FINAL REPORT

POTENTIAL UTILIZATION OF RECYCLED WASTE GLASS IN ALASKAN PAVEMENTS

by

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DISCLAIMER

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ABSTRACT

In this study the performance feasibility and economic practicality of using recycled waste glass in highway construction in Alaska is addressed. The potential use of recycled waste glass in asphalt concrete, base, subbase and subgrade, and other construction materials is discussed based on published information. In addition, a laboratory investigation was conducted to assess the influence of using recycled waste glass in asphalt concrete mixtures using Alaskan AC 2.5 and AC 5 asphalt grades. The laboratory study also included the effect of using variable quantities of recycled glass on the compaction characteristics and the penetration resistance (CBR) of a typical silt subgrade. Results of the laboratory study are used in conjunction with other similar published data to investigate the economic design/performance aspects of glass recycling in Alaska.

Results indicate that up to 15% of crushed glass passing 3/8 in. sieve could be used with Alaskan AC 2.5 and AC 5 mixtures and satisfy Alaskan mix specifications. Optimum results, however, were obtained for glass content that did not exceed 7.5%. The AC 2.5 and AC 5 glass-asphalt concrete mixtures showed no evidence of stripping or loss of stability under extended exposure to moisture. These mixtures were prepared using Pavebond anti-stripping agent (0.25% by weight of asphalt cement). Glass-silt mixtures prepared using varying proportions of glass exhibited no change in compaction characteristics or significant change in CBR for glass contents up to 15%. Higher glass content could result in loss of the mix CBR.

The tendency of glass-asphalt concrete mixtures to retain more heat and therefore exhibit a slower cooling rate than similar mixtures with no glass should be accounted for in construction in order to enhance the economic value of the glass-asphalt mix. Such behavior could result in increased rolling time, thicker compaction lifts, less fuel, and improved cold weather paving. Although more glass could probably be used in base, subbase, and subgrade, this will not be cost effective unless the addition of glass results in significant increase in stiffness and strength. The laboratory study on the glass-silt mixtures does not indicate any significant improvement. In this case, economic incentives should be provided by State agencies to promote the use of crushed glass particularly since its average cost is about $40 per ton in comparison with $10 per ton for aggregates.

INTRODUCTION

The demand for solid waste recycling in Alaska continues to grow particularly in lieu of the common difficulties of disposing of solid waste in Alaska through landfilling. Sanitary landfills are becoming a less attractive solution due to problems associated with lack of suitable cover for landfills, high water table in some areas, organic "muskeg" soils, negative impact on wildlife, limited transportation infrastructure, and changing landfill regulations. According to a recent study by the Alaska Energy Authority (1), the majority of landfills in Alaska are out of compliance with state regulations. In another publication by the Alaska Department of Environmental Conservation (2) every community in Southeast Alaska and Juneau has site and operational problems with their solid waste disposal facilities that need to be addressed. It is therefore expected that the need for more environmentally sound solid waste management in Alaska will increase for the purpose of reducing the waste stream entering the landfills. Solid waste recycling should be considered as a viable option in any solid waste management plan.

Solid wastes generated in the United States totalled 158 million tons in 1986 (3). This includes an estimated 13 million tons of glass. Glass does not burn, rust, or decay and therefore disposed glass such as bottles and jars occupy large space in comparison to their actual solid volume. Even after incineration, the amount of glass in municipal incinerator residue accounts for nearly half of the residue by weight (4).

According to Alaska Energy Authority (1), Alaska waste generation rates tend to be higher than the national averages. The average Alaska generation rates for coastal communities, interior rural communities, and urban population centers are summarized in Tables 1-3. The corresponding population figures as published by the U.S. Bureau of Census for 1990 (5) are presented in Table 4. The average composition of U.S. solid waste, shown in Table 5, indicates that glass constitutes about 8.2% of the total waste stream. It is interesting to note that the average Alaska breakup for paper, glass, and metals exceeds the national average figures (1). For example, the average solid waste glass content in Juneau is estimated at 16% in comparison with 8.2% for the national average. The projected figures for total solid waste production in major urban centers in Alaska for fiscal year 1993 are expected to be 450,000 tons and the corresponding waste glass content as 38,440 tons (Table 6). This represents an average increase of 7.5% from fiscal year 1992.

In this study, the performance feasibility and economic practicality of using recycled waste glass in highway construction in Alaska is addressed. The potential use of recycled waste glass in asphalt concrete, base, subbase and subgrade, and other construction materials such as portland cement concrete is discussed based on published information. In addition, a laboratory investigation was conducted to assess the influence of using recycled waste glass in Alaskan asphalt concrete mixtures using AC 2.5 and AC 5 asphalt grades. The laboratory study also included the influence of using variable quantities of recycled glass on the compaction characteristics and the penetration resistance (CBR) of a typical silt subgrade. Results of the laboratory study are used in conjunction with other similar published data to investigate the economic design/performance aspects of glass recycling in Alaska.

LITERATURE REVIEW

The potential use of recycled waste glass in construction materials has been summarized in Environmental Science and Technology (7) as follows:

- The best known application of recycled waste glass in road construction is as glasphalt, an asphalt concrete hot mix where crushed glass is used as part of the mix aggregates.

- Another road bed material is slurry seal, an asphalt emulsion of water and a filler consisting of 50% glass.

- Glass beads produced from incinerator residue are used commercially in reflective paints in highways.

- Both the University of California at Los Angeles and the University of Utah have been investigating the use of waste glass in foam insulation.

- The Colorado School of Mines Research Institute used waste glass as a binding agent in wall panels.

- Glass, acting as a binding agent can be used in tiles. For indoor tile, design can be applied by silk screening for firing, and for outdoor uses, refractory abrasive particles can be added to produce decorative non-skid patios or cross walks.

- The Bureau of Mines Ceramic Laboratory experimented with bricks made from incinerator residue. Adding 10% ground glass increases the strength of standard brick and reduces its water absorption and firing time by half.

- Ground glass can replace limestone dust as filler in asphalt concrete. Lake Erie Asphalt Products Inc. (Cleveland, Ohio) used glass regularly in asphalt paving. Company officials claimed that glass was a superior filler and presented no problem in handling.

- Ground glass can act as a synthetic pozzolan (a silicious and aluminous substance that reacts with calcium hydroxide at ordinary temperature in the presence of moisture to form cementatious materials) in portland cement concrete. Broken glass (3/4 in. maximum aggregate size), however, does not seem to have a significant potential for use in structural concrete. A reduction in strength of about 50% was observed when concrete aggregates were replaced by 20% broken glass (8). Further work on the use of waste glass in concrete has been reported by Johnston (9) and Ramachandran (10). These studies concluded that broken glass is susceptible to alkali-aggregate reactions that would reduce concrete strength. Acceptable mixes however could be produced with low alkali-cement.

The majority of the published work on the use of recycled glass in highway construction deals with its application as an ingredient in asphalt concrete hot mix. The resulting material, commonly known as glasphalt, has been pioneered and thoroughly investigated by Malisch et al. (11, 12, 13, 14). Other research was conducted by the Department of Highways, Ontario (DHO) (15), New York City Department of Transportation (NYC-DOT) (16), and Virginia department of Transportation (VDOT) (17). In an extensive literature search by the Connecticut Department of Transportation (ConnDOT) (18), it was reported that trial mixes of glasphalt were field placed in parking lots, driveways, and city streets by at least 19 organizations between October 1969 and June 1972. These sites plus additional sites placed between 1972 and 1988 were documented in Reference (18) and are presented in Table 7.

Physical Properties of Glasphalt

These include Marshall stability, flow, percent voids, resilient modulus, tensile strength, and resistance of exposure to water.

Marshall Stability, Flow, and Voids Content

A number of laboratory investigations were performed in order to determine the mix properties of glasphalt using the Marshall test procedure (11-17). A summary of the crushed glass gradation and mix properties are summarized in Tables 8 and 9. The general conclusion was that crushed glass could be used to replace part of the coarse and fine aggregate in hot mix asphalt concrete and still satisfy design mix specifications in terms of Marshall stability, flow, percent air voids, and percent voids in mineral aggregates (VMA). The final glasphalt mix properties seem to be mostly influenced by the gradation of the crushed glass and the proportion of the glass used. It is preferable to use crushed glass gradation with 3/8 in. maximum size and less than 6% with size smaller than 0.003 in. (No. 200 sieve). Results presented by Hughes (16) indicate that the glass content should be kept below 15% of the total weight of the mix for optimal mix properties. In this range, the influence of increasing glass content on Marshall stability and flow is not significant but would reduce unit weight, VMA, and percent air voids. A new optimum asphalt content may therefore need to be determined for a given glass proportion. Such mixes have been successfully prepared to meet a number of design mix specifications for a wide range of glass content including an all-glass asphalt mix (12). These specifications include those proposed by the Asphalt Institute (12), DHO (15), and NYC-DOT (17).

Resilient Modulus and Tensile Strength

Resilient modulus and split tensile strength were determined for glasphalt specimens as part of the study conducted by Hughes (16). The influence of glass content on resilient modulus and strength was negligible for glass content values less than 15%.

Resistance to Moisture Damage

The presence of glass in asphalt concrete mixtures could result in severe stripping problems if the appropriate anti-stripping additive is not used (12, 15, 16). The affinity of glass to water is more than its affinity to asphalt because of its high silicious composition which could induce loss of adhesion and stripping. Hughes (16) measured the resistance to moisture damage in terms of a tensile strength ratio defined as the ratio of the strength of specimens conditioned by moisture divided by the strength of the unconditioned specimens. Results show that the glass had essentially negligible effect on both the moisture conditioned strength and the tensile strength ratio when 1% hydrated lime was used as an anti-stripping agent. Malisch et al. (12) concluded that severe stripping could be avoided if a slow-setting cationic emulsion was used. Other static stripping tests conducted indicate that not all anti-stripping additives yield satisfactory anti-stripping performance. Hydrated lime, however, is recommended in many glasphalt applications (18).

Field Application and Performance

Available data on placement and performance of glasphalt field test sections are reported by Malisch et al. (14), Bennet (15), and by ConnDOT (18). These data indicate that glasphalt pavements can be placed and compacted using conventional field equipment. The mix placing temperature, however, is of extreme importance to the final quality of the glasphalt layer. Observers at a number of trial installations indicated that hot mix asphalt with crushed glass cooled at a slower rate than conventional asphalt concrete (15, 18, 19). Bennet (15) reported based on field data of two glasphalt trial sections that the optimum placing temperature was around 2750F. Higher temperatures introduced placing problems of instability, tenderness, and pickup. Lower mix temperatures caused difficulty in compaction and permitted too rapid cooling particularly when course thicknesses of 1 in. or less were used.

The trial field sections summarized in Table 7 were for parking lots, driveways, and city streets. The only location where glasphalt was used on a state facility was in the state of Vermont (18). Performance evaluation of these test sections was evaluated by Malisch et al. (14). The performance results after a two year service period indicates that generally there were no problems with pavement deterioration or cracking. Some sections (5 out of 23) showed signs of raveling that seemed to have been caused by studded tires at some locations. Results of friction measurements showed that skid resistance remained adequate for low speed (less than 30 mph) and low traffic volume (less than 6000 vpd). It was also concluded that replacement of coarse aggregate with crushed glass (passing 3/8 in. size) lowered the skid resistance whereas replacement of fine aggregate had no effect on skid resistance.

The NYC-DOT has been using, since 1989, an average of 340,000 tons per year of asphalt concrete hot mix consisting of 20% to 30% reclaimed asphalt pavement, up to 10% crushed glass (percent of total weight of mix), and 5.8% to 6.2% AC 20 asphalt cement (17). The corresponding yearly savings in landfill costs exceed $100 million. Specifications for using crushed glass in asphalt concrete hot mix have been developed by NYC-DOT (Appendix). Skid resistance ratings have been evaluated as ranging from "good" for high speed to "generally satisfactory." Continuous laboratory and field studies have shown that waste glass can be used satisfactorily as an asphalt mix aggregate for paving and resurfacing New York City streets.

LABORATORY INVESTIGATION

A laboratory study was conducted to investigate the potential use of recycled crushed glass as an ingredient in typical asphalt concrete mixtures and in pavement subgrade. Specifically, the influence of glass content on the stability, flow, and voids of asphalt concrete using typical Alaskan grades AC 2.5 and AC 5 was investigated. In addition, compaction characteristics and strength of a glass-silt mixture prepared using different proportions of crushed glass were studied.

Materials

The recycled crushed glass was obtained from Resource Recovery System, Inc. in Essex, CT. The asphalt concrete aggregates were chosen to satisfy Type II asphalt concrete specifications proposed by AKDOT&PF. The subgrade soil used in the study was Fairbanks silt classified as A-4 or ML. The grain size distribution of the crushed glass, concrete aggregates, and the Fairbanks silt is summarized in Table 10. The crushed glass gradation was essentially uniform with approximately 90% of the sizes between 3/8 in. and #8 sieve.

Testing Procedure

A) Glass-asphalt concrete

Glass-asphalt concrete mixtures were prepared using two grades of asphalt cement, AC 2.5, and AC 5, and different proportions of glass varying from 0-15% by dry weight of coarse and fine aggregates. An anti-stripping agent, with trade name Pavebond, was used in all mixes. The amount of anti-stripping agent used in this study was 0.25% by weight of asphalt cement, which is the same quantity recommended by AKDOT&PF for use in their traditional asphalt concrete mixtures. Cylindrical specimens were prepared and tested according to the Marshall Method (ASTM D1559). A compaction energy equal to 75 blows of the standard compaction hammer on both ends of the specimen was used. The optimum asphalt cement content for the AC 2.5 and AC 5 mixtures with no glass was determined to be 6.0% and 6.2% respectively, by dry weight of aggregate, according to standard mix design criteria in ATM-17. These same asphalt cement contents were used for all subsequent mixes prepared with different proportions of crushed glass.

Moisture susceptibility tests were also conducted to determine (1) the potential stripping of the bitumen from glass when the mix is exposed to water; and (2) the influence of extended exposure to water on mix stability. These tests were conducted on asphalt concrete mixtures with 15% crushed glass. The Standard Test Method for Coating and Stripping of Bitumen Aggregate Mixtures (ASTM D1664) was used. This test is based on the observed retained coated area of the aggregate at the end of 16 hr soaking at room temperature (770F). The retained coated area is reported as above or below 95%. The influence of extended exposure to moisture on mix stability was determined by soaking the compacted mix specimens in water for 24 hrs at 1400F prior to Marshall stability testing.

A summary of glass-asphalt concrete mixtures used in the study is presented in Table 11.

B) Glass-silt mixture

Crushed glass was mixed with Fairbanks silt in proportions varying from 0-20% by dry weight of silt. The mixture was then compacted at 12% moisture, which is equal to the optimum moisture content for the silt with no glass, using Modified AASHTO compaction (ASTM D1557). The specimens were soaked for 24 hrs after compaction under a surcharge of 1 psi after which they were tested to determine the load penetration resistance using the California Bearing Ratio (CBR) method (AASHTO T193-91).

Test Results

Results of tests conducted on the glass-asphalt concrete mixtures are presented in Tables 12-13 and Figures 1-6. For a given glass content, the reported results correspond to the average of 3 specimens having Marshall stability values that do not differ by more than 15%. Results indicate that for mixtures with both AC 2.5 and AC 5 having a range of glass content varying between 0-15% by dry weight of aggregate, Marshall stability, flow, and percent air voids satisfy specification limits proposed by AKDOT&PF (i.e. stability greater than 1500 lbs, flow 6-16, and percent air voids 1-5). The influence of glass content on mix density, flow, and VMA seems to be insignificant. Mix stability, however, seems to exhibit a slight increase with increasing glass content up to about 7.5% above which a decrease in stability is observed. The corresponding air voids at this glass content reaches essentially a minimum value in the range of 1% and 1.2%. Results of moisture susceptibility tests show that exposure to moisture did not induce any observed stripping between asphalt and glass particles or cause any loss of stability of compacted glass-asphalt concrete specimens (Table 13). This demonstrates that the type and amount of anti-stripping agent recommended for use by AKDOT&PF in traditional asphalt concrete mixtures seems to be adequate in preventing any adverse effects that could develop due to inclusion of glass as a mix ingredient.

In the case of compacted glass-silt mixtures, a summary of test results is presented in Table 14. The variation of dry density with increasing glass content seems to be insignificant for the glass content range of 0%-20% used in this study. The CBR remains relatively unaffected as the glass content increases up to 15%, beyond which a decrease in CBR is observed (Figure 7). A similar observation for such behavior in terms load-penetration resistance is illustrated in Figure 8.

Results based on the limited number of tests conducted in this study indicate that the use of crushed glass in typical Alaskan asphalt concrete and as an additive to pavement subgrade is possible. The amount of crushed glass added could influence the properties of the asphalt pavement or the subgrade. Limiting the crushed glass content to less than 7.5% in asphalt concrete mixtures and to less than 15% in the silt subgrade is desirable according to the test results obtained. For this recommended range of glass content, a slight improvement in Marshall stability of the asphalt mixtures is observed whereas no significant change in CBR of the glass-silt subgrade occurs.

ECONOMIC FEASIBILITY

In Alaska, there seems to be a great demand by municipalities and the publics for glass recycling. The use of crushed glass in highway construction would serve both urban areas where substantial quantities of glass are produced, and remote rural communities where hauling in gravel for road construction could be prohibitively expensive. However, this would require 1) developing the necessary specifications for the use of crushed glass in highway material design and construction, and 2) providing economic incentives for marketing the crushed glass.

The cost of solid waste disposal is currently estimated at $50 to $100 per ton. This includes the cost of collecting and landfilling. This cost is expected to increase particularly since landfilling is becoming a less attractive solution for solid waste disposal. The cost estimate for crushed glass would include the following components:

- Collection/transport $5-$10 per ton

- Processing/storage $10-$20 per ton

- Crushing to specific gradation $10-$20 per ton

Therefore the total cost per ton of crushed glass will be in the range of $25 to $50. This implies that if glass could be marketed as a potential material in highway construction, savings in the order of $25 to $50 per ton would ensue in addition to environmental benefits associated with less landfilling. Other savings also result because hot mix asphalt containing glass aggregate cools slower than conventional asphalt with no glass because of its higher heat content (19,20). This could turn out to be a major advantage in cold weather paving. Moreover, this slow rate of cooling would increase the rolling time during construction thereby making the glass-asphalt concrete mix according to Abrams (20) worth $10 to $20 per ton more. This could translate into an average saving of about $6 per ton of hot mix with 15% crushed glass and 5% asphalt cement in comparison with a conventional hot mix with the no glass but having the same asphalt content (assuming aggregate at $10 per ton, and crushed glass at $40 per ton).

The use of glass as a substitute aggregate in base course, subbase course, and subgrade is not economically feasible, if no substantial increase in strength and stiffness results. Crushed glass costs on the average $40 per ton whereas the cost of aggregates is about $10 per ton. In this case it may be necessary for State agencies to provide marketing incentives that will make the use of crushed glass in highway construction a possible economic alternative. These incentives could include for example, 1) subsidizing collection, processing, and crushing operations of recycled glass by municipalities, 2) development materials specifications for crushed glass, and 3) promote the use of crushed glass by contractors through proper prioritization of bids that include crushed glass as an alternative material in highway construction.

SUMMARY

1. Crushed glass could be used as an aggregate in asphalt concrete mixtures that satisfy general mix design criteria. This conclusion is based on available data in the literature and on results of a laboratory investigation on the use of crushed glass with typical Alaskan AC 2.5 and AC 5 asphalt mixtures. This laboratory study indicates that up to 15% of crushed glass passing 3/8 in. sieve could be used and satisfy Alaskan mix specifications. Optimum results, however, were obtained for glass content that did not exceed 7.5%.

2. Results of the laboratory investigation show that the most significant influence of glass content is on mix stability and air voids. Optimum glass content corresponding to maximum stability occurs at about 7.5% for both the AC 2.5 and AC 5 mixes. Air voids reach a minimum of about 1.2% for a glass content between 5% and 7.5%.

3. The AC 2.5 and AC 5 glass-asphalt concrete mixtures showed no evidence of stripping or loss of stability under extended exposure to moisture. These mixtures were prepared using Pavebond anti-stripping agent (0.25% by weight of asphalt cement). This is generally recommended by AKDOT&PF for use in typical Alaskan asphalt concrete mixtures.

4. Glass-silt mixtures prepared using varying proportions of glass exhibited no change in compaction characteristics or significant change in CBR for glass contents up to 15% by dry weight of silt. Higher glass content could result in loss of the mix CBR.

5. Glass-asphalt concrete mixtures have a tendency to retain more heat and therefore exhibit a slower cooling rate than similar mixtures with no glass. If this behavior is accounted for in construction (e.g. increased rolling time, less fuel, thicker pavement sections, cold weather paving) the use of glass-asphalt concrete mixtures could be made more cost effective than conventional asphalt concrete mixtures. Approximate estimates indicate that the savings per ton of glass-asphalt concrete could as much as $6 per ton.

6. Although more glass could be used in base, subbase, and subgrade than in asphalt concrete, the use will not be cost effective unless the addition of glass results in significant increase in stiffness and strength. The laboratory study on the glass-silt mixtures does not indicate any significant improvement. In this case economic incentives should be provided by State agencies to promote the use of crushed glass, particularly since its average cost is about $40 per ton in comparison with $10 per ton for aggregates. These incentives could include development of material specifications criteria for use of crushed glass, subsidizing the collection, processing, and crushing of waste glass, and establishing prioritization criteria for bids that include glass as an alternative material in highway construction.

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APPENDIX

Hot Mix Asphalt Concrete Pavement with Crushed Glass
Implemented by New York City Department of Transportation

HOT MIX ASPHALT CONCRETE PAVEMENT WITH CRUSHED GLASS

SCOPE. This specification covers the requirements for the addition of crushed glass to asphalt concrete mixes. The provisions of Section 403 - Hot Mix Asphalt Concrete Pavement shall apply except that the Contractor has the option of blending crushed glass in the following mixes:

Asphalt Concrete - Type 1 Base
Asphalt Concrete - Type 3 Binder
Asphalt Concrete - Type 6 Top
Asphalt Concrete - Type 7 Top
Asphalt Concrete - Truing and Leveling

If the Contractor chooses the crushed glass option, the following modifications to the Standard Specifications shall apply:

MATERIAL REQUIREMENTS

A. Crushed glass. Crushed glass shall be subject to the approval of the Regional Materials Engineer prior to its use. The crushed glass shall contain no more than 1% (by weight) contaminates and shall meet the following gradation:

Sieve Size	% Passing
3/8"	100
1/4"	90-100
No. 20	0-20

Note: The gradation requirements may be modified upon approval of the Regional Material Engineer.

B. Composition of Mixture. Crushed glass may be included in the mixture up to 5%, maximum, of the total aggregate weight. The crushed glass, aggregate and added asphalt cement shall meet the requirements specified in Table 401-1, Composition of Bituminous Plant Mixtures, for aggregate gradation, asphalt cement content, asphalt cement grade and temperature range.

CONSTRUCTION DETAILS

Plant Equipment. The crushed glass shall be proportioned from a separate feed bin approved by the Regional Materials Engineer. In addition, all requirements pertaining to aggregate shall apply to crushed glass including the equipment requirements for automatic proportioning and recording stipulated for aggregate in subsection 401-3.02.

METHOD OF MEASUREMENT. The provisions of subsection 401-4 shall apply.

BASIS OF PAYMENT. The provisions of subsection 403-5 shall apply.

NYC DOT Construction Division } no: 718/482-4601

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TABLE 1. Daily Per Capita Waste Generation Rates for Coastal Alaska Communities (1).

Community	Rate lb/ cap/day	Method used to estimate
Petersburg	6.6	Weight Scale, six months
Juneau	5.3	Local operator estimate
Cofman Cove	4.8	Extrapolate from other community
Craig	6.1	Local officials
Hollis	4.8	Extrapolate from other community
Hydaburg	6.8	Local officials
Kasaan	4.6	Local officials
Klawock	4.6	Local officials
Thorne Bay	11.7	Local officials
Whale Pass	4.8	Extrapolate from other community
Unalaska	27.0	Truck count
NW Kenai Peninsula Borough	6.2	Weight Study

TABLE 2. Daily Per Capita Waste Generation Rates for Urban Alaska Communities (1).

Community	Rate lb/ cap/day	Method used to estimate
Anchorage	6.96	Operator records + 10% estimated diversion to recycling
Fairbanks	4.3	Calculated from borough records
Juneau	5.3	Local operator estimate

TABLE 3. Daily Per Capita Waste Generation Rates for Roaded Interior Alaska (1).

Generation rate (lb/cap/day)	
Resident, winter	4.5
Resident, summer	5.2
Transient (per visitor day)	1.8

TABLE 4. Alaska Communities With Populations Greater than 1,000 (1).

Community	Population	Community	Population
Anchorage	226,338	Barrow	3,469
Fairbanks	72,454	Petersburg	3,207
Juneau	26,751	Unalaska	3,089
Ketchikan	13,828	Palmer	2,866
Sitka	8,588	Kotzebue	2,751
Kodiak	6,365	Nikiski	2.743
Kenai	6,327	Seward	2,699
Eielson (base)	5,266	Kodiak (base)	2,025
Adak (base)	4,633	Wrangell	2,479
Bethel	4,627	Haines	2,117
Valdez	4,068	Cordova	2,579
Wasilla	4,028	Dillingham	2,017
Homer	3,660	Metlakatla	1,469
Nome	3,500	Craig	1,260
Soldotna	3,482	Delta Jct.	1,052

TABLE 5. Characterization of Municipal Solid Waste in the United States (5).

Component	Percent
Paper and Cardboard	41.0
Yard Waste	17.9
Metals	8.7
Glass	8.2
Rubber, Leather Textiles, Wood	8.1
Food Waste	7.9
Plastics	6.5

TABLE 6. Projected Solid Waste Production and Waste Glass in Alaska Urban Communities for Fiscal Year 1993.

Community	Total Solid Waste (tons)	Waste Glass (tons)
Anchorage	350,000	28,700
Fairbanks	70,000	5,740
Juneau	25,000	4,000

TABLE 7. Glasphalt Pavements Placed in the United States and Canada (Listed by Placement Date)(16).

Location	Size	Thickness (in.)	Percent Glass	Date Placed	Maximum Size Glass (in.)	Organization
Toledo, OH (plant entrance)	18 x 50 ft	2		Oct. 4, 1969	N/A	Owens-Illinois
Winchester, IN (parking lot)	1500 sf	1 1/2		June 8, 1970	N/A	Anchor Hocking
Rolla, MO (campus road)	20 x 525 ft	1 1/2	63	July 10, 1970	3/4	Univ. of Missouri-Rolla U.S. EPA, GCMI
Scarborough, Canada (residential street)	26 x 600 ft	1	65	Oct. 17, 1970	1/2	Glass Container Corp. of Canada
Fullerton, CA (industrial park street)	30 x 600 ft	3	63	Oct. 26, 1970	1	Glass Container Corp.
Brockway, PA (parking lot)	14,400 sf	1 5	54	Oct. 28, 1970	1/2	Brockway Glass Co.
New Orleans, LA (parking lot)	10,000 sf	2		Feb. 1, 1971	N/A	LA Coca Cola Co.
Des Moines, IA (fairgrounds road)	12 x 300 ft	1		May 15, 1971	N/A	Keep Iowa Beautiful State and City Agencies
San Francisco, CA (parking lot)	7,500 sf	1 1/2		May 20, 1971	N/A	Lucky Lager Breweries

TABLE 7. Glasphalt Pavements Placed in the United States and Canada (Listed by Placement Date)(16).

Location	Size	Thickness (in.)	Percent Glass	Date Placed	Maximum Size Glass (in.)	Organization
Rolla, MO (campus road)	12,000 sf	2		May 27, 1971	N/A	Univ. of Missouri-Rolla U.S. EPA, GCMI
Burnaby, BC, Canada (city street)	20 x 700 ft	1 1/2	67	June 18, 1971	1/2	Municipality of Burnaby Dominion Glass Co.
Big Flats, NY (plant entrance)	9 x 58 ft	1 1/2		July 6, 1971	N/A	Thatcher Glass Co.
Omaha, NE	60 x 280 ft	1	20	Aug. 6, 1971	3/8	Keep Nebraska Beautiful City of Omaha
Azusa, CA (city street)	40 x 300 ft	1 1/2		Aug. 1971	N/A	Miller Brewing Co. City of Azusa
Holland, MI (parking lot)	50,000 sf	1 1/2		Sept. 28, 1971	N/A	Brooks Products City & Local Groups
Albuquerque, NM (parking lot)	40 x 200 ft	1 1/2		Sept. 1971	N/A	Keep New Mexico Beautiful City Groups
Toledo, OH (city street)				Sept. 1971	N/A	Owens-Illinois
surface course	24 x 1000 ft	1 1/2				State of Ohio
levelling course	24 x 800 ft	1 1/2				City of Toledo
base course	24 x 600 ft	3				
subgrade	24 x 200 ft	6				
South Bulington, VT	22 x 2200 ft	1	15	June 1972	3.8	Vermont Dept. of

TABLE 7. Glasphalt Pavements Placed in the United States and Canada (Listed by Placement Date)(16).

Location	Size	Thickness (in.)	Percent Glass	Date Placed	Maximum Size Glass (in.)	Organization
(state highway)						Highways
Royal Oak, MI (parking lot)	1.2 acre			Oct. 1972	N/A	Royal Oak Beautification Council
Baltimore, MD (20 city streets)	1-2 blocks each 12-40 ft wide	variable 1 1/2 - 2	30-40	1971-88	3/4	City of Baltimore
Brooklyn, NY Manhattan, NY	4 locations variable		20	1988	3/8	City of New York
Oyster Bay, NY	0.8 miles		15	1988	3.8	Town of Oyster Bay, NY

TABLE 8. Typical Gradiation for Recycled Waste Glass.

Sieve Size (in.)	Percent Passing Ref (12)	Ref (15)	Ref (16)	Ref (17)
1/2	100	100	100	-
3/8	88	76	98	100
1/4	-	-	-	85
#4	67	40	70	-
1/8	-	-	-	53.2
#8	48	22	32	-
#16	37	10	19	-
#20	-	-	-	17.1
#30	28	5	10	-
#40	-	-	-	8.8
#50	18	2.5	6	-
#80	-	-	-	3.6
#100	11	1.5	4	-
#200	6.3	0.5	2.9	1.2

TABLE 9. Typical Glasphalt Mix Properties

Source	Mix Aggregates Coarse	Fine	Glass	Ashpalt Cement %	Grade	Density (lb/cu ft)	Marshall Stability (lbs)	Flow	% Air Voids	VMA	Compaction
Ref (10)	-	-	95	5.0	(85-100 pen)	138.7	839	7.4	4.5	15.57	50 blows
Ref (15)*	-	56	37	5.0	(85-100 pen)	-	800-880	10.4-13.0	2.2	13.8	50 blows
Ref (16)*	-	84	15	6.2	AC-20)	152	1970	12	3.5	18.0	50 blows
Ref (16)*	-	84	15	5.75	(AC-20)	151	2100	10.5	4.0	18.0	75 blows
Ref (17)	63.8	30	0	6.2	(AC-20)	-	1500	9	2-5	-	50 blows
Ref (17)	48.8	25	20	6.2	(AC-20)	-	1580	11	2.5	-	50 blows
Ref (17)	53.8	20	20	6.2	(AC-20)	-	1925	16	2.5	-	50 blows

Note: * 1-2 percent of hydrated lime was used as anti-stripping agent.

TABLE 10. Grain Size Distribution of Materials Used.

Sieve Size (in.)	Percent Passing Asphalt Concrete Aggregate	Crushed Glass	Fairbanks Silt
3/4	100	-	-
1/2	86	100	-
3/8	75	96	-
#4	56	38	-
#8	39	7.7	-
#40	23	1.2	100
#100	-	-	85.9
#200	3.5	0.2	65.8
0.002	-	-	61.4
0.0012	-	-	37.9
0.00047	-	-	16.9
0.00024	-	-	11.7
0.00008	-	-	9

TABLE 11. Summary of Glass-Asphalt Concrete Mixtures Used.

% Glass % Glass by % Glass % Asphalt
Sample replacing Total Wgt. by Total by Total Asphalt Name Aggregate of Mix
Aggr. Mix Wgt. Mix Wgt. Grade

G00A2	0.0	0.0	0.00	5.663	AC2.5
G05A2	5.0	2.5	2.36	5.685	AC2.5
G10A2	10.0	5.0	4.76	5.780	AC2.5
G15A2	15.0	7.5	7.15	5.727	AC2.5
G20A2	20.0	10.0	9.53	5.700	AC2.5
G20A2	30.0	15.0	14.29	5.735	AC2.5
G00A5	0.0	0.0	0.00	5.837	AC5
G05A5	5.0	2.5	2.35	5.877	AC5
G10A5	10.0	5.0	4.76	5.847	AC5
G15A5	15.0	7.5	7.13	5.840	AC5
G20A5	20.0	10.0	9.51	5.850	AC5
G30A5	30.0	15.0	14.27	5.847	AC5
SG00A2	0.0	0.0	0.0	5.690	AC2.5
SG00A5	0.0	0.0	0.0	5.853	AC5
SG30A2	30.0	15.0	14.29	5.697	AC2.5
SG30A5	30.0	15.0	14.27	5.850	AC5

Note: An "S" before a Sample Name denotes a Stripping Test.

TABLE 12. Summary of Glass-Asphalt Concrete Test Results

Marshall Method (ASSHTO T245/ASTM D1559)
Density-Voids Calculations for HMA
Number of Blows/side: 75

	Specific		%	Specific		% of Total Mix				% Voids	Maximum		
Sample Name	Gravity of Mix Aggr.	Specific Gravity of Asph.	Asphalt by Mix Weight	Gravity of AC (g/cm3)	Unit Wgt. of AC (lb/cu.ft.)	Volume of Mix Aggr.	Volume of Asphalt	Volume of Air Voids	% VMA	filled with Aspahlt	Theor. Specific Gravity	Average Stability (lbs)	Average Flow
G00A2	2.624	1.005	5.663	2.366	147.64	85.06	13.33	1.61	14.94	89.22	2.405	1634	9.0
G05A2	2.622	1.005	5.685	2.374	148.14	85.39	13.43	1.18	14.61	91.92	2.402	1730	9.4
G10A2	2.620	1.005	5.780	2.371	147.95	85.27	13.64	1.09	14.73	92.60	2.397	1791	10.0
G15A2	2.618	1.005	5.727	2.366	147.64	85.20	13.48	1.32	14.80	91.08	2.398	1789	9.0
G20A2	2.617	1.005	5.700	2.355	146.95	84.86	13.36	1.78	15.14	88.24	2.398	1522	8.8
G30A2	2.613	1.005	5.735	2.364	147.51	85.28	13.49	1.23	14.72	91.64	2.393	1558	10.0
G00A5	2.624	1.008	5.837	2.367	147.70	84.94	13.71	1.35	15.06	91.04	2.399	1813	9.6
G05A5	2.622	1.008	5.877	2.358	147.14	84.65	13.75	1.60	15.35	89.58	2.396	1781	9.0
G10A5	2.620	1.008	5.847	2.361	147.33	84.85	13.70	1.45	15.15	90.43	2.396	1724	8.7
G15A5	2.618	1.008	5.840	2.366	147.64	85.10	13.71	1.19	14.90	92.01	2.394	1982	10.0

TABLE 12. Summary of Glass-Asphalt Concrete Test Results

Marshall Method (ASSHTO T245/ASTM D1559)
Density-Voids Calculations for HMA
Number of Blows/side: 75

Sample Name	Specific Gravity of Mix Aggr.	Specific Gravity of Asph.	% Asphalt by Mix Weight	Specific Gravity of AC (g/cm3)	Unit Wgt. of AC (lb/cu.ft.)	% of Total Mix Volume of Mix Aggr.	Volume of Asphalt	Volume of Air Voids	% VMA	% Voids filled with Aspahlt	Maximum Theor. Specific Gravity	Average Stability (lbs)	Average Flow
G20A5	2.617	1.008	5.850	2.361	147.33	84.94	13.70	1.36	15.06	90.97	2.394	1814	10.0
G30A5	2.613	1.008	5.847	2.348	146.52	84.60	13.62	1.78	15.40	88.44	2.391	1611	10.0
SG00A2	2.624	1.005	5.690	2.363	147.45	84.93	13.38	1.69	15.07	88.79	2.404	1831	8.5
SG00A5	2.624	1.008	5.835	2.362	147.39	84.75	13.72	1.53	15.25	89.97	2.399	1892	12.0
SG30A2	2.613	1.005	5.697	2.347	146.45	84.70	13.30	2.00	15.30	86.93	2.395	1469	10.0
SG30A5	2.613	1.008	5.850	2.351	146.70	84.71	13.64	1.65	15.29	89.21	2.390	1610	10.4

Note: Samples "G05A2" is prepared using AC2.5 Asphalt and 5% Glass "S" before a sample name denotes a Stripping Test Specific Gravity of Crushed Glass = 2.51 Results for a given sample are the average of three specimens for a given Asphalt Cement and Crushed Glass content.

TABLE 13. Summary of Moisture Susceptibility Test Results.

Moisture Susceptibility Test Results

Sample Name	Asphalt Grade	% Asph. by Total Mix Wgt.	% Glass by Total Mix Wgt.	Average Stability (lbs) Soaking for 40 mns @ 140F	Soaking for 24 hrs @ 140F	Coating & Stripping Test (ASTM D1664)
G00A2	AC2.5	5.663	0.00	1634	-	-
SG00A2	AC2.5	5.690	0.00	-	1831	-
G00A5	AC5	5.837	0.00	1813	-	-
SG00A5	AC5	5.853	0.00	-	1892	-
G30A2	AC2.5	5.735	14.29	1558	-	-
SG30A2	AC2.5	5.697	14.29	-	1469	>95%
G30A5	AC5	5.847	14.27	1611	-	-
SG30A5	AC5	5.850	14.27	-	1610	>95%

Note: A "Mix" consists of a mixture of Aggregate, Glass and Asphalt Cement.
An "S" before a Sample Name denotes a Stripping Test.
A ">95%" Stripping Test result means an estimated coated area of "above 95%."

TABLE 14. Summary of Test Results for Different Crushed Glass-Silt Combinations.

Crushed Glass (%)	Dry Unit Weight (pcf)	Compaction Moisture Content (%)	Moisture Content After Test (%)	CBR (%)
0	115.3	11.9	20.0	17
5	117.8	12.9	18.8	18
10	117.8	12.2	17.0	18
15	119.4	12.2	16.8	19
20	118.4	11.5	15.4	9

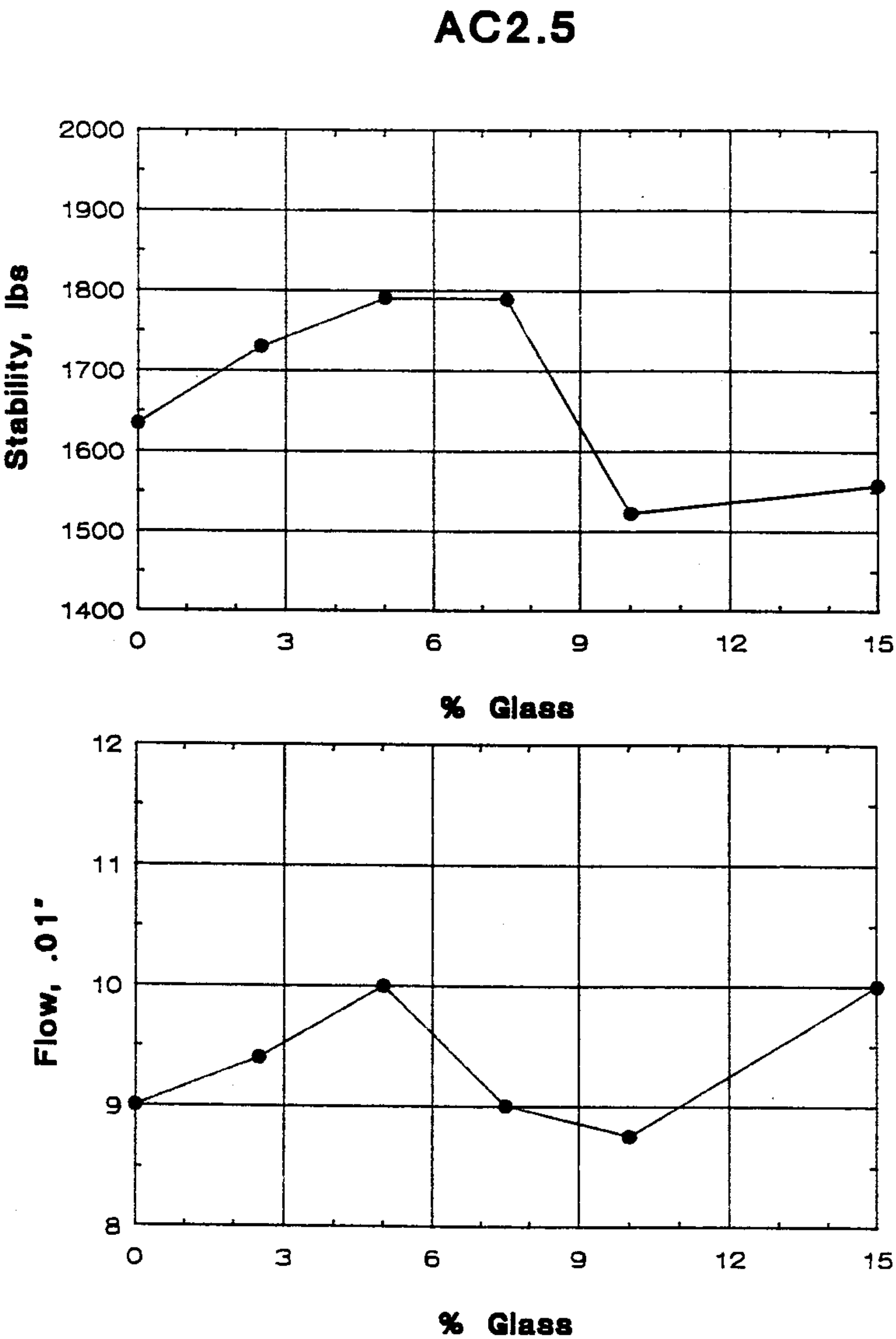

FIGURE 1. Influence of Crushed Glass Content on Stability and Flow for AC2.5 Grade Asphalt.

AC2.5

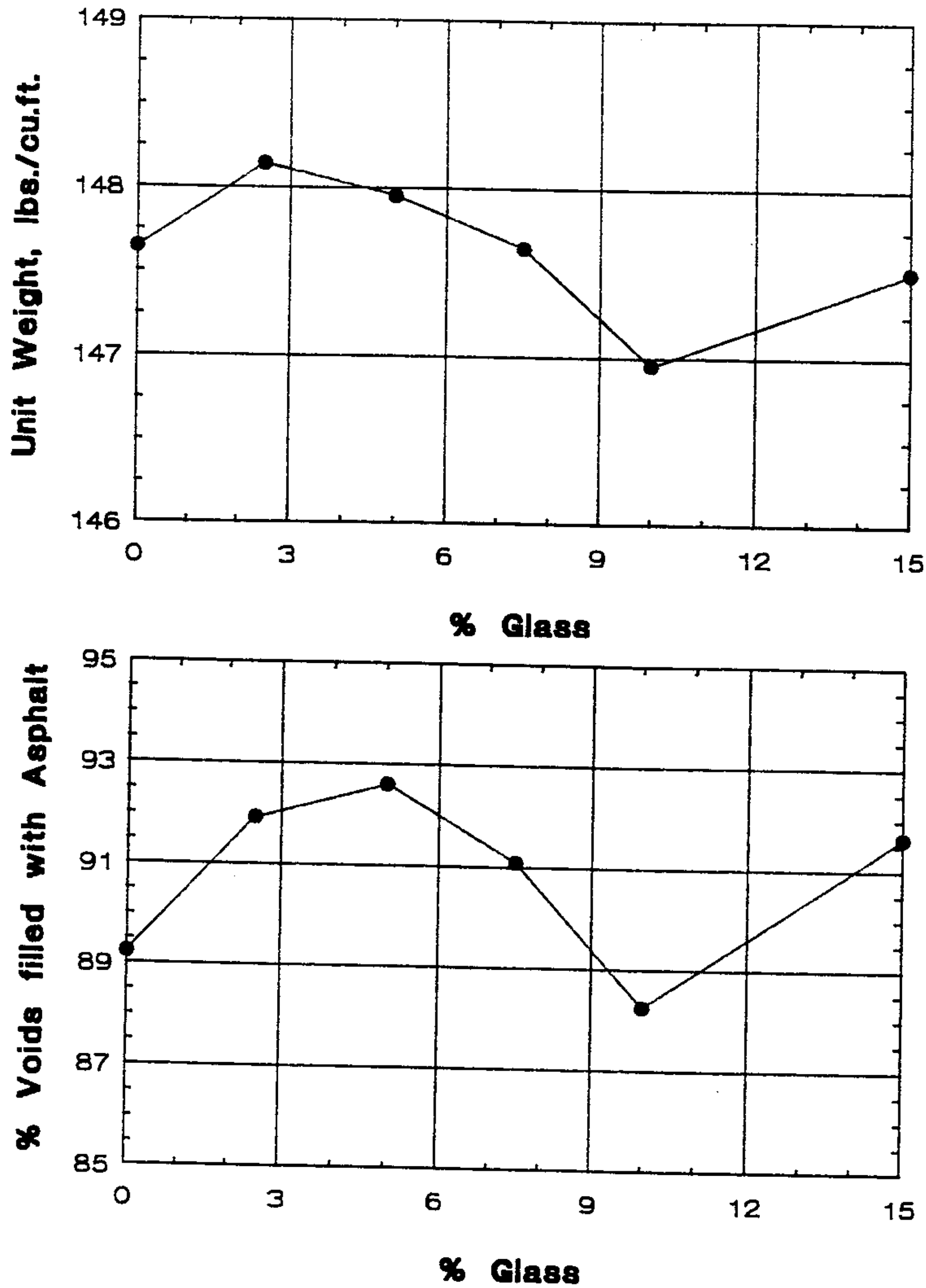

FIGURE 2. Influence of Crushed Glass Content on Unit Weight and % Voids filled with Asphalt for AC2.5 Grade Asphalt.

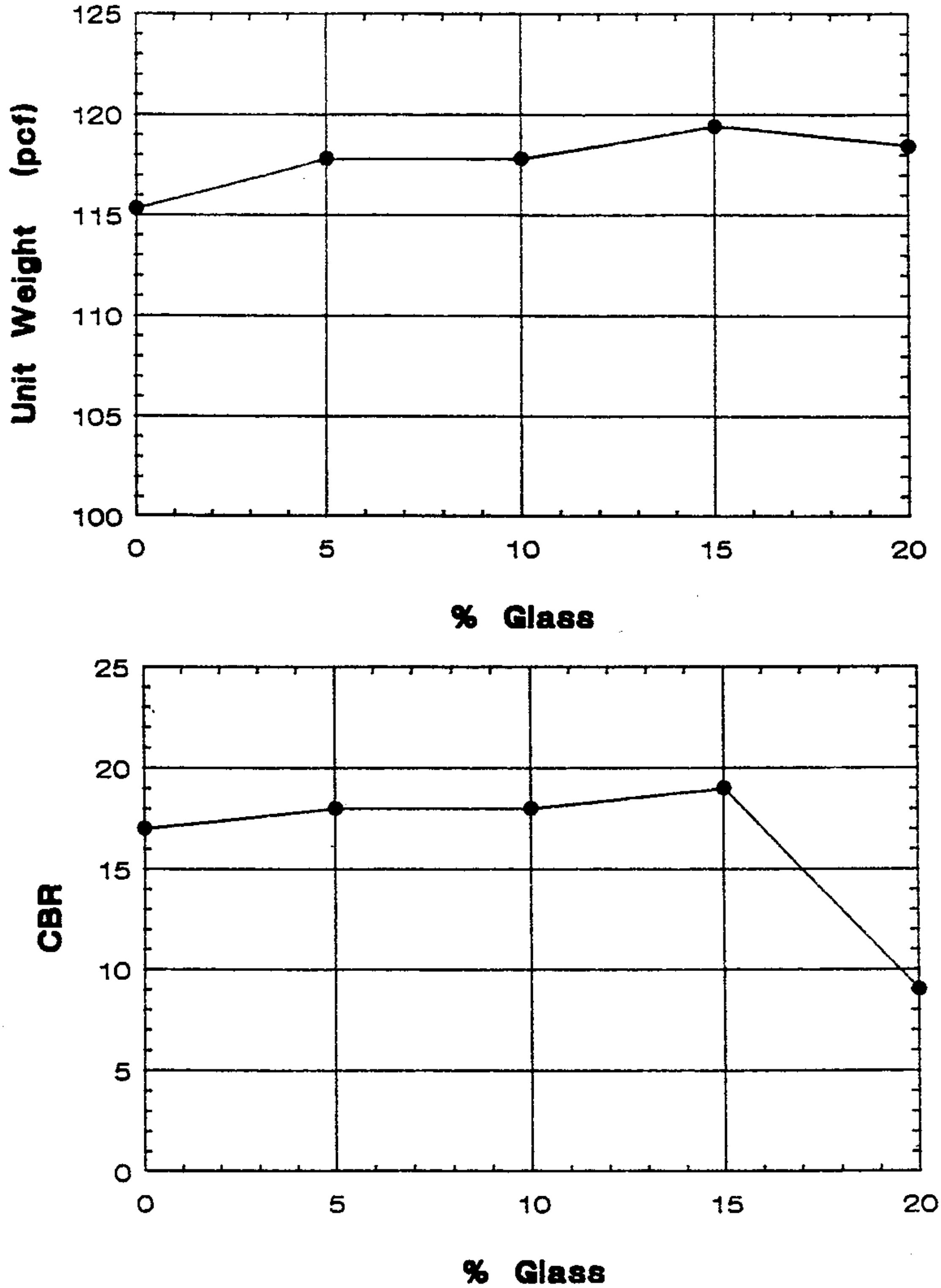

FIGURE 7. Variation of Unit Weight and CBR of Crushed Glass-Silt Mixtures.

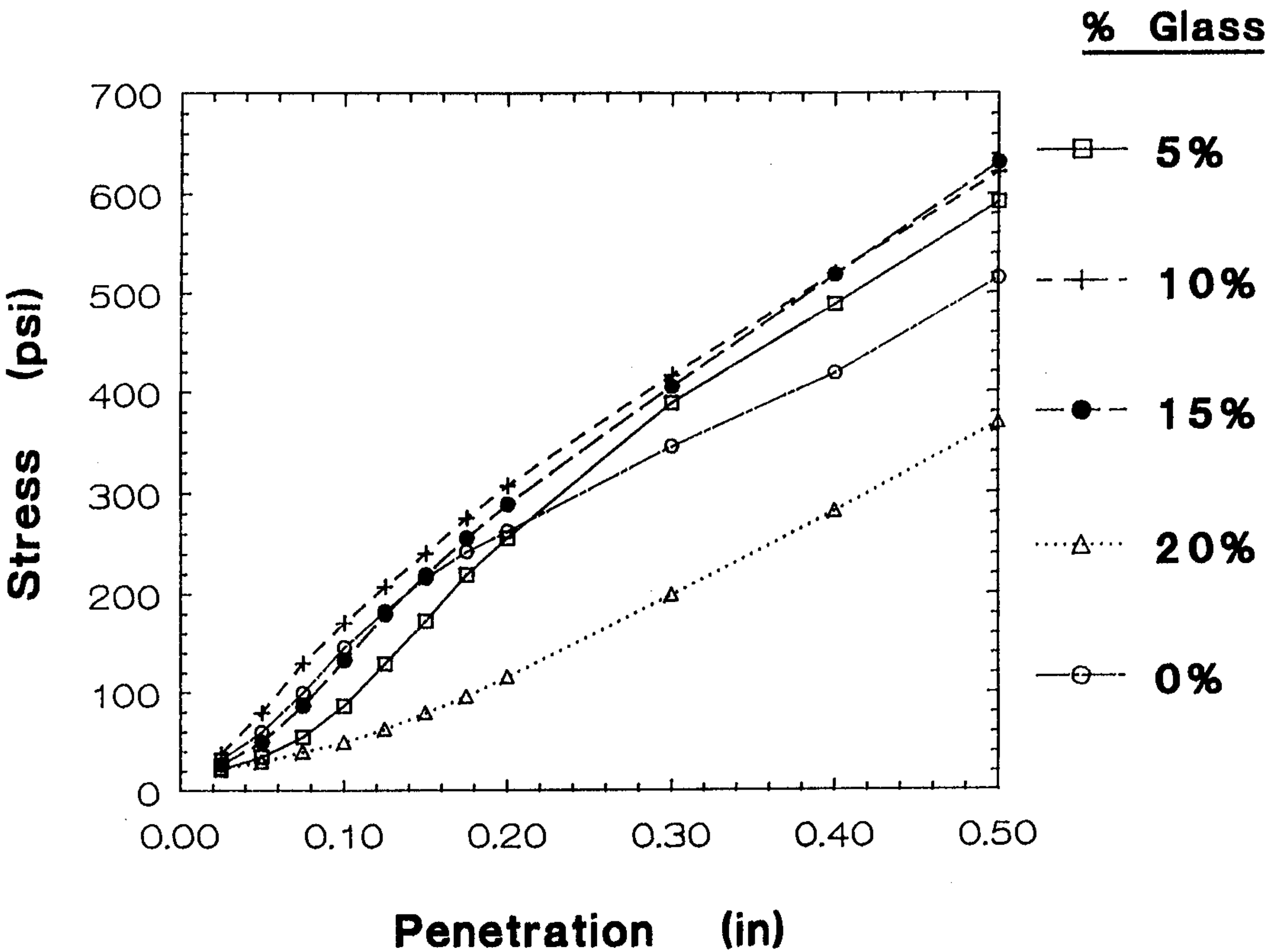

FIGURE 8. Resistance to Penetration of Compacted Crushed Glass-Silt Mixtures.

AC2.5

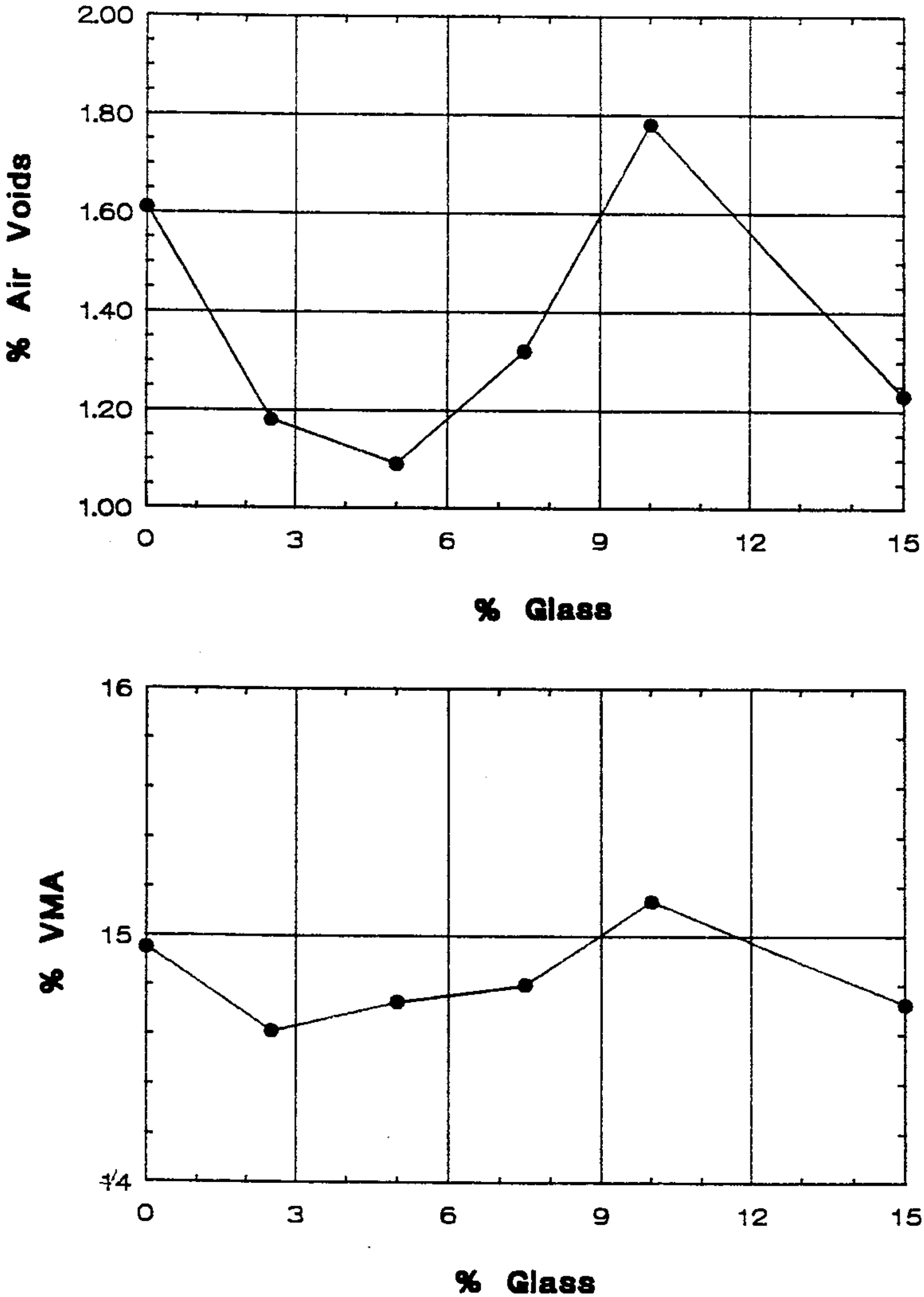

FIGURE 3. Influence of Crushed Glass Content on % Air Voids and % VMA for AC2.5 Grade Asphalt.

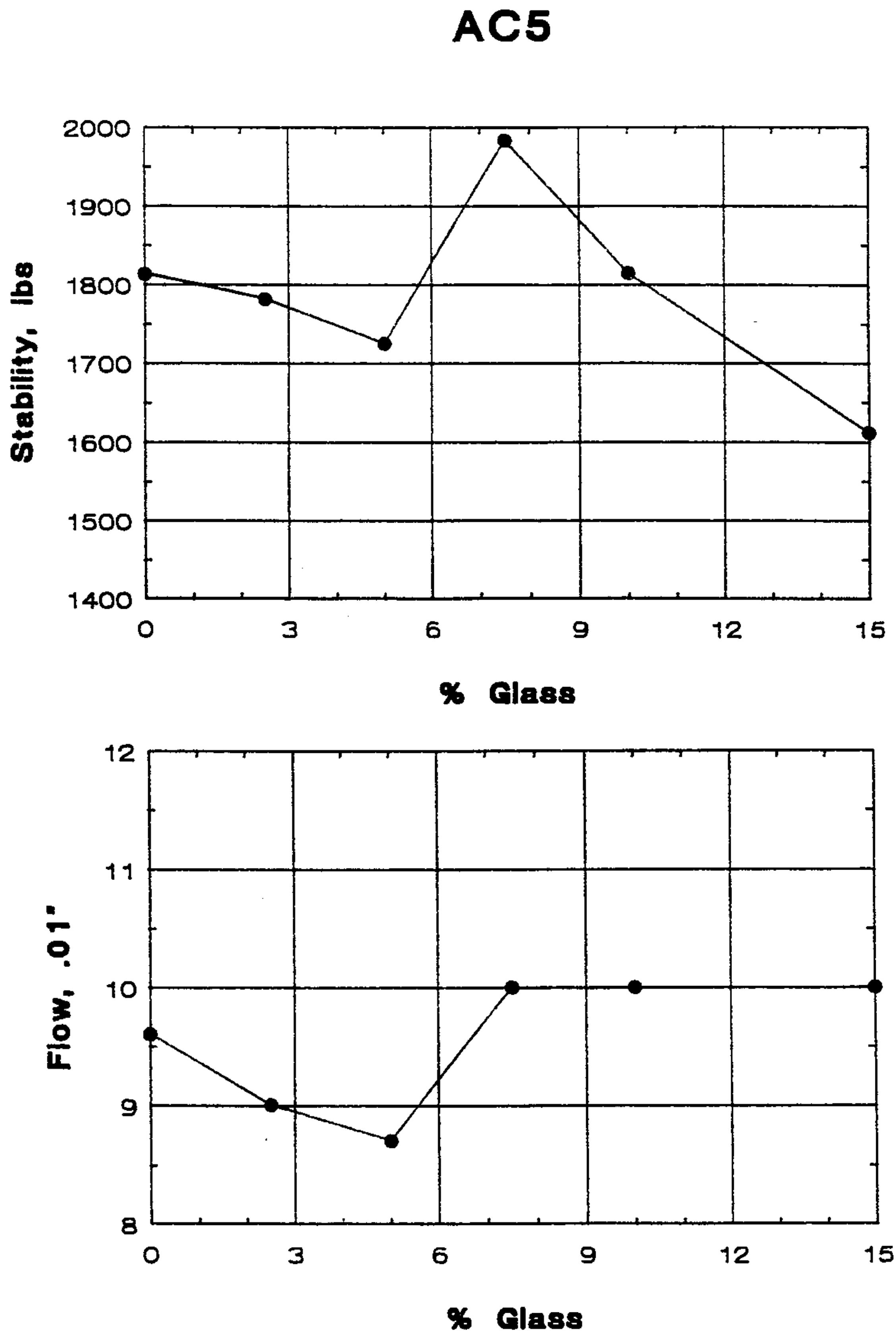

FIGURE 4. Influence of Crushed Glass Content on Stability and Flow for AC5 Grade Asphalt.

AC5

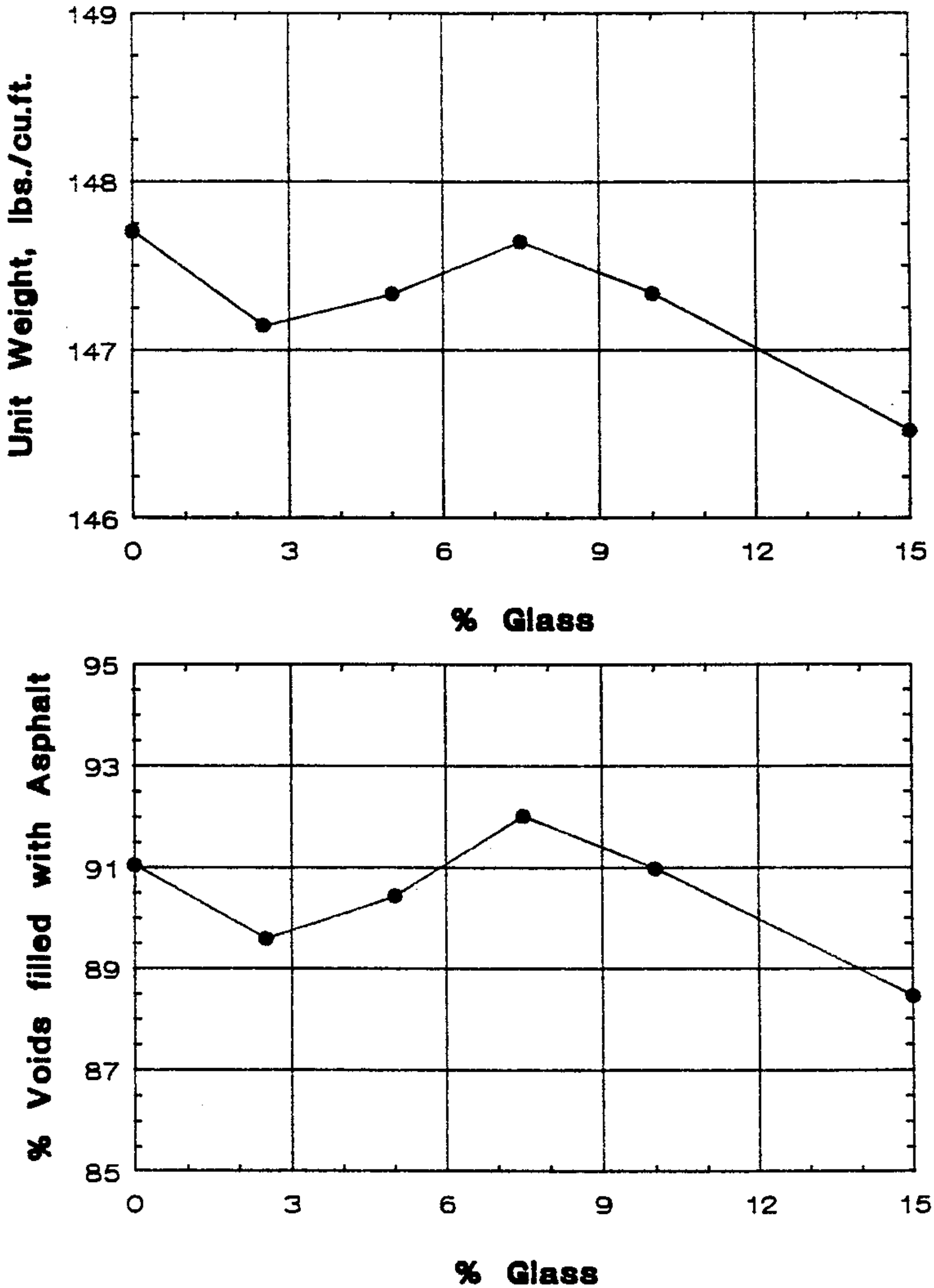

FIGURE 5. Influence of Crushed Glass Content on Unit Weight and % Voids filled with Asphalt for AC5 Grade Asphalt.

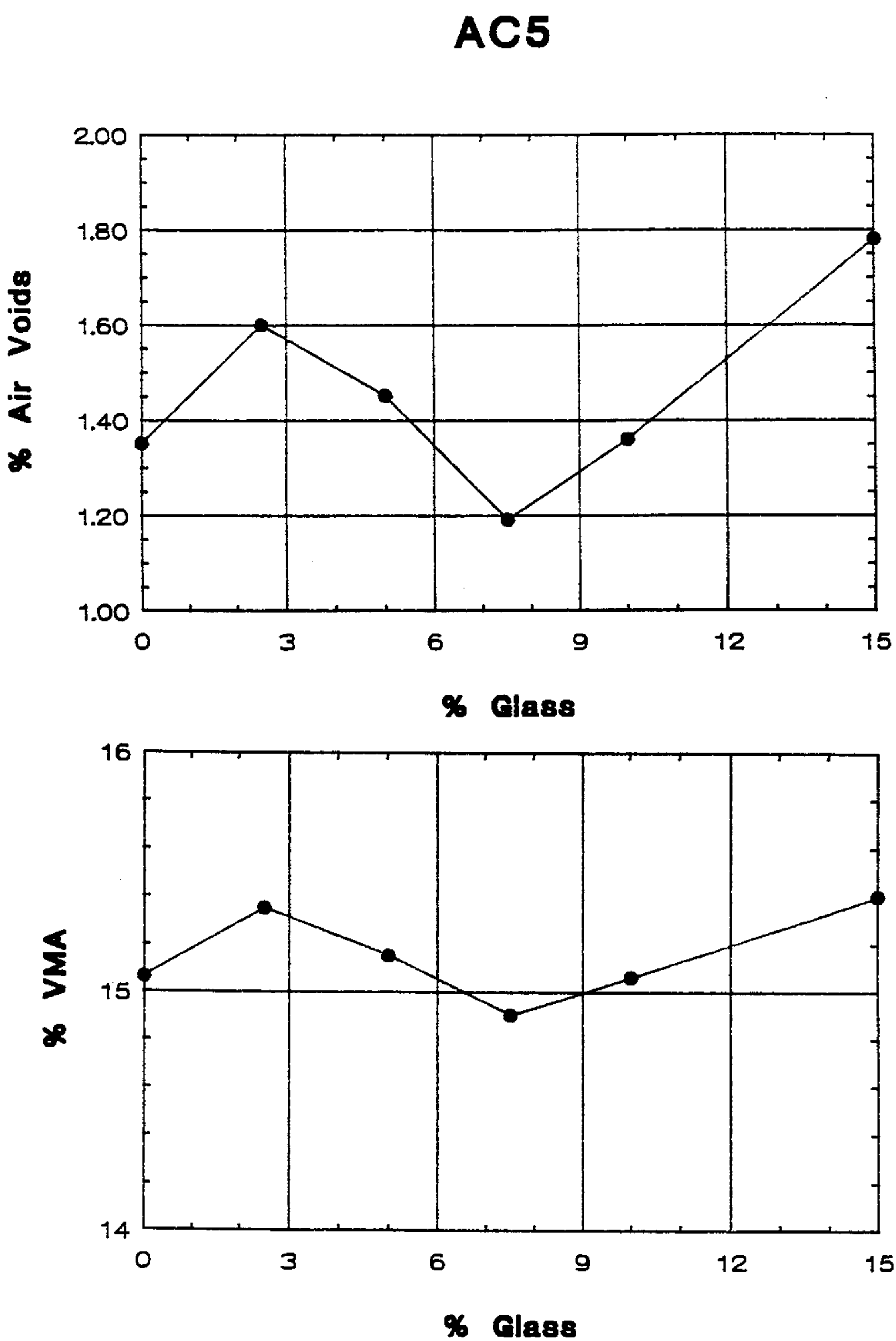

FIGURE 6. Influence of Crushed Glass Content on % Air Voids and % VMA for AC5 Grade Asphalt.