PAVING
Summary Report

National Environmental Research Center
Office of Research and Development
U.S. Environmental Protection Agency
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USE OF DOMESTIC WASTE GLASS FOR URBAN PAVING

Summary Report

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FOREWORD

Man and his environment must be protected form the adverse effects of pesticides, radiation, noise and other forms of pollution, and the unwise management of solid waste. Efforts to protect the environment require a focus that recognizes the interplay between the components of our physical environment--air, water, and land. The National Environmental Research Centers provide this multidisciplinary focus through programs engaged in

- studies on the effects of environmental contaminants on man and the biosphere, and
- a search for ways to prevent contamination and to recycle valuable resources.

In an attempt to solve the problem of solid waste management, this study, published by the National Environmental Research Center - Cincinnati, examines research on the use of waste glass as an aggregate in asphalt paving mixtures. The potential for using waste glass in asphaltic pavements is demonstrated in this summary report.

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ABSTRACT

Recycling has been suggested as a solution to the problem of disposing of the increasing quantities of solid wastes generated in the United States each year. This report summarizes research on the use of waste glass as an aggregate in asphaltic paving mixtures. Re-using waste glass in this manner would provide an outlet for large quantities of the glass and would permit recycling in urban areas where large accumulations of glass are found.

Initial laboratory studies showed that asphaltic mixtures satisfying Marshall design requirements could be designed using all-glass aggregates and that adequate water-resistance could be achieved by adding hydrated lime to the aggregates. Conventional aggregate gradations for dense-graded mixtures could be used in the mixture and the presence of flat and elongated particles in the coarse fraction was found to cause little change in the Marshall properties of glass-asphalt mixtures.

Field installations of asphaltic paving mixtures containing glass have been placed in several states and in Canada and field tests as well as observations of the pavement performance have indicated that these installations have generally maintained adequate skid resistance and performed acceptably from a structural standpoint. Surface deterioration or raveling, however, has occurred on some of the pavements and further study of the cause of this raveling is needed.

Based upon the results of a laboratory wear test developed in this investigation, paving mixtures containing glass aggregates are more abrasive than mixtures containing some conventional aggregates. However, the data obtained in the laboratory wear test are not in agreement with the findings reported in a British study of tire wear resulting from surfaces with varying roughness and micro-texture. Further road testing to compare tire wear produced by pavements containing glass and conventional aggregates is recommended.

The economic feasibility of using waste glass as an aggregate in asphaltic concrete is dependent primarily upon the development of resource recovery systems which can separate glass along with other recyclable components and generate enough revenues from their sale plus disposal and processing fees to produce an acceptable return on equity. At the present time it appears that such a system can be economically viable in a limited number of municipalities. The maximum contribution to reclaimed product revenues would result if the glass were color sorted and marketed as cullet. However, if an acceptable level of color sorting is not possible or if there are no local markets for the cullet, use of the waste glass as aggregate should be considered.

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CONCLUSIONS

Asphaltic mixtures satisfying Marshall design criteria recommended by the Asphalt Institute can be designed using penetration grade asphalts and aggregates composed entirely of crushed glass or mixtures of glass and conventional aggregates. Optimum asphalt contents are in the same range (4 to 7 percent) as those required for conventional aggregates.

Water resistance of glass-asphalt mixtures as measured by laboratory immersion-compression tests is adequate if hydrated lime is added to the mixture in an amount equal to at least one percent by weight of the aggregate. Commercial anti-stripping agents are less effective and the addition of limestone dust does not improve water resistance.

Higher densities for asphaltic mixtures containing glass aggregates can be obtained by altering the grading ratio normally used to produce maximum densities with conventional aggregates. However, this results in air voids and voids in the mineral aggregate which are below minimum acceptable values. Thus, higher stabilities which accompany increased density are obtained at the expense of maintaining a minimum void content to reduce flushing of asphalt to the surface.

Substitution of angular but nearly equidimensional coarse glass particles for flat and/or elongated particles obtained by crushing container glass does not appreciably affect Marshall properties of asphaltic concrete at a constant asphalt content.

Standard batch plants can be used for mixing asphaltic mixtures containing glass aggregates, but a mechanical dust feeder would be desirable since hydrated lime is necessary to control stripping and manual addition of the lime may result in delays or inconvenience in the mixing process.

Asphaltic mixtures containing glass aggregates can be placed and compacted using conventional equipment. These mixtures may be difficult to compact due to horizontal mix displacement (crawl) during rolling, and this may necessitate a delay before breakdown rolling. However, breakdown rolling should commence as soon as the mat can support the roller without lateral deformation.

Aggregate degradation as a result of compaction and subsequent traffic over pavements containing glass aggregates is relatively small for roads carrying light to medium traffic except when studded tires are used.

The skid resistance of pavements containing glass aggregates is adequate for streets carrying up to 6000 vehicles per day with speeds up to 30 mph and in service for up to two years. The substitution of coarse container glass particles for conventional coarse aggregate may result in lower skid resistance but the replacement of river sand with crushed glass fines has no effect upon skid resistance.

Properly designed and constructed asphaltic pavements containing glass aggregates can be expected to perform well structurally, with little rutting, cracking, or potholing occurring. Excessive raveling, however, may develop in pavements exposed to studded tire traffic and raveling to a lesser degree may occur due to normal traffic.

Based upon the results of a laboratory wear test developed in this investigation, paving mixtures containing glass aggregates are more abrasive than mixtures containing some conventional aggregates. However, the data obtained in the laboratory wear test are not in agreement with the findings reported in a British study of tire wear resulting from surfaces with varying roughness and micro-texture.

The economic feasibility of using waste glass as an aggregate in asphaltic concrete is dependent primarily upon the development of resource recovery systems which can separate glass along with other recyclable components and generate enough revenues from their sale plus disposal and processing fees to produce an acceptable return on equity. At the present time, it appears that such a system can be economically viable in a limited number of municipalities. The maximum contribution to reclaimed product revenues would result if the glass were color sorted and marketed as cullet. However, if an acceptable level of color sorting is not possible or if there are no local markets for the cullet, use of the waste glass as aggregate is preferable to disposing of it in a sanitary landfill. This usage would generate some revenues without incurring additional disposal costs.

RECOMMENDATIONS

Design of asphaltic paving mixtures containing glass aggregates should be carried out in accordance with standard design methods such as the Marshall test procedures outlined in Mix Design Methods for Asphalt Concrete, published by The Asphalt Institute. It is recommended that local gradation requirements commonly specified for dense-graded asphaltic concrete be used for mixtures containing glass aggregates and that the aggregate contain at least one percent hydrated lime by weight.

Conventional batch plants and paving and compaction equipment can be used in paving with glasphalt but it is recommended that a mechanical dust feeder be used at the batch plant for adding hydrated lime to the mixture. The hydrated lime may be added manually at the pugmill but this may result in delays or inconvenience in the mixing process.

Standard construction methods should be used in placing glasphalt pavements, with care being taken to insure adequate field density. If horizontal mix displacement occurs during rolling, a lighter roller, a delay in rolling to permit cooling of the mix, or a combination of the two should be employed to compact the pavement.

Although adequate Marshall properties have been obtained for asphaltic mixtures containing glass aggregates, the raveling of some glasphalt pavements which has occurred under service conditions points to the need for further observation of the abrasion resistance of glasphalt pavements. The interaction of factors such as the amount of studded tire traffic, traffic volume and pavement density which affect the raveling characteristics of pavements containing glass aggregates should be studied in more detail. If studded tires are the primary cause of excessive raveling it will be necessary to restrict the use of glasphalt to binder or base course applications in areas where studded tires are in use. If excessive raveling is caused by higher traffic volumes, regardless of whether or not studded tires are in use, it may be necessary to restrict the maximum size of glass particles used in the pavement or to confine the use of glasphalt mixtures to binder or base courses.

Since results of laboratory wear tests indicate that the use of glass aggregates may produce a more abrasive pavement surface, a comparison of the tire wear resulting from glass aggregates and conventional aggregates is needed. Road tests are preferred to laboratory tests on a stationary specimen, due to the difficulties in interpreting results obtained when abrasion of the test surface is caused by the test wheel.

While the skid resistance of pavements containing glass aggregates has proved to be adequate, tests have shown that replacement of crushed stone coarse aggregate with glass particles in mixtures of similar gradation and asphalt content reduces skid resistance. Thus it is recommended that for surface courses, the use of coarse glass aggregates should be restricted to roads carrying low-speed traffic (30 mph or less).

The experimental field installations of glasphalt placed to this date have utilized clean glass containers which were crushed to obtain the desired gradation. Placing and performance characteristics of the pavements were of primary interest and crushing costs for the glass were not a major concern. However, unit crushing costs are likely to be high when relatively small amounts of glass are crushed because of the time consumed in adjusting crusher settings for feeding the containers, making necessary modifications to produce the desired gradation and cleaning glass out of the crusher upon completion of the crushing operation. For this reason, small volumes of crushed glass prepared in this manner cannot be processed at as low a cost as conventional aggregate, and use in glasphalt is not recommended as an economical means for reusing glass under these conditions. Resource recovery systems which are currently being developed incorporate crushing at several stages in the process, though, so that the glass fraction produced would be in a usable form without further crushing. It is recommended that this glass fraction be considered for use as aggregate since such a usage has been shown to be technically feasible.

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INTRODUCTION

Need for the Study

The increasing quantity and changing character of solid wastes generated in the United States each year have resulted in an urgent need to develop improved means for processing and disposing of these wastes. Recycling and re-use of materials have been suggested as a solution to this problem.

The rationale for recycling generally includes reduction of the volume of the waste stream destined for final disposal as well as conservation of resources. Factors of importance when considering a recycling program for any waste component are, therefore, the volume or size of the fraction of the waste stream constituted by a particular type of waste, and the nation's source of raw materials from which the item or group of items were made. Obstacles to recycling are the heterogenity of wastes, high transportation costs if reclaimed materials cannot be used in the area where they are generated, lack of stable markets and prices for salvageable materials, and absence of a suitable technology for separating and treating mixed refuse.[1] All these factors have been considered in the development of a new means for recycling one of the waste components -- glass.

Approximately 250 million tons of household, commercial, and municipal wastes are generated in the United States each year,[2] and studies of refuse composition indicate that glass comprises some 6 to 11 percent by weight of this material[3-5] or at least 15 million tons annually.[6] While this does not represent a major portion of the total waste stream, recycling a significant amount of glass would decrease the volume of material destined for ultimate disposal. However, due to the abundance and low cost of the principal raw materials used for glass manufacture, conservation of resources is not a major incentive for recycling at the present time.

Waste glass (cullet) has historically been used in the manufacture of new glass containers.[7] This represents the highest value of re-use since cullet of suitable quality has a raw material replacement value of 10 to 20 dollars per ton. However, glass used in this manner must be essentially free of non-glass components and color-sorted. Even if suitable technology is developed for separating municipal wastes, the economic benefits from such a separation will depend upon the availability of markets, with an important consideration being the transportation costs involved.

The research described in this final report deals with the use of waste glass as an aggregate in asphaltic mixtures used for urban paving and street maintenance operations. Many of the problems in recycling waste glass to glass furnaces can be avoided by using the glass as an aggregate. If waste glass is to be returned to the furnaces, impurities must be removed since they may cause erosion of the furnace refractories or alter the color characteristics of the glass.[8] As little as a tenth percent copper or a few tenths percent iron will produce appreciable color in clear glass. While the separation of glass from other refuse is still necessary if it is to be used as aggregate, contamination by non-glass components is not as critical. Laboratory tests have indicated that asphaltic mixtures can be designed to meet requirements for stability, flow and void content using glass separated from municipal refuse and containing up to 17 percent non-glass components.[9] Color separation is not necessary for glass used as aggregate, and transportation costs are minimized since the waste glass can be used in the urban area where it is generated. By substituting glass for portions of the conventional aggregates used in city street construction or maintenance, a steady market would be assured for this waste component.

The diminishing natural aggregate supplies in some urban areas further enhance this concept since aggregate costs increase with increasing haul distances. The depletion of suitable aggregate sources in localized areas and regions has led national highway officials to study promising replacements for conventional aggregates for highway use. The volume of waste glass is small when compared to the amounts of aggregate required for highway construction; consequently, it is not expected that glass will comprise a significant percentage of the aggregate used for this purpose. However, this use has the potential for utilizing all of the waste glass that can be economically separated from refuse in urban areas of the United States.

Development and Resume of the Study

The possibility of using waste glass as an aggregate in asphaltic concrete grew out of a special problem assignment in a ceramic engineering class at the University of Missouri-Rolla. A preliminary assessment of the potential problems which might be encountered included consideration of possible poor adhesion between asphalt and glass in the presence of water, adverse effects of flat and elongated particles on mixture density, low strengths and poor skid resistance due to the smooth surface texture of glass, and increased tire wear due to the sharp, angular particles.

Promising results obtained in pilot tests conducted on asphaltic mixtures containing glass aggregates led to the funding of a research project by the U. S. Public Health Service Bureau of Solid Waste Management. The overall purpose of this project was to determine whether waste glass could be used as an aggregate in asphaltic mixtures for street construction or maintenance and to demonstrate its potential use as a method for disposing of urban glass waste. The specific objectives were to:

1. Acquire engineering data on glass-asphalt mixtures with respect to suitable particle size ranges for the glass aggregate, proper type and grade of asphalt to be used, and the range of asphalt contents satisfying stability, durability, and workability requirements.

2. Institute a field testing program in which glass-asphalt mixtures would be used in actual paving operations.

3. Compile the information resulting from the study for use in recommending design and construction procedures which permit the effective utilization of waste glass.

Initial mix design studies showed that asphaltic mixtures satisfying standard design criteria could be designed using aggregates composed entirely of glass. However, these mixtures had very poor water resistance due to stripping of the asphalt from the glass particles when specimens were immersed in water. Tests were then conducted to investigate means by which the water resistance could be improved. Commercial anti-stripping agents improved the water resistance to a limited extent, but the most effective additive was hydrated lime. The addition of one percent hydrated lime by weight of the aggregate eliminated stripping in laboratory tests.

Upon learning of our work in evaluating glass-asphalt paving mixtures, Owens-Illinois, Inc. became interested in the project and volunteered to install a small test section at their technical center in Toledo, Ohio. In October of 1969, the first pavement containing glass aggregates was placed by Owens-Illinois and the word "glasphalt" was used to describe the material. The publicity resulting from this first field installation generated wide interest in the concept and since then 19 additional experimental glasphalt pavements have been placed in the United States and Canada. The Glass Container Manufacturers Institute and several member glass companies were instrumental in planning and financing many of these installations, in cooperation with the project staff at the University of Missouri-Rolla. Several state and municipal agencies as well as private industries also became involved in the construction of glasphalt pavements. A current listing of the glasphalt test sections installed during the duration of our research project is given in Table 1. Tests and observations of the performance of these test sections which were subjected to varying types and volumes of traffic and climatic conditions have provided valuable data for assessing the technical feasibility of glasphalt pavements.

Further laboratory testing was also conducted to determine the effects of particle size distribution upon mechanical properties and to compare the abrasiveness of asphaltic mixtures containing glass with mixtures containing conventional aggregates.

Results of laboratory and field tests on asphaltic mixtures containing glass aggregates have demonstrated that acceptable pavements can be constructed using this material. Conventional methods for placing and compaction can be employed and adequate performance has resulted in most installations. Surface deterioration or raveling has occurred on some of the glasphalt pavements, but otherwise the structural performance has been good and the skid resistance has been found to exceed tentative minimum recommended limits.

The potential for using waste glass in asphaltic pavements has been demonstrated and there are no insurmountable technical problems associated with this usage. However, present techniques for recovering glass from refuse impose economic limitations on the successful utilization of this method for re-using the glass. Hand-picking is expensive and even if containers are collected at recycling centers using donated labor, crushing is required. Due to the relatively small volume of glass involved, unit crushing costs are high. Consequently, the economic feasibility of employing waste glass as aggregates will depend on the development of large scale systems for separating refuse into usable components including a glass fraction which could preferably be used in glasphalt with a minimum of further processing.

TABLE 1
GLASPHALT PAVEMENTS PLACED
IN THE UNITED STATES AND CANADA

Location	Size	Thickness	Date Placed	Organization
Toledo, Ohio (plant entrance)	18 x 50 ft.	2-in.	Oct. 4, 1969	Owens-Illinois
Winchester, Ind. (parking lot)	1500 sq. ft.	1½-in.	June 8, 1970	Anchor-Hocking
Rolla, Mo. (campus road)	20 x 525 ft.	1½-in.	July 10, 1970	Univ. of Missouri-Rolla U.S. Env. Protection Agency, GCMI
Bramalea, Canada (truck access road)	18 x 500 ft.	3-in.	Aug. 29, 1970	Dominion Glass Co.
Scarborough, Canada (residential street)	26 x 600 ft:	1-in.	Oct. 17, 1970	Glass Container Council of Canada
Fullerton, California (industrial park street)	30 x 600 ft.	3-in.	Oct. 26, 1970	Glass Container Corporation
Brockway, Pa. (parking lot)	14,400 sq. ft.	1-in. 5-in.	Oct. 28, 1970	Brockway Glass Co.
New Orleans, La. (parking lot)	10,000 sq. ft.	2-in.	Feb. 1, 1971	Louisiana Coca-Cola Company
Des Moines, Iowa (fairgrounds road)	12 x 300 ft.	1-in.	May 15, 1971	Keep Iowa Beautiful State and City Agencies

TABLE 1 (cont.)
GLASPHALT PAVEMENTS PLACED
IN THE UNITED STATES AND CANADA

Location	Size	Thickness	Date Placed	Organization
San Francisco, Calif. (parking lot)	7500 sq. ft.	1½-in.	May 20, 1971	Lucky Lager Breweries
Rolla, Mo. (parking lot)	12,000 sq. ft.	2-in.	May 27, 1971	Univ. of Missouri-Rolla U.S. Env. Protection Agency, GCMI
Burnaby, B.C. (city street)	20 x 700 ft.	1½-in.	June 18, 1971	Municipality of Burnaby Dominion Glass Co.
Big Flats, N.Y. (plant entrance)	9 x 58 ft.	1½-in.	July 6, 1971	Thatcher Glass Co.
Omaha, Nebraska (city street)	60 x 280 ft.	1-in.	Aug. 6, 1971	Keep Nebraska Beautiful - City of Omaha
Baltimore, Md. (city street)	6500 sq. ft.	1-in.	Aug. 19, 1971	City of Baltimore
Azusa, California (city street)	40 x 300 ft.	1½-in.	Aug. 1971	Miller Brewing Co. City of Azusa
Holland, Michigan (parking area)	50,000 sq. ft.	1½-in.	Sept. 28, 1971	Brooks Products City & Local Groups
Albuquerque, N. M. (parking lot)	40 x 200 ft.	1½-in.	Sept. 1971	Keep New Mexico Beautiful City Groups

TABLE 1 (cont.)
GLASPHALT PAVEMENTS PLACED
IN THE UNITED STATES AND CANADA

Location		Size	Thickness	Date Placed	Organization
Toledo, Ohio (city street)	Surface course	24 x 1000 ft.	1½-in.	Sept. 1971	Owens-Illinois
	Levelling course	24 x 800 ft.	1½-in.		State of Ohio
	Base course	24 x 600 ft.	3-in.		City of Toledo
	Base course	24 x 600 ft.	9-in.		
	Subgrade	24 x 200 ft.	6-in.		
South Burlington, Vt. (state highway)		22 x 2200 ft.	1-in.	June 1971	Vermont Department of Highways

PROPERTIES OF GLASS-ASPHALT MIXTURES

Marshall Properties

To determine the feasibility of using waste glass as aggregates, initial studies were conducted using mixtures consisting of asphalt and all-glass aggregates. Non-returnable glass containers were washed to remove labels and other foreign material, dried and then crushed and separated into size fractions ranging from 1/2-in. through minus 200 mesh material.

Using the gradation shown in Table 2, and an 85-100 penetration asphalt cement, a mixture was designed which met requirements for stability, flow and voids recommended by The Asphalt Institute for pavements subjected to medium traffic. The properties of this mixture containing 5.5 percent asphalt on a total weight basis are shown in Table 3.

TABLE 2

GRADATION OF CRUSHED GLASS USED IN INITIAL DESIGN STUDIES

Sieve Size	Percent Passing
1/2-in.	100
3/8-in.	88
No. 4	67
No. 8	48
No. 16	37
No. 30	28
No. 50	18
No. 100	11
No. 200	6.3

TABLE 3

INITIAL MIX DESIGN MARSHALL PROPERTIES AT OPTIMUM ASPHALT CONTENT

Stability, lbs	770
Flow, .01-in.	8
Air Voids, %	3.39
VMA, %	15.52
Unit Weight, pcf	139.4

Initial mix design studies with glass aggregates utilized a gradation which produces maximum density for aggregates with nearly equidimensional particle shapes. However, since the coarse crushed glass contained a large number of flat or elongated particles, studies were conducted to determine whether higher stabilities could be obtained by modifying the gradation to produce a denser mixture. Dry density tests were conducted on mixtures of glass particles with varying shape and angularity by altering the gradation and noting the effects upon density. Types of glass used in this investigation included crushed container glass with a large number of flat and elongated particles and an angular shape, drain cullet and tempered glass which consists of angular nearly equidimensional particles and glass beads which were rounded and equidimensional. The gradations used were computed from the relationship:

$$P = \left(\frac{d}{D}\right)^n$$

where P is the cumulative percent passing a sieve having an opening of size d for an aggregate having a maximum size of D. The grading ratio, n, was varied from 0.30 to 0.55 and the resulting changes in density were noted. It was found that maximum density for the glass spheres occurred at n = 0.475, but at n = 0.375 for crushed container glass and 0.400 for the drain cullet and tempered glass combination.

Since maximum bulk density was obtained with the container glass at a grading ratio of 0.375, Marshall test specimens were molded using this gradation (Table 4) and asphalt contents ranging from 4.0 to 6.0 percent. Results of stability, flow, air voids and voids in the mineral aggregate determinations for these mixtures indicated that there was no asphalt content at which acceptable mixture properties were obtained since air voids and voids in the mineral aggregate were too low. The gradation was then modified as shown in Table 4 and a second series of specimens was made with asphalt contents ranging from 3.5 to 6.0 percent. Specimens with an asphalt content of 5.25 percent met Marshall requirements specified by The Asphalt Institute. The properties of this mixture are shown in Table 5. However, the stability obtained with this gradation was approximately equal to the stability of specimens using the initial gradation shown in Table 2. Consequently, although higher densities did produce larger stability values, low air voids for the high density mixtures made them unacceptable, and when gradation was modified to produce high enough void contents, the stability decreased to previously obtained levels.

The effects of angularity and sphericity of aggregates on Marshall properties were determined from specimens made using the modified gradation shown in Table 4, and an asphalt content of 5.25 percent. The four different combinations of glass used are shown in Table 6. Mixes A, B, and C all contained crushed container glass in sizes smaller than a No. 8 sieve, but container glass coarse aggregate was used in Mix A, drain cullet and tempered glass coarse aggregate were used in Mix B, and glass spheres were used as coarse aggregate in Mix C. The aggregate for Mix D consisted entirely of glass spheres. Three specimens were molded and tested for each aggregate combination and the results are shown in Table 7.

TABLE 4

GRADATIONS USED IN ANGULARITY STUDIES

Sieve Size	Percent Passing n = .375	n = .375 (modified)	n = .550
1/2-in.	100	100	100
3/8-in.	90	91	85
No. 4	69	71	58
No. 8	50	57	41
No. 16	38	45	28
No. 30	28	30	18
No. 50	20	19	13
No. 100	15	9	9
No. 200	10	5	6

TABLE 5

MARSHALL PROPERTIES AT OPTIMUM ASPHALT CONTENT FOR GLASS AGGREGATE WITH MODIFIED GRADATION

Stability, lbs.	750
Flow, .01-in.	10
Air Voids, %	3.5
VMA, %	15.25
Unit Weight, pcf	139.6

Substitution of the more nearly equidimensional drain cullet and tempered glass for coarse bottle glass particles caused a slight increase in air voids and VMA with a slight decrease in stability. When glass spheres were substituted for the coarse container glass, air voids and VMA decreased, but there was also a substantial decrease in stability. The decrease in stability was probably due to a reduction in the interlocking resistance developed between the coarse particles. This effect was even more pronounced when container glass was replaced by glass spheres in all sizes, with the specimens having virtually zero stability and a higher air void content. This mixture was very difficult to compact since it rebounded after each blow of the compaction hammer.

To further assess the effects of angularity and sphericity of coarse particles, a second series of tests was made using a gradation containing a higher percentage of material coarser than the No. 8 sieve. A gradation computed with an exponent of 0.55 (Table 4) was used at an asphalt content of 5.25 percent

TABLE 6

COMPOSITION OF GLASS-ASPHALT MIXTURES
USING GLASS AGGREGATES OF VARYING SHAPE AND ANGULARITY

Sieve Size		Type of Glass Aggregate for Mix			
Passing	Retained	A	B	C	D
1/2-in.	3/8-in.	Bottle Glass	Drain Cullet	Glass Spheres	Glass Spheres
3/8-in.	No. 4	Bottle Glass	Temp. Glass	Glass Spheres	Glass Spheres
No. 4	No. 8	Bottle Glass	Temp. Glass	Glass Spheres	Glass Spheres
No. 8	No. 16	Bottle Glass	Bottle Glass	Bottle Glass	Glass Spheres
No. 16	No. 30	Bottle Glass	Bottle Glass	Bottle Glass	Glass Spheres
No. 30	No. 50	Bottle Glass	Bottle Glass	Bottle Glass	Glass Spheres
No. 50	No. 100	Bottle Glass	Bottle Glass	Bottle Glass	Glass Spheres
No. 100	No. 200	Bottle Glass	Bottle Glass	Bottle Glass	Glass Spheres
No. 200	PAN	Bottle Glass	Bottle Glass	Bottle Glass	Glass Spheres

TABLE 7

MARSHALL PROPERTIES OF GLASS-ASPHALT MIXTURES
CONTAINING GLASS AGGREGATES OF VARYING SHAPE AND ANGULARITY

		Test Properties*					
Gradation+	Aggregate Combination+	Asphalt Cont-TWB (%)	Unit Weight (pcf)	Air Voids (%)	VMA (%)	Stability (lbs.)	Flow (.01-in.)
n = .375 (modified)	A	5.25	138.1	4.57	16.06	590	8.3
n = .375 (modified)	B	5.25	137.8	4.79	16.26	560	8.7
n = .375 (modified)	C	5.25	141.3	3.89	15.66	415	9.5
n = .375 (modified)	D	5.25	140.9	6.82	18.54	---	---
n = .55	A	5.25	142.4	1.57	13.42	705	12.2
n = .55	B	5.25	142.5	1.52	13.38	660	14.3
n = .55	C	5.25	146.6	1.13	13.32	435	17.0

*Average of three specimens
+See Table 6

and mixtures with crushed container glass, drain cullet and tempered glass, and glass spheres were compared. Substitution of drain cullet for container glass had little effect upon air voids and VMA and decreased stability only slightly. Glass spheres in the coarse fraction once again reduced air voids and VMA and resulted in a significant decrease in stability as shown in Table 7.

The large percentage of flat and elongated particles in the coarse fraction of the crushed container glass aggregates had little effect upon the Marshall properties of the glass-asphalt mixtures, since the substitution of more nearly equidimensional particles in the coarse sizes did not improve the stability and there was little change in void content or flow. The results show that particle angularity, however, has a pronounced effect on stability with less angular particles producing lower stabilities. Thus the large percentage of flat particles in the coarse fraction of glass aggregates should not be a problem with respect to their effects upon Marshall properties, and the angularity of these particles is beneficial to the stability of the mixture. Spherical glass particles should be avoided due to the adverse effect upon stability, but since little if any of a crushed waste glass fraction is likely to contain spherical particles, a restriction on such particles should not create any difficulties in producing glass aggregates.

Water Resistance

In initial mix design studies it was noted that stripping or loss of adhesion between the asphalt and glass occurred when specimens were immersed in water. Immersion-compression tests were used to evaluate the effectiveness of several anti-stripping agents added at varying addition levels.

The agents investigated included three commercially manufactured asphalt additives, hydrated lime and limestone dust. These were used in specimens containing all-glass aggregates and having an asphalt content of 5.5 percent by weight. The aggregate gradation is shown in Table 2. The commercial anti-stripping agents were added to the asphalt at three addition levels of 1, 2 and 4 percent by weight of the asphalt. Hydrated lime was substituted for minus 200 mesh glass at three different addition levels (5.4, 1.9 and 0.9 percent by weight of the aggregate) and limestone dust was substituted for minus 200 mesh glass at one addition level (6.5 percent by weight of the aggregate).

Results of the tests are given in Tables 8 and 9. The percent retained strength given is the average strength of three specimens tested dry divided by the average strength of three specimens tested after immersion in water at 140F for 24 hours. The commercial anti-stripping agents were only marginally effective in improving water resistance. At the 4 percent addition level, which is more than double the manufacturer's recommended amount, the maximum retained strength was 71 percent. The addition of limestone dust resulted in no improvement in water resistance but a substantial increase in water resistance was achieved by additions of hydrated lime. The use of approximately 1 percent hydrated lime by weight of the glass aggregate resulted in 100 percent retained strength which was considered to be satisfactory.

TABLE 8

IMMERSION-COMPRESSION TEST RESULTS FOR COMMERCIAL ANTI-STRIPPING ADDITIVES

Additive	Retained Strength, %
Control	0
Pavebond	
1%*	0
2%	41
4%	71
No-Strip	
1%	0
2%	47
4%	67
De-Hydro H86C	
1%	18
2%	0
4%	32

*Percent added by weight of asphalt

TABLE 9

IMMERSION-COMPRESSION TEST RESULTS FOR HYDRATED LIME AND LIMESTONE DUST ADDITIVES

Additive	Retained Strength, %
Hydrated Lime	
5.4%*	110
1.9%	192
0.9%	100
Limestone Dust	
6.5%	0

*Percent added by weight of aggregate

Degradation of Glass Aggregates

Sieve analyses were conducted on all-glass aggregates recovered from Marshall specimens which had been tested for stability. This was done to assess the degree to which the gradation of glass aggregates changed due to breakage caused by laboratory mixing, compacting and testing procedures.

Six specimens were chosen from each of two trial mix series and Hudson's $\bar{A}$ was calculated for uncompacted and compacted mixtures. Hudson's $\bar{A}$ is one-hundredth of the sum of the percentages passing the ten U. S. Standard sieves starting with the 1 1/2-in. and including the No. 200 sieve. In the first trial mix series, Hudson's $\bar{A}$ increased from 5.03 for uncompacted mixtures to an average of 5.11 for compacted specimens which had been tested at asphalt contents varying from 4.5 to 7.0 percent. In the second trial mix series the increase was from 5.03 to an average of 5.19. In previous studies of aggregate degradation[10] an increase in the Hudson's $\bar{A}$ value of 0.25 due to field compaction and an increase of 0.39 due to field compaction and traffic were both considered to be minor and insufficient to affect the service behavior of the pavement. Thus, the degradation of glass aggregates due to laboratory mixing, compacting and testing was not considered to be excessive.

Abrasiveness of Glass-Asphalt Mixtures

In order to determine the effects of glass aggregates upon tire wear, a laboratory testing apparatus was developed to determine the relative abrasiveness of compacted paving mixtures containing varying combinations of glass and conventional aggregates. The apparatus consisted of a rubber wheel of standard composition which was rotated while in contact with the surface of a small sample of the compacted paving mixture. Weight loss for the wheel was measured and used as an indication of the abrasiveness of the surface.

Two sets of sixteen specimens each were molded in the laboratory. Each compacted specimen was 3 1/2-in. wide and 6-in. long with a thickness of 1 1/2-in. One set contained four different coarse aggregates (plus No. 8 material): glass, traprock, limestone and river gravel, combined with a crushed container glass fine aggregate. The asphalt content was 5.5 percent and 1 percent hydrated lime by weight of the aggregate was added. Each specimen was compacted with 100 blows using a standard Marshall compaction hammer which was modified by adding a rectangular compaction plate 3 1/2-in. wide and 6-in. long.

The other set of specimens contained four different fine aggregates (minus No. 8 material): glass, traprock sand, limestone sand and river sand combined with a limestone coarse aggregate. Composition and preparation procedures for the specimens were identical to those used for the coarse aggregate test series.

In order to assess the abrasiveness of asphaltic mixtures which had been subjected to traffic and weathering, specimens were cut from field patches which had been placed for use in studying the skid resistance of mixtures containing glass and conventional aggregates. Samples were sawed from patches containing five different combinations of glass and conventional aggregates which had been subjected to traffic for 23 months. These combinations were: all-glass, limestone-glass, gravel-sand, gravel-glass, and limestone-sand.

Ten locations on the specimen surface were chosen by superimposing a numbered grid on the surface and randomly choosing ten numbers corresponding to ten different locations.

The test wheel was weighed and mounted in the apparatus, placed on the first location, then rotated for three minutes at 100 rpm while in contact with the surface. It was then moved within thirty seconds to a new location and rotated for three minutes at 100 rpm. This procedure was repeated at each of the remaining locations with a thirty second interval in which to position the wheel, after which the wheel was removed from the apparatus and weighed to determine weight loss.

A test was conducted on both sides of each laboratory compacted specimen and a different wheel was used for each of the four mixtures containing different aggregates which were made on the same day. Thus, there were four replications requiring four wheels for each the coarse and fine series testing.

In testing the samples cut from patches which had been in service for two years, six specimens were cut from each of the five patches. Three different wheels were used and each wheel was used on two specimens.

During testing, as the temperature of the wheel increased, the specimen surface was severely abraded by the wheel. An attempt was made to decrease this abrasion by inserting a spring between the top sleeve bearing and the loading platform. This reduced the contact pressure on the wheel from 55 to 31 psi. However, in tests conducted at this loading, wheel weight losses were extremely small, making it difficult to draw conclusions about differences in specimen composition. A further attempt to decrease the abrasion was made by increasing the number of locations on the test specimen from 10 to 15 and decreasing the test period from 3 to 2 minutes per location. This procedure, however, still produced surface abrasion. Consequently, it was decided to conduct the tests at 10 locations with a three minute duration at each location.

Wheel weight losses measured in the three sets of tests conducted are shown in Tables 10 through 12. An analysis of variance procedure was used to compare mean weight losses produced by the varying aggregate combinations. Where significant difference among the means was indicated, single degree of freedom comparisons were made to compare mixtures containing glass aggregates with conventional aggregate mixtures.

TABLE 10

WHEEL WEIGHT LOSSES ON ASPHALTIC MIXTURES WITH VARIOUS COARSE AGGREGATES

Replications		Weight Loss (g.)			
		Glass	Traprock	Limestone	Gravel
1	Top	1.9	1.1	1.0	1.4
	Bottom	1.7	1.1	0.8	1.0
2	Top	1.8	2.15	1.30	1.2
	Bottom	1.4	1.80	1.50	1.3
3	Top	1.35	1.65	0.95	1.1
	Bottom	1.70	1.00	1.10	1.3
4	Top	2.4	1.4	1.1	1.5
	Bottom	1.2	1.2	1.0	1.0
Mean Weight Loss		1.70	1.45	1.10	1.25

TABLE 11

WHEEL WEIGHT LOSSES ON
ASPHALTIC MIXTURES WITH VARIOUS
FINE AGGREGATES

Replications		Weight Loss (g.)			
		Glass	Traprock	Limestone	Sand
1	Top	0.8	0.6	0.4	0.8
	Bottom	0.6	0.8	0.6	0.6
2	Top	1.2	0.6	0.6	1.1
	Bottom	0.4	0.2	0.6	0.8
3	Top	1.3	0.8	0.9	0.9
	Bottom	0.8	0.3	0.4	1.1
4	Top	1.2	0.6	0.8	0.7
	Bottom	0.9	0.2	0.6	1.0
Mean Weight Loss		0.9	0.5	0.6	0.9

TABLE 12

WHEEL WEIGHT LOSSES ON
FIELD PATCHES WITH
VARIOUS AGGREGATES

Replications		Weight Loss (g.)				
		All-Glass	Limestone-Glass	Gravel-Sand	Gravel-Glass	Limestone-Sand
1	First	1.7	0.8	0.5	1.3	0.4
	Second	2.5	0.8	0.9	2.0	0.8
2	First	2.0	0.6	0.6	1.6	0.6
	Second	1.3	0.9	1.1	1.1	0.4
3	First	2.8	1.0	0.6	1.7	0.4
	Second	1.6	0.9	0.6	1.4	0.6
Mean Weight Loss		2.0	0.85	0.70	1.50	0.55

In the set of specimens containing different coarse aggregates, a statistically significant difference among means was indicated at a 0.05 significance level. The mean wheel weight loss for tests on mixtures containing coarse glass was greater than that for mixtures containing either limestone or gravel coarse aggregates, but was not significantly different from the weight loss produced by mixtures containing traprock.

For specimens containing different fine aggregates, a statistically significant difference among means was also indicated at a 0.05 significance level. The mean wheel weight loss for tests on mixtures containing glass fines was greater than that for mixtures containing either limestone or traprock fine aggregates, but was not significantly different from the weight loss produced by mixtures containing river sand.

Results of wear testing on the field samples were in agreement with the tests on laboratory compacted specimens when mixtures containing coarse glass aggregates were compared with mixtures containing conventional coarse aggregates. The mean weight loss resulting from tests on all-glass mixtures was significantly higher than weight losses measured for gravel-glass and limestone-glass mixtures. Comparison of weight losses between limestone-glass and limestone-sand mixtures also confirmed the finding that no significant difference in wear resulted from the substitution of fine glass for river sand. However, a significant difference in weight loss was found when comparing gravel-sand and gravel-glass mixtures. The gravel-glass mixture produced higher weight losses than were found with gravel-sand mixtures.

It is interesting to compare these results with the results of studies by Lowne[11] on the effects of road surface texture on tire wear. His data indicate that wet coefficient of friction and a factor related to the density and shape of asperity tips can be used to predict tire wear ratings for differing surfaces, with higher coefficients of friction and greater density and sharpness of the asperity tips resulting in higher wear. Macro-texture, indicated by surface roughness which can be seen by eye, was found to be only a slightly modifying factor in tire wear.

In our studies, the coefficient of wet friction was measured with a British Portable Tester on the field patches immediately before they were tested in the laboratory wear apparatus. The average wear corresponding to differing coefficients of friction is shown in Table 13. There is a trend toward decreasing weight loss with increasing skid resistance, whereas Lowne's study indicates that the reverse should be true. Furthermore, the data from tests on laboratory compacted specimens with differing fine aggregates show a trend toward decreasing wear or wheel weight loss with increasing angularity, while Lowne's data suggests that sharper asperity tips should increase wear. Since the surface of specimens tested in the laboratory wear test was severely abraded by the spinning wheel, the effect of initial coefficient of friction was minimized. Abrasion would also be expected to continuously expose new particle tips so that polishing of the surface which might take place under traffic conditions would not occur in the laboratory test. Consequently, the laboratory testing method may not accurately reflect differences in tire wear resulting from surfaces of varying composition.

TABLE 13

WHEEL WEIGHT LOSSES FOR SURFACES
WITH VARYING COEFFICIENT OF FRICTION

Mixture	Wet Coefficient of Friction	Av. Wt. Loss (g.)
All glass	0.485	2.0
Limestone-glass	0.528	0.85
Limestone-sand	0.561	0.55
Gravel-glass	0.503	1.50
Gravel-sand	0.483	0.70

FIELD EXPERIENCE WITH GLASS-ASPHALT PAVEMENTS

Asphaltic concrete pavements utilizing glass aggregates have been placed at several locations in the United States and Canada. In all of these installations, glass has been blended with conventional aggregates with varying percentages of glass being used. Design and construction data for several of these pavements are summarized in Tables 14 and 15 and in the following discussion.

University of Missouri-Rolla

A road to the University general services building and central receiving area was paved with glasphalt on July 10, 1970. Traffic density on this road is approximately 700 vehicles per day with 10 percent heavy trucks. The portion paved was 525 feet long and 20 feet wide with a thickness of 1 1/2 inches. It was placed over an existing surface treatment in which chuck-holes had been patched with cold mix prior to tacking with a diluted SS-1 emulsion.

The glass used for this project was donated by member companies of the Glass Container Manufacturers Institute and was a relatively coarse mixture of drain cullet and clean broken bottle glass. The mix was designed to include 63 percent glass, 33 percent fine sand and 4 percent hydrated lime. While only 1 percent hydrated lime is necessary to provide adequate water resistance, 4 percent was used because the fine aggregate employed in the mixture did not contain enough minus 200 mesh material and only two cold bins were available so that a third aggregate could not be blended into the mixture. Thus, the hydrated lime was used as a source of fines as well as an anti-stripping agent.

During construction, the material was mixed in a batch plant at 275F with an 85-100 penetration asphalt cement at an asphalt content of 5.75 percent (total weight basis). Aggregate gradation based upon hot bin analysis is given in Table 14. After placing half of the pavement the supply of coarse glass was nearly exhausted and the gradation was modified as shown in Table 14. This gradation with an asphalt content of 5.5 percent was used for the remainder of the paving operation. Marshall properties of laboratory compacted field samples for both mixtures are given in Table 15.

A conventional paver and 2-ton roller were used for placing and compaction. Both mixtures were tender and it was necessary to defer breakdown rolling until the mixture temperature had dropped to 225F.

TABLE 14

AGGREGATE GRADATIONS FOR
GLASPHALT FIELD INSTALLATIONS

	Percent Passing							
	Rolla							
Sieve	Coarse	Fine	Fullerton	Bramalea	Scarborough	Brockway	Burnaby	Omaha
1-in.	100	100	100	100	100	100	100	100
3/4-in.	100	100	99	100	100	100	100	100
1/2-in.	98	100	93	100	100	100	100	100
3/8-in.	93	99	86	92	95	98	93	100
No. 4	75	87	67	60	67	74	62	89
No. 8	49	58	54	42	49	51	43	61
No. 16	38	44	31	31	35	30	30	43
No. 30	30	35	18	21	25	19	19	33
No. 50	15	17	12	10	14	12	11	24
No. 100	6	6	9	5	7	8	6	12
No. 200	5	5	6	4	5	6	4	8

TABLE 15

MARSHALL PROPERTIES
OF SAMPLES FROM GLASPHALT FIELD INSTALLATIONS

	Marshall Property				
Location	Stability (lbs)	Flow (.01-in.)	Unit Weight (pcf)	Air Voids (%)	VMA (%)
Rolla					
Coarse Mix	840	13	141.5	2.0	14.9
Fine Mix	710	8	139.1	4.2	16.3
Fullerton	1770	13.5	140.5	4.9	15.9
Bramalea	1170	10.3	--	3.8	15.6
Scarborough					
Normal Mix	1090	8.9	--	4.4	16.1
Asbestos Mix	950	19.7	--	0.6	16.3
Brockway	1390	10.7	142.7	5.4	16.5
Burnaby	540	6.6	140.3	5.7	15.9
Omaha	2170	10	145.4	2.9	--

Sawed samples of the compacted pavement were taken 3 days after compaction and at one year intervals thereafter. After 2 years the coarse mixture had reached 98.0 percent of the 50 blow Marshall density while the fine mixture had reached 98.2 percent. After extracting the asphalt from these samples, washed sieve analyses were conducted on the aggregate. Hudson's $\bar{A}$ had increased from 5.12 for an uncompacted plant sample to 5.27 for a pavement sample of the coarse mixture after two years of service. The fine mixture Hudson's $\bar{A}$ had increased from 5.43 to 5.60 after two years.

A British Portable Skid Tester was used to measure the skid resistance of the pavement at approximately 1 to 3 month intervals for the first year and at approximately 6 month intervals thereafter. Measurements were made in the wheel tracks at 10 different locations for each mixture. After two years of service the average British Pendulum Number was 49.5 for the coarse mixture and 52.0 for the fine mixture. The pavement was in good condition after two years of service except for an area of alligator cracking caused by base failure.

Glass Containers Corporation

A street in the Fullerton Air Industrial Park in Fullerton, California, was paved with glasphalt on October 26, 1970. The street was 600 feet long and 40 feet wide. Thirty feet of the width was paved with a 3-in. thick layer of glasphalt with the other 10 feet of width being paved with conventional asphaltic concrete. The base course was a 7 1/2-in. thick layer of crushed rock equivalent to California Division of Highways Class 2 aggregate base. The subgrade was a silty sand which had been compacted to at least 90 percent of maximum density as determined in the laboratory in accordance with the requirements of the California Standard Specifications.

All of the glass used for this project was obtained by crushing clean non-returnable bottles in a hammermill. The glass was blended with rock dust and hydrated lime in a mixture of 63 percent glass, 36 percent rock dust and 1 percent hydrated lime.

The design asphalt content chosen was 5.5 percent (total weight basis) with a 60-70 penetration asphalt cement being used. Aggregate gradation based on hot bin analyses is shown in Table 14. Results of Marshall tests on a sample taken at the plant are given in Table 15.

The material was mixed in a batch type plant with a 4000 lb pugmill and the hydrated lime was added by hand at the pugmill. The 3-in. thick layer was placed and compacted with an 8-10 ton tandem roller. Initial attempts at compaction resulted in excessive crawl even at temperatures of 220F. Breakdown rolling was carried out at temperatures of 220F and below.

Tests conducted on cores removed from the compacted pavement indicated a unit weight of 131.4 pcf or 93.5 percent compaction. This low unit weight is believed to be due to the difficulties in compacting the mixture at temperatures above 220F. Little further increase in density had occurred after one year when additional cores were obtained. Aggregate gradations based upon wet sieve analyses of the cores after extraction were used to calculate changes in Hudson's $\bar{A}$ due to degradation. Hudson's $\bar{A}$ had increased from 4.58 for a plant sample to 4.87 for a pavement sample after one year of service.

On March 2, 1971, skid tests were conducted on the glasphalt pavement by the California Division of Highways. The towed trailer method (ASTM E-274) was used at a test speed of 25 mph and the skid number at 25 mph ranged from 61 to 69 which converts to 54 to 62 at 40 mph.

After one year of service, the pavement surface exhibited some raveling caused by the fracture of larger glass particles at the surface. However, the overall condition of the surface was good and its performance has been considered to be satisfactory.

Bramalea, Ontario

A private road at the Dominion Glass Company's Bramalea, Ontario, plant was paved with glasphalt on August 29, 1970. The roadway width paved was 18 feet and the length was approximately 500 feet. The mix was placed in two courses, each of 1 1/2-in. compacted thickness, giving a total compacted thickness of 3 inches.

Glass bottles for the project were crushed in a Pioneer Model 40V duplex crusher to produce coarse and fine fractions which were blended with a natural sand. Trial mixes at various asphalt contents using an 85-100 penetration asphalt cement were tested and the mix selected consisted of 39 percent coarse glass, 29.5 percent fine glass, 29.5 percent natural sand, 2 percent hydrated lime and 5 percent asphalt on a total weight basis. The gradation of the combined aggregate is shown in Table 14.

A Barber-Greene 4000 lb. Batch-o-matic batch plant was used for mixing the material at 275F and the haul distance from the plant to the Bramalea project was approximately 25 miles. The paving operation used a Barber-Greene Model SA-40 paver and three rollers were used on the project: a Buffalo-Springfield KT8-4-6 ton steel-tired roller, a Galion Rollomatic 12-14 ton steel-tired roller and a Bros 7-wheeled SP-6000 rubber tired roller. The first two loads of glasphalt were breakdown-rolled with the 14-ton steel-tired roller. The mix was too tender to support this heavy roller initially and the mix had to be left to cool. The procedure was then changed to breakdown with the 5-ton steel tired roller followed by the pneumatic-tired roller. This sequence gave good results with no difficulty in rolling or pick-up. Average Marshall properties of field samples are shown in Table 15.

In September 1970, four skid tests were conducted using an ASTM skid trailer at 20 mph. The skid numbers obtained were 47, 56, 53, and 61 with an average of 54. Skid tests are normally carried out at speeds of 30 and 60 mph but these speeds could not be obtained because of the configuration of the test area. The minimum skid number fo a 30 mph speed is 36 and based upon experience, as well as a study of the surface texture, it was concluded that the glasphalt skid number at the higher speeds would be higher than the minimum requirement.

Approximately 10 weeks after the glasphalt had been placed cores were cut from the pavement. The average percent compaction for four cores was 95.9 percent.

Inspection of the pavement 14 months after placing revealed little raveling or loss of surface material. In one area, however, there were several "punching" failures consisting of rectangular depressions approximately 4 inches long, 2 inches wide, and over an inch deep. These were found to have been caused by large steel garbage bins which were parked filled on the pavement for a period of three months during hot weather due to a strike at the plant. The 6 cu yd capacity bins with an empty weight of 650 lbs rested on steel casters and this resulted in large concentrated loads under the casters. Other than these holes, the pavement surface was in good condition and its performance has been satisfactory.

Scarborough, Ontario

Scarden Avenue, a public road in the Borough of Scarborough, Ontario, was paved with glasphalt on October 17, 1970. Approximately 600 feet of 26-foot wide pavement was placed in one course of 1-in. compacted thickness on a previously placed conventional binder course.

Materials used and the design mix were similar to those used for the Dominion Glass Company installation except that one load of the mix was modified by the addition of 2 percent asbestos and an additional 2 percent of asphalt cement to determine characteristics of asbestos-modified glasphalt. The gradation of the combined aggregate is given in Table 14.

The paving operation was performed using a Barber-Greene Model SA-35 paver and an 8-10 ton Galion steel-tired roller for breakdown with a 9-ton rubber-tired roller for finishing. No difficulties were encountered in compacting the mixture in that pushing, rutting or pick-up did not occur. However, the air temperature was 35F and the mix temperature in the paver varied from 200 to 380F.

Field Marshall test results for the regular glasphalt and asbestos modified mixture are given in Table 15. The addition of asbestos resulted in increased flow, and a marked decrease in air voids due to the increased asphalt content but a slight decrease in stability. No cores were obtained from the compacted pavement.

On May 3, 1971, the pavement was skid-tested using an ASTM skid trailer. At 30 mph the skid numbers ranged from 47 to 61 with an average of 55. These values are well above tentative minimum requirements and indicate good skid resistance.

Inspection of the pavement 14 months after placing revealed a considerable degree of raveling with many of the larger glass particles being dislodged from the surface. This may have been due to fracture of the surface particles by studded tires, although inadequate density resulting from low mix temperatures during compaction may also have contributed to the deterioration.

Brockway Glass Company

Approximately 1600 square yards of roads through the employees parking lot at the Brockway Glass Company in Brockway, Pennsylvania, were paved with glasphalt on October 28, 1970. Three strips were paved with the longest being 212 feet by 24 feet wide. Thickness was 1 inch except for 156 square yards which were placed in two layers to a total depth of 5 inches. The 1-in. layer was placed as a surface course over two 2-in. layers of conventional Pennsylvania Department of Highways ID-2 binder which had been placed one week previously. The subgrade under all paving was composed of shale and ash spread over old refractory rubble and compacted through years of use.

Glass used for the project was obtained by crushing nonreturnable bottles in two passes through a jaw crusher. The glass was blended with sand to produce an aggregate mixture containing 54 percent glass and 46 percent sand. The design asphalt content was 5.0 percent (total weight basis) and the composition of the mix based upon cold feed quantities is given in Table 14. No hydrated lime was used in the mixture. Marshall properties of laboratory compacted specimens are shown in Table 15.

A Cedar Rapids spreader-finisher was used to place the material with a 10-12 ton tandem steel wheel roller and 2 ton vibratory roller being used for compaction. No difficulties were encountered in compacting the mixture. However, the unit weight of cores obtained on the day following construction was only 132.5 pcf or 92.9 percent of the laboratory compacted unit weight.

On July 8, 1971, cores were taken from the pavement for testing by the Pennsylvania Department of Transportation. Using the British Portable Tester, the cores provided skid numbers of 62, 63, 58 and 63 with 55 being generally regarded as acceptable by the Pennsylvania Department of Transportation.

An inspection of the pavement one year after placing revealed a slight amount of raveling but in general the surface was in good condition. Since no hydrated lime was used in this installation, the absence of any significant stripping indicates that under some conditions the water-resistance may be adequate without the use of anti-stripping agents.

Burnaby, British Columbia

A 700 foot section of Royal Oak Avenue in Burnaby, British Columbia, was paved with glasphalt on June 18, 1971. The 20 foot wide existing asphalt pavement was tacked with a diluted emulsion before placing a 1 1/2-in. overlay. Traffic density on the road is 6000 vehicles per day (both lanes) at a maximum posted speed of 30 mph, with deceleration and acceleration occurring at the intersection with Moscrop Avenue.

Approximately 90 tons of bottles were crushed for use in the glasphalt and blended with conventional aggregates to produce the combined gradation given in Table 14. The combined aggregate consisted of approximately 67 percent glass, 31 percent conventional aggregate and 2 percent hydrated lime with 4.75 percent (total weight basis) of 85-100 penetration asphalt cement added to the mix.

The glasphalt was delivered to the job site at temperatures between 270 and 290F. Breakdown rolling was carried out at 230 to 270F with an 8-ton tandem roller, and subsequent rolling was done with a 7-ton pneumatic roller at temperatures from 180 to 230F. The mix was tender and required a cooling period before rolling. Results of Marshall tests on plant samples are given in Table 15.

Seven cores were cut from the compacted pavement and the density ranged from 96.4 to 98.5 percent of the laboratory density with an average density of 97.0 percent.

On September 16, 1971, skid tests were conducted on the glasphalt pavement as well as a conventional asphalt pavement placed during the same time period. The average British Pendulum Number (BPN) measured in the wheel paths was 48.9 for the glasphalt and 56.0 for the conventional asphalt.

Inspection of the pavement on March 30, 1972, indicated that severe raveling had occurred in the wheel paths. Loose, uncoated glass particles were prevalent along the shoulder and surface pitting was extensive. One pothole had developed. This deterioration was attributed primarily to heavy studded-tire traffic resulting from an abnormally severe winter. However, low pavement density and insufficient asphalt content may also have contributed to the condition.

On May 23, 1972, additional skid tests were conducted on the glasphalt and conventional asphalt pavements. The average BPN measured in the wheel paths had risen to 64.0 for the glasphalt and to 57.4 for the conventional asphalt. The substantial increase in skid resistance for the glasphalt was probably due in part to the surface raveling.

Omaha, Nebraska

One block of a city street in Omaha, Nebraska, was paved with a 1-in. glasphalt overlay on August 6, 1971. The roadway width paved was 60 feet and the length was approximately 280 feet.

Glass for the project was gathered during a bottle collection drive and crushed at a local gravel pit. Considerable difficulty was encountered in crushing the bottles. They were crushed in a Pioneer Three Roll Crusher normally used for crushing gravel with a maximum size of one inch. Several times, broken bottles became wedged in the opening to the crusher and severely cut the rubber input feed belts. Bits of glass flew from the crusher and were a definite safety hazard, resulting in several workers receiving cuts. Due to this, the time required for crushing the glass was much longer than the contractor had estimated and the cost was extremely high.

The mixture was designed to include 20 percent crushed glass, 30 percent crushed gravel, 10 percent blow sand and 40 percent limestone screenings. Design asphalt content was 6.25 percent and no hydrated lime was used to control stripping. Aggregate gradation based upon cold feed quantities is shown in Table 14 and Marshall properties of plant samples are given in Table 15.

Paving operations using conventional equipment proceeded smoothly and performance of the mat has been satisfactory. During the winter months, larger glass particles at the pavement surface were broken by studded tires and whipped out by traffic leaving numerous pock marks. Otherwise, there have been no indications of poor performance.

EVALUATION OF GLASS-ASPHALT PAVEMENT PERFORMANCE

Skid Resistance

The skid resistance measured on several of the glasphalt pavements described has, with one exception, been adequate after periods of service up to two years in duration.

A British Portable Tester was used to measure skid resistance on the Rolla, Brockway and Burnaby installations. After two years of service, the average British Pendulum Number (BPN) for the Rolla Street was 49.5 for the coarse mixture and 52.0 for the fine mixture. Natural rubber sliders were used for these measurements rather than ASTM E249 synthetic rubber sliders. Tests conducted by Kummer and Moore[12] show that the synthetic rubber sliders give BPN values that are 10 to 15 percent higher than numbers obtained with natural rubber sliders. In "Tentative Skid-Resistance Requirements for Main Rural Highways"[13], Kummer and Meyer list tentative minimum skid resistance requirements for various testing methods and test speeds. These requirements for the British Portable Tester are given in Table 16. A 10 percent correction for use with data obtained with natural rubber sliders has been applied to these figures and is shown in the table. Based upon these corrected figures, the minimum recommended BPN for both coarse and fine mixtures is above this minimum value.

TABLE 16

RECOMMENDED MINIMUM SKID RESISTANCE REQUIREMENTS

Mean Traffic Speed (mph)	Skid Number		British Pendulum No.	
	SN*	SN_{40}+	BPN_{SR}±	BPN_{NR}¢
0	60	--	--	--
10	50	--	--	--
20	40	--	--	--
30	36	31	50	45
40	33	33	55	50
50	32	37	60	55
60	31	41	65	59

*Measured at mean traffic speed
+Measured at 40 mph
±Measured in accordance with ASTM E 303 using ASTM E 249 rubber
¢Corrected for use of natural rubber sliders as suggested by Kummer and Moore

The average BPN for cores from the Brockway parking lot was 61.5, which is well above the recommended minimum value of 50 for 30 mph speed using ASTM E249 sliders.

The average BPN measured in the wheel paths of the Burnaby glasphalt road after 3 months of service was 48.9 which is slightly below the recommended minimum value of 50. The BPN had risen to 64.0 after 11 months of service, but raveling probably caused much of this increase. Measurements were also made on an adjacent conventional asphalt pavement which had been placed at the same time and the average values obtained in the wheel paths were 56.0 and 57.4 after 3 and 11 months respectively.

The Fullerton, Bramalea, and Scarborough roads were tested using the ASTM towed trailer (ASTM E274). The Fullerton tests were conducted at 25 mph and yielded skid numbers (SN) ranging from 61 to 69. These values, converted to 40 mph were 54 and 62 respectively, which are well above minimum requirements shown in Table 16.

Tests on the Bramalea road, conducted at 20 mph, yielded SN values ranging from 47 to 61 with an average of 54. Skid test results on the Scarborough street tested at 30 mph ranged from SN47 to SN61 with an average of SN55. These values are also well above minimum requirements shown in Table 16.

The results of these skid tests show that pavements containing glass aggregates have generally maintained adequate skid resistance levels under the service conditions described and for the time periods indicated.

Only limited data were available from the Burnaby installation to permit a comparison of the skid resistance of glasphalt and conventional asphaltic concrete. However, additional data were obtained from a series of test patches with varying composition which were placed in a Rolla city street. Five different combinations of aggregate were used in the test patches. One mixture contained an all-glass aggregate with particles ranging in size from 1/2-in. through minus 200 mesh material. Two mixtures contained crushed limestone in the coarse sizes (1/2-in. to plus No. 8 material) with river sand fines in one mixture and glass fines in the other. The other two mixtures consisted of river gravel in the coarse sizes, with river sand fines in one mixture and glass fines in the others.

Since specific gravities for the different aggregates varied from 2.50 to 2.57, the weight of aggregate was adjusted so that the volume of aggregate in each size fraction remained the same regardless of the aggregate composition. The gradation used, based on volume, is given in Table 17.

Each mixture was designed with an effective asphalt content of approximately 5.5 percent (total weight basis) and all mixtures contained one percent hydrated lime by weight of the aggregate. Results of laboratory Marshall tests on the mixtures are given in Table 18.

TABLE 17

GRADATION OF AGGREGATES USED IN PATCHES FOR SKID RESISTANCE TESTS

Sieve	Percent Passing (by Vol.)
1/2-in.	100
3/8-in.	87
No. 4	69
No. 8	50
No. 16	38
No. 30	28
No. 50	22
No. 100	11
No. 200	3

TABLE 18

MARSHALL PROPERTIES OF LABORATORY SPECIMENS FOR SKID RESISTANCE PATCHES

Mix Type	Effective Asphalt Content	Unit Weight (pcf)	Air Voids (%)	VMA (%)	Stability (lbs)	Flow (.01-in.)
All Glass	5.50	138.8	3.64	15.72	515	9
Stone-Glass	5.40	140.4	3.63	15.71	760	10.5
Gravel-Sand	5.50	140.0	2.91	15.15	1230	9
Gravel-Glass	5.60	136.7	4.06	16.12	750	8
Stone-Sand	5.40	143.4	2.70	14.91	1275	10

Two lines of five 12 by 18 inch patches were placed in one lane of the road and each line of patches contained all five of the different mixtures. A vibrating plate compactor was used to compact the patches. Results of tests on laboratory compacted field samples from each of the mixtures are given in Table 19.

Skid resistance of these patches was measured periodically over a 23 month period with the British Portable Tester. Eight individual measurements were made on each patch each time the skid resistance was evaluated, from which an average BPN was calculated.

TABLE 19

MARSHALL PROPERTIES OF LABORATORY COMPACTED FIELD SAMPLES FROM SKID RESISTANCE PATCHES

Mix Type	Effective Asphalt Content	Unit Weight (pcf)	Voids (%)	VMA (%)	Stability (lbs)	Flow (.01-in.)
All Glass	5.40	138.1	4.43	16.24	350	7.3
Stone-Glass	5.50	138.3	4.96	16.33	510	10.3
Gravel-Sand	5.50	137.5	3.45	15.59	1360	11.3
Gravel-Glass	5.60	135.8	4.63	16.61	1095	9.7
Stone-Sand	5.50	143.4	2.49	15.01	1650	9.3

Data obtained after 23 months are shown in Table 20. Comparisons between the average British Pendulum Numbers for the various treatments were made using a t-test and only two significant differences between treatment means were indicated at a 0.05 significance level. The average BPN for the all-glass mixture was significantly lower than the BPN for the stone-sand mixture and the stone-glass mixture. However, there was no significant difference between the stone-sand and the stone-glass mixtures or the gravel-sand and gravel-glass mixtures. Nor was there a significant difference between the all-glass mixture and the gravel-glass or gravel-sand mixture. This indicates that a replacement of stone by coarse glass lowered the skid resistance, but the replacement of gravel by coarse glass has no effect upon skid resistance. The replacement of river sand by fine glass resulted in no significant change in skid resistance for mixtures with either gravel or stone coarse aggregate.

TABLE 20

SKID RESISTANCE OF FIELD PATCHES AFTER 23 MONTHS OF SERVICE

Mix Type	British Pendulum Number (BPN)	
	Average	Range
All Glass	47.4	43.8 - 51.4
Stone-Glass	53.3	47.5 - 61.2
Gravel-Sand	47.8	44.3 - 52.5
Gravel-Glass	48.5	43.1 - 55.5
Stone-Sand	54.6	47.2 - 62.7

Since the measured skid resistance was lower during the summer months, and differences among the skid numbers of the various mixtures were not as pronounced, a similar analysis was conducted using the British Pendulum Numbers obtained after 19 months and shown in Table 21. The results of this analysis indicate several significant differences among the mixtures. The average BPN for the all-glass mixture was significantly lower than the BPN for either stone-sand or gravel-sand mixtures. Stone-glass and gravel-glass mixtures also had higher average BPN's than the all-glass mixture. There was again no significant difference between the stone-sand and stone-glass mixtures or the gravel-sand and gravel-glass mixtures. This indicates that the replacement of either gravel or stone by coarse glass lowered the skid resistance while replacement of fine sand by fine glass had no effect upon skid resistance.

TABLE 21

SKID RESISTANCE OF FIELD PATCHES AFTER 19 MONTHS OF SERVICE

Mix Type	British Pendulum Number (BPN) Average	Range
All Glass	50.4	46.4 - 58.6
Stone-Glass	62.7	60.0 - 65.6
Gravel-Sand	56.1	51.6 - 62.4
Gravel-Glass	56.1	50.4 - 58.6
Stone-Sand	64.1	58.4 - 69.4

Based upon the above analyses, the replacement of river sand by fine glass results in no significant change in skid resistance. Substitution of coarse glass for crushed stone reduces the skid resistance, but the effect of substituting coarse glass for gravel is inconclusive. After 19 months of service the results indicated that the glass for gravel replacement lowered the skid resistance, while results obtained after 23 months showed no difference in the skid resistance.

Aggregate Degradation

There was no indication of excessive aggregate degradation based upon sieve analyses of pavement samples taken from the Rolla and Fullerton glasphalt roads. A comparison of plant samples and samples sawed from the Rolla pavement after two years of service shows an increase in Hudson's $\bar{A}$ of 0.15 and 0.17 for the coarse and fine mixtures respectively. Hudson's $\bar{A}$ increased from 4.58 for the plant sample taken at Fullerton to 4.87 for cores obtained after one year of service giving a total increase of 0.29. Thus, the effect of field compaction and subsequent traffic on the aggregate gradation was minimal.

Surface Deterioration

Raveling has been a problem in two of the glasphalt installations. The Burnaby road exhibited the greatest degree of deterioration. Pronounced raveling was noted in the wheel paths after the first winter. Glass aggregates which had been dislodged from the pavement had no asphalt remaining on the surface. A similar, though not as severe, deterioration had occurred on the Scarborough street after a year of service. The material lost from the surface in this case was primarily coarse glass particles which had fractured and then been dislodged by further traffic. The deterioration in both of these cases was probably initiated by studded tire traffic with subsequent asphalt stripping from the loose particles.

Raveling in the Fullerton, Brockway and Omaha pavements was less severe and was confined primarily to the loss of large particles at the surface. Little raveling had occurred on the Rolla and Bramalea pavements.

In a laboratory study of raveling characteristics of hot mix asphalt paving mixtures, Gallaway and Vavra[14] found that increasing voids in the pavement (lower densities) resulted in increased raveling. In their studies, raveling was not found to be significant except where the void content was 10 percent and higher for specimens made with good aggregates. Specimens made with poor aggregates showed significant raveling at all void contents, but the raveling definitely increased with increasing void content. Based upon field density tests of the Burnaby glasphalt, the void content of the compacted pavement was 8.67 percent. Since this is below the 10 percent figure suggested by Gallaway and Vavra, it is unlikely that inadequate density alone accounts for the raveling which occurred, although it may have contributed to the severity of the problem.

No cores were taken from the Scarborough pavement and thus the void content of the compacted pavement could not be computed. However, due to the low ambient temperatures during construction, it is possible that a high void content in the pavement may have been a contributing factor in the raveling observed.

The void content of the compacted pavements at Fullerton and Brockway was higher than 10 percent, but the lower traffic volumes at these sites may explain the fact that extensive raveling has not occurred.

There was little deterioration of other types occurring in the glasphalt pavements described. One pot hole had developed in the Burnaby road and alligator cracking was found in one small area of the Rolla road. Punching failures due to sustained concentrated loads during hot weather occurred in the Bramalea road, but there was no rutting or other evidence of low stability in any of the other pavements containing glass aggregates.

ECONOMIC ANALYSIS

The economic feasibility of using waste glass as an aggregate is dependent upon several factors which include the cost of disposing of waste by conventional methods of disposal such as sanitary landfilling or incineration, the cost of separating refuse into recyclable components and the cost of conventional aggregates.

Costs of Conventional Disposal Methods

Cost ranges for sanitary landfill disposal have been estimated at $0.50 to $2.00 per ton by Cannela[15] and more recently at $1.50 to $3.00 per ton.[16] Incineration costs are generally somewhat higher with an average operating cost of $5.00 per ton being reported by DeMarco et al[17] on the basis of results from a 1968 National Survey of Community Solid Waste Practices. Based upon data from 78 facilities at which incoming refuse was actually weighed, 73 percent of the incinerators studied had operating costs below $5.00 per ton while four of the 78 plants reported operating costs above $10.00 per ton.[17]

Costs of Refuse Separation Facilities

Costs of separating refuse for the purpose of recycling the separated components vary with the methods used for separation. Non-profit organizations and community action groups have set up recycling centers throughout the United States using volunteer labor, and industry groups such as glass container and can manufacturers have also established reclamation centers. Materials such as paper, glass containers and metal cans are collected for recycling and, in some cases, donors are paid for material brought to the center. Up to $20 per ton has been paid for reasonably clean glass containers. The volume of material collected in this manner, however, is relatively small. In Los Angeles, for instance, 130,000 tons per year of residential materials are salvaged, but 4.20 million tons of solid wastes are landfilled.[18]

If recycling is to be practiced on a large scale, automated systems for segregating and recovering portions of residential solid waste will be necessary. Several such resource recovery systems are currently being developed by the U. S. Bureau of Mines[19], Black Clawson Company[20], Combustion Power Company and Garrett Research. These include both dry and wet separation systems for treating either incinerator residue or raw refuse. Processing steps that have been utilized include crushing, screening, air classification, heavy media separation, and magnetic separation. Detailed data on the capital and operating costs for these systems is scarce, however. Costs of treatment for the Black Clawson system have been reported to be an estimated $7.50 per ton of raw refuse processed[21] minus the credits for salable separated components. Sullivan and Stanczyk[22] give cost data on the Bureau of Mines system which treats incinerator residue.

The most comprehensive analysis of the costs for separating refuse is given in an engineering feasibility study for a materials recovery system which is being developed by the National Center for Resource Recovery, Inc.[23] Their plan calls for a facility which would process 500 tons of refuse per day and would incorporate "off-the-shelf" equipment used in other process industries. Major separation equipment items would include a shredder, air classifier, magnetic belt separator, roll crusher, electrostatic separator and optical separator along with the required hoppers, conveyors and other processing equipment.

Recovered material from the system is predicted to be 15 to 20 percent of the input by weight, with the remainder being disposed of by conventional methods. Since the value of recovered products does not cover the cost of extracting them from the refuse, economic viability of the system requires benefits as a result of shredding -- either lowering the cost of landfill due to less cover requirements or increasing the efficiency of an incinerator. Also, there are savings incurred by simply not having to dispose of the recovered materials.

A cost analysis for the system details estimated capital requirements of $2,416,000 which includes $100,000 working capital. Under the conditions outlined in the report, annual revenues from sale of materials and collection of dumping and processing fees would approximate $1,030,000 while annual net expenses would be $818,000. Thus, an expected profit of $212,000 per year would yield a return on equity of 14.6 percent for a debt-equity ratio of 40-60. Several assumed conditions, especially those relating to the glass fraction, are of interest.

The facility was targeted for a city that has a disposal cost of $6.50 per ton or higher. Thus the facility charges the city $6.50 for every ton of solid waste that is delivered and therefore does not have to be disposed of by traditional means. A $2.00 per ton processing charge is assumed for shredding and removing the inerts from the unrecovered refuse.

Estimated revenues generated by the recoverable glass fraction are dependent upon whether color sorting is employed. Glass is assumed to comprise 10 percent by weight of the raw feed input to the system or 50 tons per day. Of this 50 tons, 32 tons are expected to be recovered while the remainder is landfilled. Twenty of the 32 tons recovered may be color sorted and are assumed to have a market value of $12 per ton after color sorting while the remaining 12 tons consists of material smaller than a 3/16-in. screen but retained on a 20 mesh screen and suitable for aggregate with a market value of $1 per ton. Since color sorting equipment is optional, however, one portion of the economic analysis assumes that no color sorting is carried out and all recovered glass has a market value of $1 per ton. This lowers the return on equity from the previously stated 14.6 percent to 10.2 percent.

Costs of Conventional Aggregates

Costs of conventional aggregates generally range from $1.00 to $7.00 per ton depending upon the locality and type of aggregate. Monthly market quotations reported by Engineering News Record[24] for January 1973, give sand prices ranging from $1.00 per ton in Detroit to $5.40 per ton in Pittsburgh. The price of 3/4-in. gravel in Birmingham was $1.65 per ton while in New Orleans the price was $7.00 per ton. Crushed stone with a 3/4-in. maximum size had a price range from $1.55 per ton in St. Louis to $6.50 per ton in Minneapolis. The average aggregate prices per ton in the twenty U.S. cities surveyed were $3.17, $3.79, and $3.55 for sand, gravel and crushed stone respectively.

The variations in aggregate prices for different cities reflect the availability of aggregates in these areas. The Gulf Coast in Texas, Louisiana, Alabama and portions of Florida is an area in which quality aggregates are lacking and consequently the prices are higher in this area. A study by the American Road Builders' Association was used in NCHRP Report No. 135[25] to estimate the yearly tonnage of aggregates needed in various regions of the United States through 1985. The results of this study indicated that the aggregate demands for highways in the Northwestern United States will not be met in the future unless:

1. Aggregate production increases in excess of 5 percent per year are encountered,

2. The amount of aggregate for highway consumption expressed as a percentage of total aggregate production for the region is greatly increased over 40 percent,

3. Conventional aggregate is transported into the region from other regions,

4. Supplemental aggregates are manufactured and used for highway construction, or

5. Low quality aggregates are beneficiated and used.

Some of these possibilities such as transporting aggregate into the region, would probably increase the cost of aggregate while the effect of others, such as increasing aggregate production, might have little effect on cost or even reduce aggregate prices.

Economic Feasibility of Using Waste Glass as Aggregate

It is apparent from the above discussion, that the economic feasibility of using waste glass as aggregate will vary considerably in different localities throughout the United States. The optimum conditions for successful utilization of this approach to recycling glass would include high landfill costs and high aggregate costs in an area. Even with these conditions present, however, the cost of separating refuse and processing the glass would be a critical consideration. It is very unlikely that glass collected at recycling centers can be economically recycled as aggregate. If donors are paid for the glass bottles at rates as low as $10 per ton, it is obviously not practical to use this material as a replacement for aggregate costing at most $7.00 per ton. Even if the bottles and labor at the recycling center are donated, crushing is required and, due to the relatively small volumes of glass involved, unit crushing costs would be high. Thus, when waste glass is collected at recycling centers, recycling into new containers offers more promise for economical utilization of the glass than using it as aggregate.

For a materials recovery system such as the one proposed by the National Center for Resource Recovery, however, the prospects for economical utilization of the glass fraction as an aggregate are more promising. The estimated revenues for this system have been calculated by assuming that 63 percent of the recovered glass is color sorted and marketed at $12 per ton. However, if color sorting equipment is not used in the system, due either to the absence of a market for cullet in the area or an inability to sort the glass to the desired degree of purity, use of the glass as an aggregate is preferable to simply disposing of it in a landfill. Crushing and screening equipment are included in the plant facilities and thus gradation control would not require additional equipment. Although the glass would have a lower value when used as aggregate, this usage would make a contribution to product revenues rather than incurring an additional cost for disposal. The variations in estimated annual revenue for varying end uses of the glass from a resource recovery system are shown in Table 22 and the return on equity for each of these assumptions is given in Table 23. The figures given in these tables are based upon data contained in the report by the National Center for Resource Recovery.

The first column in Table 22 gives product revenues for a 500 ton per day plant assuming that the glass fraction is not marketable and must be disposed of in a sanitary landfill. In column 2, glass revenues and disposal and processing fees are calculated assuming that 40 percent of the glass input is color sorted and marketed at $12 per ton while 24 percent is too small for sorting and is sold as aggregate for $1 per ton. Column 3 gives glass revenues and disposal and processing fees assuming that 64 percent of the glass input is marketed as aggregate at $1 per ton. Return on equity for these options is given in Table 23 for a case where 40 percent of capital is borrowed. Return on equity is only 6.4 percent if all of the recovered glass is landfilled, but rises to 10.2 percent if the recovered glass is sold as aggregate for $1 per ton and 14.6 percent if 63 percent of the recovered glass is sold for cullet at $12 per ton and 37 percent is sold for aggregate at $1 per ton. The $1 per ton value for glass used as aggregate is quite conservative, based upon the previously stated aggregate prices throughout the United States. If a value of $3 per ton is assumed, the return on equity rises to 11.7 percent when all of the glass is used as aggregate. It should be noted again that these figures are based upon assumed disposal fee of $6.50 and processing fee of $2.00 per ton. Other assumptions concerning operating costs, equipment costs, and product revenues are detailed in the report by the National Center for Resource Recovery.

This analysis indicates that waste glass can be economically reclaimed from municipal refuse for use as aggregate only if the recovery system produces revenues from marketing additional components such as ferrous metals, aluminum, other non-ferrous metals, and paper and from disposal or processing fees. Disposal and processing fees are of particular importance since the value of recovered products does not cover the cost of extracting them from the refuse. This means that recycling of refuse components in general, and glass in particular, is not likely to be economical in a classical sense (not considering social costs) when costs for landfill disposal are low. In areas where conventional disposal costs are relatively high, and recycling offers an alternate means for treating solid wastes, the use of glass as aggregate can contribute revenues to the system even though the glass is not color sorted or the system is not conveniently located for transporting glass to a container manufacturer. The advantage of a local market for the glass as aggregate, especially in areas which have a deficiency in conventional aggregate supplies, may make this usage more attractive than shipping the glass some distance to a container manufacturer. Under conditions of high disposal costs and adequate market prices for other recoverable components, resource recovery systems may be able to obtain an adequate return on equity even though the glass aggregate brings in revenues of only $1 per ton. Higher aggregate prices will enhance the desirability of using glass as aggregate under these same conditions but even at $7.00 per ton, revenue generated by the use of glass as aggregate would represent less than 10 percent of the total revenue necessary to insure a profitable operation of the resource recovery system.

TABLE 22

ASSUMED ANNUAL REVENUES FROM RESOURCE RECOVERY SYSTEM

Revenue Source	Conditions Outlined Below 1	2	3
Product Revenues			
Ferrous	$105,760	$105,760	$105,760
Aluminum	218,400	218,400	218,400
Glass	0	78,624	9,984
Fiber	62,400	62,400	62,400
Non-ferrous Materials	124,800	124,800	124,800
Total Product Revenues	$511,360	$589,984	$521,344
Disposal Fee	$120,458	$185,354	$185,354
Refuse Processing Fee	274,936	254,968	254,968
Total Revenues	$906,754	$1,030,306	$961,666

1. No optical sorting and no market for recovered glass. All glass landfilled.
2. Optical sorting. 63% of recovered glass selling at $12 per ton, 37% selling at $1 per ton.
3. No optical sorting. All recovered glass selling at $1 per ton.

Other assumptions:

a. 6.8% of input stream assumed to be recovered ferrous selling at $10 per ton.
b. 0.7% of input stream assumed to be recovered aluminum selling at $200 per ton.
c. 6.4% of input stream assumed to be recovered glass.
d. 4.0% of input assumed to be a mixture of hand picked newspaper, Kraft and corrugated selling at $10 per ton.
e. 0.4% of input assumed to be other non-ferrous metal selling at $200 per ton.
f. Assumes a fee of $6.50 per ton charge for every ton of refuse that does not have to be disposed of.
g. Assumes a $2 per ton refuse processing fee for shredding and air classifying the refuse.

TABLE 23

ASSUMED RETURN ON EQUITY FROM RESOURCE RECOVERY SYSTEM

	Conditions Outlined Below 1	2	3
Equity	$1,429,045	$1,445,513	$1,429,045
Debt	970,000	970,000	970,000
Capitalization	$2,399,045	$2,415,513	$2,399,045
Annual Revenue	$906,754	$1,030,306	$961,666
Annual Operating Cost	814,770	818,511	814,770
Profit	$ 91,984	$ 211,795	$146,896
Return on Equity	6.4%	14,6%	10.2%

1. No optical sorting and no market for recovered glass. All glass landfilled.
2. Optical sorting. 63% of recovered glass selling at $12 per ton, 37% selling at $1 per ton.
3. No optical sorting. All recovered glass selling at $1 per ton.

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16. ABSTRACT
This report summarizes research on the use of waste glass as an aggregate in asphaltic paying mixtures. Reusing waste glass in this manner would provide an outlet for large quantities of the glass and would permit recycling in urban areas where large accumulations of glass are found. Field tests as well as observations of pavement performance have indicated that field installations of asphaltic paving mixtures containing glass have generally maintained adequate skid resistance and performed acceptably from a structural standpoint. The economic feasibility of using waste glass as an aggregate in asphaltic concrete depends primarily on developing resource recovery systems that can separate glass along with other recyclable components and generate enough revenues from their sale, plus disposal and processing fees, to produce an acceptable return on equity.

17. KEY WORDS AND DOCUMENT ANALYSIS

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Skid resistance, *Urban areas, *Glass, *Asphalts, Bituminous concretes, Aggregates, Pavements, Economic analysis, Revenue, Surface properties, Texture, Sieve analysis	Recycling; *Solid waste management; *Resource recovery; Marshall design; Hydrated lime; Glass-asphalt; Cullet	11B; 13B

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