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Flexible Pavement Mixture Design Using Reclaimed Asphalt Concrete

Asphalt Inst., College Park, MD

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FLEXIBLE PAVEMENT MIXTURE DESIGN USING RECLAIMED ASPHALT CONCRETE

US Department of Transportation

Federal Highway Administration

Research, Development, and Technology

Turner Fairbank Highway Research Center
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McLean, Virginia 22101

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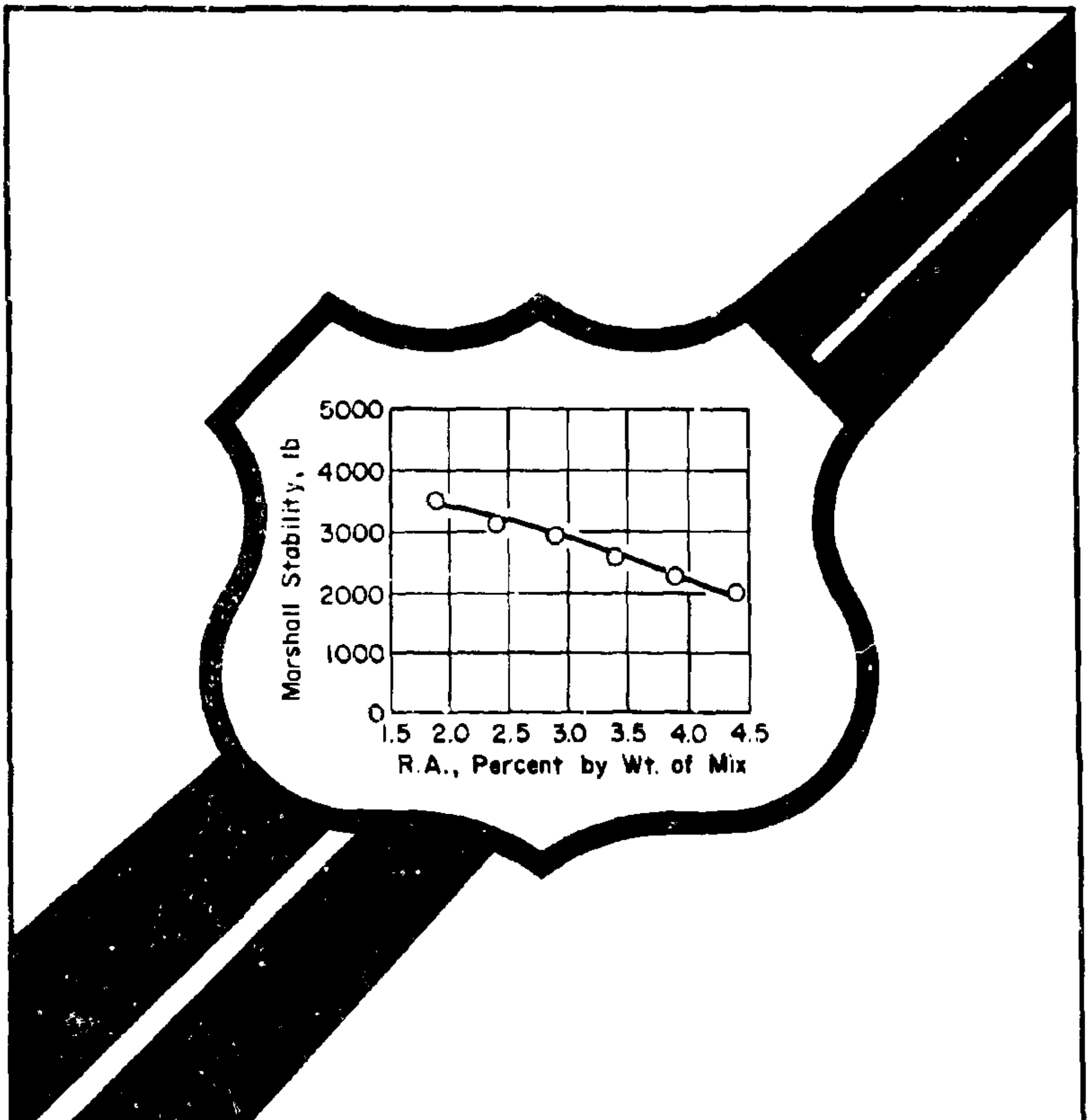

FOREWORD

This report, FHWA/RD-84/088, presents a summary of the research conducted to develop a design procedure for hot-mix recycled asphalt concrete using Marshall and Hveem test apparatus. The procedure includes sampling plans and tentative design criteria based on studies of materials and cores from five recycling projects.

The design procedures are summarized in the Appendices. Two different procedures for proportioning mixes were investigated. In one method the ratio of the new aggregate to recovered aggregate was held constant as the ratio of the new asphalt or recycling agent to aged asphalt was varied. In the other method, the ratio of the new asphalt or recycling agent to aged asphalt was held constant as the ratio of the new aggregate to recovered aggregate was varied. The former method was determined to be more practical and is recommended by the report.

The contributions of the five State transportation agencies, namely California, New Mexico, North Carolina, Utah, and Virginia, who provided materials, pavement cores, and information on the recycling construction projects are gratefully acknowledged.

This report is being widely distributed. Copies for State highway agencies are disseminated through the division offices.

Richard E. Hay, Director
Office of Engineering and
Highway Operations
Research and Development

NOTICE

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16. Abstract

Statistical sampling plans were developed for obtaining samples of reclaimed asphalt concrete from the roadway prior to recycling, from trucks transporting processed reclaimed asphalt concrete, and from stockpiles of materials to be used for hot-mix recycling. The plans were tested on five recycling projects.

Physical and chemical tests were run on aged asphalts, salvaged binder from reclaimed asphalt concrete, recycling agents, and blends of the materials. It was found that for a wide range of typical asphalts and recycling agents, an asphalt viscosity blending chart could be used to establish proportions of aged asphalts and recycling agents to produce a blend of materials generally meeting standards.

Detailed test procedures, based on National Cooperative Highway Research Program Reports 192 and 246, "Predicting Moisture-Induced Damage to Asphaltic Concrete," were developed for determining the effects of water and freeze-thaw on the indirect tensile strength of recycled asphalt mixtures. Use of this test on materials from five recycling construction projects indicated that the procedures should be useful for determining moisture damage susceptibility.

Detailed procedures were developed for designing hot-mix recycled paving using Marshall and Hveem test apparatus. Tentative mix design criteria are proposed based on studies of the mix design procedures using materials from five recycling projects and from tests on cores from these projects.

17. Key Words: mixture design, reclaimed asphalt concrete, Marshall Method, Hveem Method, statistical sampling, salvaged binder, moisture damage, recycling, design criteria

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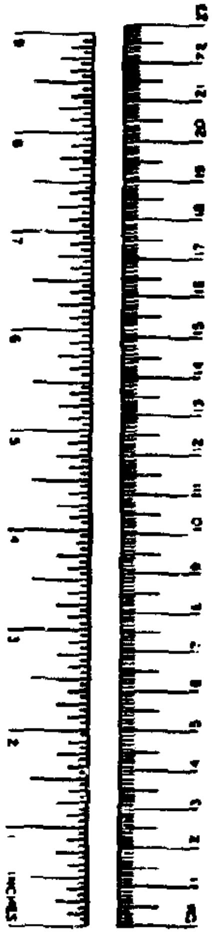
METRIC CONVERSION FACTORS

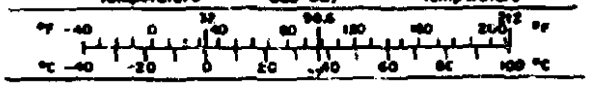
APPROXIMATE CONVERSIONS FROM METRIC MEASURES

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



APPROXIMATE CONVERSIONS FROM METRIC MEASURES

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	36	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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INTRODUCTION

Recycling Hot-Mix Design Methods

The Marshall and Hveem mix design methods are widely used by road building agencies for designing hot-mixed, dense-graded asphalt concrete made with paving grade asphalt cement. These methods and their criteria for the various mechanical, density and void properties have proven satisfactory for designing mixtures containing the types of materials for which the various test properties and design criteria have been correlated with pavement performance. If differences between materials and processes used for recycled and conventional mixes are taken into account and necessary changes are made in the methods, they should also be suitable for designing hot-mixed asphalt concrete containing reclaimed asphalt concrete. Because the mechanical tests used in the methods are empirical, it is likely that additional correlations between laboratory test properties and pavement performance will be necessary when the methods are used for designing recycled mixes.

Design information for mixtures containing reclaimed asphalt concrete has been developed by a number of researchers and agencies. Guidelines for designing recycled mixes which emphasize characteristics of the recycling agents were presented in studies by Davidson (1) (2). Kari (3) presented mixture design procedures in which the salvaged asphalt and the recycling agent ratio was kept constant while the amount of new aggregate was varied in the preparation of specimens for Marshall and Hveem tests. The use of recycled asphalt concrete pavement mix proportion chart along with Marshall tests and design criteria was described by Betenson (4). Studies by Dunning (5)(6) were primarily concerned with the properties of aged asphalt and recycling agents in the design of recycled mixes. Kennedy (7) subdivided recycled mix design into general, preliminary, and final design categories. The final design utilized Texas State Department of Highway and Public Transportation standard tests which include Hveem stabilometer tests. Studies by Lee, Terrel and Mahoney (8) on the efficiency of mixing recycled mixtures concluded that a 60-second mixing time for preparing laboratory specimens produced adequate dispersion of the recycling agent in the mix. Epps (9) outlined procedures for designing recycled mixes including a method for selecting types and amounts of recycling agents. Guidelines for recycling hot-mix design are included in the Asphalt Institute's manual on asphalt hot-mix recycling (10). In addition to the published information on the design of recycled mixes, many road-building agencies are testing recycled mixes with Marshall and Hveem apparatus using changes in standard procedure based on experience in their laboratories.

Research Needs

Although considerable work has been done, information is limited or lacking in a number of areas of recycled mix design. The variability of the reclaimed asphalt concrete and its effects on mix design have not been well defined. Because there is greater potential for variability in reclaimed asphalt concrete, more study is warranted on the use of statistically based sampling procedures for recycled mix design.

The rate and extent the new asphalt or recycling agent or both change the consistency of the asphalt in the reclaimed asphalt concrete during the laboratory mix design may affect mechanical test properties. This may require changes in mix design procedures and criteria. A variety of physical and chemical tests have been used or proposed for characterizing the aged binders in reclaimed asphalt concrete as well as the new asphalt or recycling agents. It has not been established which tests are necessary for routine recycled mix design.

Asphalt consistency is one of the factors related to moisture damage and stripping behavior of some mixes. The combination of lower viscosity new asphalt and recycling agents with aged asphalt and new aggregate in recycled mixes may affect their susceptibility to moisture damage or stripping. Tests to evaluate stripping behavior of recycled mixes in conjunction with mix design procedures are desirable. The differences between recycled mixes and mixes made with new materials should be considered in the development of modified or expanded standard Marshall and Hveem procedures for designing hot recycled asphalt paving mixtures.

Project Objectives

This is a report on a Federal Highway Administration-sponsored project investigating a number of the areas of recycled mix design where information is limited or lacking. The overall objective of the project was to develop procedures for designing recycled asphalt paving mixtures utilizing standard Marshall and Hveem test equipment. Specific objectives of the study were as follows:

1. To develop a statistically sound sampling procedure for stockpiled, blended, or in situ asphalt pavements to be recycled;

2. To select test methods to determine important physical and chemical properties of salvaged binders required for effective rejuvenation with asphalt modifiers;

3. To select a stripping test for evaluating the moisture damage susceptibility of a recycled mixture; and

4. To develop mixture design criteria for producing durable asphalt mixtures and establish criteria for properties of the recycled paving mixture.

The five tasks established to accomplish the study objectives are listed below:

Task A - Statistical Sampling Plan

Task B - Test Methods to Characterize the Salvaged Binder

Task C - Development of Stripping Test

Task D - Development of Mixture Design Criteria

Materials Used for the Project

The research was conducted using materials from five hot-mix recycling projects constructed by five state highway agencies. Samples of materials from the projects were furnished by the state highway agencies according to sampling plans and provisions developed under Task A. Pavement cores taken shortly after the construction of the pavements were furnished by four of the state highway agencies (none from California) in addition to the samples of in situ pavements to the recycled, reclaimed processed asphalt pavement, new aggregate, and new asphalt or recycling agent.

Additional samples of asphalt representing major crude sources common in the U.S. and typical recycling agents were obtained from U.S. commercial sources for Task B. The materials, designs, and construction techniques used in the projects were representative of those used by state highway agencies during 1981 and 1982.

STATISTICAL SAMPLING PLANS

Purpose and Scope

One of the objectives of this study was to develop a simple statistical plan for obtaining samples of reclaimed asphalt concrete pavement from the roadway prior to recycling, and from stockpiles of material to be used for recycling. The test samples would provide data that could be used to estimate the variability to be expected from pavements to be recycled and to estimate how this variability might affect the quality of the final recycled asphalt mixture.

Several statistical sampling plans were developed, using simple statistical techniques. They can be used to obtain random samples of asphalt concrete from existing pavements, from milled material sampled from trucks, or from milled or other material processed and stored in stockpile, and can be modified to include belt sampling and other sources, if desired. The plans are described in Appendix A.

The plans were tested on four hot recycling projects in four different states: California, North Carolina, Utah and Virginia. Material for recycling was obtained by milling a portion of the pavement surface. Samples of the material to be recycled were obtained for extraction and recovery testing using some version of the plans referred to above. All projects (except New Mexico) were sampled from the roadway prior to milling. Samples of milled material were obtained from trucks on two projects and from stockpiled milled material in two others. Results of extraction and recovery testing on the samples were analyzed using the procedures outlined for the sampling plans. In addition, the data were analyzed for sample variability in relation to the different variables included in the study. Project locations and sources used for sampling material to be recycled are summarized in Table 1. Specific information about each project, test data obtained, results of statistical analyses of the test data, discussion, conclusions, and recommendations are included in the following articles.

Plans for the Study

It is highly likely that existing asphalt pavements to be recycled will consist of layers of asphalt concrete of different composition, or road mixes or surface treatments having different characteristics. Similarly, existing stockpiles of salvaged material may have been obtained from pavements having different characteristics. It is likely that a length of pavement selected for recycling will vary in composition from one end to the other or from one lane to another. These variations could result from normal construction practices or they could be the results of different maintenance practices. Test data from samples obtained from highly cracked areas may display different properties than test samples taken from uncracked areas. Variability introduced by these characteristics may be high in many cases. On the other hand, some pavements will be relatively uniform from one end to another. In any case, a sampling plan will be required that anticipates the possibility of variability, that provides a means whereby the variability can be determined, and that helps establish a construction unit (length of project or quantity of material) that will provide a recycled pavement with characteristics which vary within acceptable limits.

The specific purpose of this phase of the study was to develop plans for obtaining materials for mix design of recycled pavements that would take into consideration expected variability using statistical techniques. Statistical sampling plans were to be developed that could be used for sampling in situ from the roadway prior to recycling, for sampling material obtained at the job site for processing for use on the same job, and for sampling stockpiled material that might have been collected from more than one source. Simple, classical statistical sampling and analysis techniques were to be used.

Five recycling projects were selected for sampling and testing. Three projects were to be selected for sampling from the pavement before recycling and two for sampling from stockpiled material. A sufficient number of samples were to be obtained at each site to test the validity of the proposed procedures and to provide material for use in conducting other phases of the study.

Each sample obtained was to be used for an asphalt extraction and recovery tests. Tests were to include (1) aggregate gradation, (2) asphalt content, (3) viscosity at 140°F (60°C) and 275°F (135°C), and (4) penetration at 77°F (25°C). It was expected that approximately 60 to 70 extraction and recovery tests would be performed in this phase of the study. Additional extraction and recovery tests, one from each project, were to be performed in this phase of the study. The variability obtained from the test program was to be used to estimate the expected variability for hot-mix recycled pavements.

Extraction and Recovery Tests

Asphalt extraction tests and tests on recovered asphalts and aggregates performed on cores and samples of processed materials to be recycled followed standard ASTM procedures. The tests performed were as follows:

ASTM D 1856	Test for Recovery of Asphalt from Solution by Abson Method
ASTM D 2172	Test for Quantitative Extraction of Bitumen from Bituminous Paving Mixtures
ASTM D 5	Test for Penetration of Bituminous Materials
ASTM D 2171	Test for Viscosity of Asphalts by Vacuum Capillary Viscometer

ASTM D 2170	Test for Kinematic Viscosity of Asphalts (Bitumens)
ASTM C 117	Test for Materials Finer than (75-μm) No. 200 Sieve in Mineral Aggregates by Washing
ASTM C 136	Test for Sieve Analysis of Fine and Coarse Aggregates.

Statistical Sampling Plans

Tentative procedures for sampling and statistical analysis of in-place pavements and blended or stockpiled materials for recycling were developed prior to the construction of the projects. Minor modifications were made to these plans during the course of the study to reflect experiences gained in trying to implement them. In general, sampling from the roadway was not a problem. Plans for sampling from stockpiles were modified, primarily to accommodate the need to use hand sampling procedures, rather than using power equipment as originally planned. A plan for sampling milled material from trucks was also added.

The basic sampling plans used in this study are described in Appendix A. The plans provide for sampling, testing and the statistical determination of a minimum number of specimens, but they can be expanded easily to provide for more samples, if desired, or otherwise modified to fit the conditions of the proposed recycling project. The basic statistical plans first divide the roadway or stockpile of material being considered for recycling into construction units expected to have reasonably uniform characteristics, using construction and maintenance records when possible. Each construction unit is further divided into sections of approximately equal size. One or more random samples are obtained from each of these sections for extraction and recovery testing.

Figure 1 contains a flow chart for the process underlying all of the statistical sampling and analysis plans proposed in this study. Appendix A contains plans for sampling asphalt paving mixtures to be recycled by sampling from the pavement in place before recycling, from trucks hauling processed material to be recycled, and from stockpiles of materials to be recycled. Appendix B includes a procedure for random selection of sampling locations. Techniques for performing analyses of test data obtained using the sampling plans are given in Appendix C. Further discussion of these procedures follow the presentation and analysis of the test data collected in this phase of the study.

Analysis Procedures

The analysis techniques proposed for the study were to serve two purposes: to provide data which could be used to evaluate the proposed sampling plans, and to provide data which, along with data from other sources, would be used to develop alternative plans. Simple analysis of variance techniques were selected as the basic analysis procedure. The procedures are described in Appendix C.

A problem encountered in setting up the analysis procedure was the time and costs involved in performing extraction and recovery tests on samples of materials to be recycled. It was estimated that a minimum of 12 samples should be needed. This number of samples appeared to be consistent with normal state highway practices. Mix designs were made on composite samples, which appeared to represent reasonably well the material produced by the recycling process.

In all cases, the plan for recycling was established ahead of time and no effort was made to modify it on the basis of the plans developed in this study. This aspect of the study will be discussed in reference to each project in subsequent paragraphs.

Test data on samples of material to be recycled were obtained from four of the five projects included in the study, as shown in Table 1. A brief description of the plan followed at four of the projects is given in the following paragraphs. Appropriate test data are summarized in Table 2 through Table 23.

California

This project consisted of a section of state Route 97 in Siskiyou County approximately 10.5 mi (16.9 km) long and two lanes wide. Material for recycling was obtained by milling approximately 1.5 in. (38 mm) deep from the surface of the pavement. The milled material was transported by truck to a small stockpile for mixing, but all of the reclaimed asphalt concrete was not stockpiled before construction was started.

Samples for extraction and recovery testing were obtained from the roadway prior to recycling and from a stockpile of milled material obtained from the roadway during construction. Samples from the roadway were obtained using the Plan for Sampling Asphalt Concrete Pavement in Place, given in Appendix A. The pavement was divided into six sections, approximately 9,240 ft (2,816 m) long and two lanes wide. One randomly located core sample was obtained from each lane of each of the six sections for a total of 12 core samples. Each of these samples was subjected to extraction and recovery testing. Selected test data were subjected to an analysis of variance using the procedure described in Appendix C for samples obtained from more than one lane or level. Test data are summarized in Table 2. Results of the analysis of variance are given in Table 3.

Stockpile samples were taken full depth at five locations within the stockpile. Although neither of the plans for sampling stockpiles was used, the samples were judged to be "representative" of the stockpile at the time of sampling. Results of extraction and recovery testing on these samples are given in Table 4.

Inspection of the test data from core samples obtained from the pavement before recycling (Table 2) indicates that there was considerable variability associated with some of the test properties included in the study. The results of the analysis of variance (Table 3) show that the variability was statistically significant between sections but not across lanes, except for asphalt content, which was significantly different at the 75 percent significance level both between lanes and between sections. Viscosity data obtained on the extracted asphalt displayed the highest degree of variability between sections and was fairly consistent across lanes, and was not significant. Penetration and percent aggregate passing the No. 4 sieve displayed significant differences at the 95 percent significance level between lanes but were not significantly different between lanes.

Inspection of the test data and results of the analysis of test data from pavement core samples indicate that both aggregate grading and asphalt content can be expected to vary along the length of the project, which could have a practical effect on the variability of the final mixture. Similarly, the test data and results of the analysis indicate that significant variability can be expected in the properties of the recovered asphalt. This also could affect the properties of the final mixture and possibly the performance of the recycled pavement. It is interesting to note, however, from Table 4, that the variability of the five samples of milled material obtained from the stockpile is considerably less than the variability obtained from the 12 pavement core samples. This can be seen by comparing the standard deviations which have been summarized in Table 5.

North Carolina

The North Carolina project consisted of recycling the 2.0 in. (50 mm) surface course in the outside southbound lane of highway I-95 between U.S. Route 74 south of Lumberton and the South Carolina border. This portion of I-95 is about 13.5 mi (2.2 km) long. For sampling purposes, the length was divided into twelve equal sub-sections, approximately 2.25 mi (3.6 km) long. One 6-in. core sample was randomly located in each sub-section and obtained for extraction and recovery testing. In addition, approximately two samples were taken each day (12 total) from randomly selected trucks hauling milled material from the job site to the plant. Portions of these samples were used to prepare a composite sample for extraction and recovery testing, Marshall and Hveem mix design and for a study of stripping. The remaining portions were reserved for further testing as needed.

Core samples from the 12 sub-sections were analyzed using the procedure described in Appendix C for samples obtained from one lane. In order to compare variability from one end of the project to the other with variability in shorter segments of pavement, the 12 sub-sections were combined into six sections, sequentially along the project, for the analysis of variance. Results of the extraction and recovery testing are summarized in Table 6. Results of the analysis of variance are summarized in Table 7, in the form of overall means and standard deviations for selected test values and an indication of statistical significance for section variance only.

The analysis of variance indicates that there were no statistically significant differences between the six sections for any of the test variables. Inspection of the test data in Table 6 shows that, except for results of the tests on the recovered asphalt, the mixture exhibited good uniformity, and considering the entire project as one mixture for mix design purposes probably can be justified.

Results of penetration and viscosity tests exhibited considerably more variability than asphalt content or aggregate grading. However, the variability appears to be random and dividing the project into smaller units having similar levels of penetration or viscosity does not appear to be justified from the data available. Additional sampling and testing would be needed to establish the extent of the existing pavement represented by the more extreme penetration and viscosity test values.

Since the tests were randomly located within each division, it may be assumed that they represent reasonably well the variability that can be expected from the existing pavement, which in turn will affect the variability of the recycled mixture. How this variability would affect the recycled mix and, possibly, the performance of the recycled pavement cannot be determined at this time.

Results of extraction and recovery tests on the milled material obtained from trucks is summarized in Table 8. The five sets of test data were obtained from one composite sample, and no attempt was made to measure day-to-day variability.

A comparison of extraction test data obtained from core samples and from the milled material may be made using Table 9. The aggregate grading obtained from the milled samples appears to be somewhat finer than that obtained from the core samples. The percent asphalt did not change however. The standard deviations for both aggregate grading and percent asphalt were lower for the milled samples than for the pavement core samples. The T-test was used to test for statistical significance between the test data for roadway samples and milled samples. Only differences associated with aggregate grading proved to be statistically significant.

Utah

A 9.1 mi (14.6 km) portion of U.S. 89, Bryce Canyon Junction to Hatch, Utah, was selected for inclusion in the study. The roadway consisted of two 18-ft (5.5 m) lanes. All of the asphalt layers were removed, approximately 4 in., to the top of the aggregate base by milling. The cold milled material was hauled to the plant site, dumped into a windrow and from there deposited into a stockpile by front end loaders. The stockpiles were composed of single layers approximately 10 ft (3 m) high. Material was transported from one large stockpile to smaller stockpiles for feeding the plant.

Samples were taken both from the pavement prior to milling and from two stockpiles of milled, reclaimed material at the mixing plant site. The 9.1 mi (14.6 km) section of roadway was divided into six sections approximately 7,972 ft (2,430 m) and two lanes wide. One 6-in. core sample was taken from a random location in each lane of each section, for a total of 12 samples, for extraction and recovery testing. The procedure followed that described in Appendix A. Selected test data were subjected to the analysis of variance procedure described in Appendix C for samples taken from two lanes. The test data are summarized in Table 10 and results of the analysis of variance are summarized in Table 11. These results indicate that, except for a small difference in asphalt content, statistically significant differences between lanes did not exist. There was a difference between sections, at a low level of significance, for all variables except asphalt content. In general, however, the results of this series of tests show that the in-place pavement had relatively uniform properties.

Two stockpiles were sampled. Stockpile No. 1 was located near the plant and was the smaller of the two. It was composed of approximately 6,500 tons (6,000 metric tons) of reclaimed pavement. This stockpile was divided into three sections. One sample of milled material was taken by hand from the top of the pile in each section for extraction and recovery testing. Sample locations were randomly located. Results of tests on these samples are summarized in Table 12.

Stockpile No. 2 was composed of approximately 18,000 U.S. tons (20,000 metric tons) of reclaimed material. The stockpile, approximately rectangular in shape, was divided into 10 sub-sections in such a way that it could be analyzed as five sections, each composed of two side-by-side subsections. One sample was taken by hand from a random location in each subsection for a total of 10 samples, for extraction and recovery testing. The test data are summarized in Table 13. An analysis of variance using the same technique that was used for a two-lane pavement was performed on the data. Results of the analysis of variance are summarized in Table 14.

A comparison between the extraction and recovery test data obtained from pavement core samples and from stockpile samples of milled material may be obtained from Table 15. The data indicate that there was a slight increase in the percent passing the No. 8 and No. 200 sieves for the aggregate after milling and a decrease in the asphalt content. Viscosities of the recovered asphalt increased and penetration values decreased after milling. The T-test was used to test for statistical significance between means of test data from each stockpile and means of test data from roadway samples. (See Appendix C for a discussion of the T-test.) Only the differences in percent passing the No. 8 sieve, penetration on recovered asphalt and percent asphalt for stockpile No. 1 proved to be statistically significant. Differences associated with tests on the recovered asphalt did not.

Virginia

A 3-mile (5 km) section of U.S. 220 near Roanoke, Virginia was selected for study. The outer two lanes in two directions were cold milled approximately 2 in. deep and one lane wide and removed for recycling. Samples were taken from the roadway before milling and from trucks hauling milled material to the plant site.

Samples from the roadway were obtained by sawing from the pavement an approximate 1-ft (0.3-m) square sample, located by a random selection process as indicated in Appendix A. The 3 mi (5 km) section was divided longitudinally into six sections of equal length and one sample taken from each lane of each section for extraction and recovery testing. An analysis of variance was made on the results using the appropriate procedure from Appendix C. The results of the extraction and recovery testing are summarized in Table 16. Results of the analysis of variance are summarized in Table 17.

The analysis of variance on the roadway samples indicated that there were statistically significant differences between lanes and between sections for aggregate grading and asphalt content. Penetration on recovered asphalt also displayed significant differences between both lanes and sections; although, viscosity test data were only slightly significant or not significant for lanes and sections.

Approximately two samples were taken each day (12 total) from randomly selected trucks hauling milled material from the job site to the plant. Portions of these samples were used to prepare a composite sample for extraction and recovery testing, Marshall and Hveem mix design, and for a study of stripping. The remaining portions were reserved for further testing as needed. Results of the extraction and recovery testing are summarized in Table 18.

Comparisons between results of selected tests run on extracted aggregate and asphalt from roadway samples and samples of milled material may be made using Table 19. The percent passing the No. 8 and No. 200 sieves for samples of milled material were higher than for the roadway samples. Percent asphalt remained the same, and viscosity of recovered asphalt decreased. The T-test (Appendix C) was used to test for statistical significance where more than one test value was available. Results of the T-test for significance indicated that only the differences in aggregate grading were statistically significant.

The results of the analysis of variance on data from U.S. 220 in Virginia indicate that statistically significant variations were found for many of the test variables from lane to lane and section to section. However, neither aggregate grading nor asphalt content exhibited large practical differences; and the recycled mixture was fairly uniform in respect to these routine control tests. The variability in recovered asphalt properties may indicate further variations in pavement performance, but this cannot be determined at this time.

Discussion

The results of the analysis of variance on test data obtained from roadway samples can serve to indicate if variations between sections or between lanes can be identified, and, possibly, overcome by proper processing of the material to be recycled before mixing or by making changes in the mix design. Unfortunately, major random variations may not be amenable to correction by either method, although some mixing can be accomplished in the handling process. Results of the analyses performed on samples taken from the roadway before recycling in the four projects included in this study indicate that in two of the four projects, California and Virginia, statistical differences were detected which could have led to a decision to consider some action, such as mixing the material from separate sections of roadway, in a stockpile or, perhaps, specifying more than one mix design for the project. These two projects did not display a greater degree of variability for all test variables, however, than did the other projects.

This indicates that a major factor in determining the practical significance of the results of a statistical sampling and analysis plan is the variability associated with the test results. Minor differences in mean values may prove to be statistically significant because variability is low. On the other hand, major differences in mean values may not be statistically significant because variability is high. In either case the decision to require additional manipulation of the material to promote mixing or to provide more than one mix design per project may have to be made using engineering judgement. In some cases additional testing may be required to determine the extent of areas of apparently different properties.

Also pertinent to making a decision regarding the determination to mix, prepare more than one design, or require additional testing is how the test data obtained from the pavement or stockpile to be recycled compares to normal expectations. In this regard, additional comments or expected variability are in order.

Table 20 contains a summary of pooled averages, standard deviations and coefficients of variation for selected test variables for individual samples obtained from the roadway on all four projects, from individual samples obtained from milled material from the two Utah stockpiles, and from composite samples of milled material from trucks on the North Carolina and Virginia projects and from the California project stockpile. (See Appendix C for descriptions of the procedures mentioned.)

Use may be made of the coefficients of variation in Table 20 to arrive at conclusions regarding the relative variability associated with the test variables summarized. It will be noted that the largest coefficients of variation are for the tests on asphalt recovered from individual samples obtained from the roadway before recycling. This, apparently, reflects extensive differences that occur in pavements in service. Since the results appear to be random, from previous discussions, it would follow that extensive sampling would be required to identify the extent of the different values represented by the test results.

Except for the viscosity measurements on recovered asphalt on roadway samples mentioned above, viscosity at 140°F for the individual stockpile samples from Utah and percent passing the No. 200 sieve for the roadway samples, coefficients of variation are equal to or less than 11 percent. This can be compared to a value of 10 percent often used as a practical measure of test variability.

The standard deviations can be used to compare the variability of the aggregate grading and percent asphalt to job-mix formula limits recommended in ASTM D3515 - Standard Specification for Hot-Mixed, Hot-Laid Bituminous Paving Mixtures. These limits, for the test variables under study, are:

Sieve No. 8	± 5%
Sieve No. 200	± 3%
Percent Asphalt	± 0.5%

Two sets of limits were calculated for percent passing the No. 8 and No. 200 sieves and percent asphalt for each source of samples given in Table 20. These limits are shown in Table 21. In one case 1.96 σ limits were calculated. Here, 3.7 σ is the average standard deviation from Table 20. It is used to represent the population standard deviation. The value ± 1.96 σ represents the range about the population mean that 95 percent of all values would lie.

The limits identified as "sampling limits" were calculated using the same standard deviation, but, in this case, the standard deviation, s, was considered a sample standard deviation, not the population standard deviation. Using a technique described in Reference (24) for calculating two-sided tolerance limits for a normal distribution, the value ± Ks represents the range about the sample mean within which the probability is 95 percent that 95 percent of the test values in a sample of N = 12 would fall.

The same technique can be used to estimate the probability that a certain number of test values out of a sample of N tests would fall within the job-mix limits specified in ASTM D 3515. The number of tests required in one sample to produce the probability that 99 percent of the time the ASTM limits would include 75 percent of the test values have been calculated and also are listed in Table 21. (Because of a high level of variability the report includes the 75 percent level to test for significant differences.)

Comparisons of the ASTM job-mix limits to both sets of derived limits indicates that, in most cases, the test results would not conform to the ASTM limits. In three cases, percent passing the No. 200 sieve from roadway samples and percent passing both the No. 8 and No. 200 sieves would require that twice as many tests be taken as actually were taken, for example, to be reasonably sure that 80 percent of the material conformed to the ASTM limits. It is also interesting and significant to note that while the samples of milled material were less variable than the samples taken from the roadway before recycling, the trend could not be considered highly significant. From the point of view of obtaining data to be used to devise a recycling plan, therefore, it is likely that the material itself will be more variable than would be expected from quality control guidelines such as ASTM job-mix control limits.

Since the tests from roadway samples obtained before milling or recycling were quite variable, a limited comparison was made to other data obtained on samples obtained from in-service pavements. Three previous investigations were included in the comparison: a pre-construction coring and testing program made by the North Carolina Department of Transportation prior to construction of the project used in this study; a nationwide study conducted by FHWA from 1967 to 1970; and a study made for the National Cooperative Highway Research Program during the same period. Selected data from these investigations are given in Table 22.

In the North Carolina study (11) cores were taken from the outside lane with the objective of recycling the 2-in. asphalt concrete surface layer that was cracked and ravelled. Ten cores from the same lanes as used for the recycling study were subjected to extraction and recovery tests. Selected results given in Table 22 indicate that the two sets of tests by two different organizations compare closely.

The Federal Highway Administration, during the period 1954 to 1956, initiated a study to relate properties of asphalts with performance observed on in-service pavements. Following an initial study, during the period 1967 to 1970, an extensive field and laboratory investigation of properties obtained from pavement cores was conducted on 34 of the pavements included in the original study and that had not been overlaid. Samples were obtained from two to six sites per project by a random selection process from the outer wheelpaths, at least one in. (25 mm) in depth. Results of selected extraction and recovery test data from these samples, reported by Zenewitz and Welborn (12), are summarized in Table 22.

The other study was reported in NCHRP Report 67 by Sisko and Brunstrum (13). The purpose of this study was to relate pavement durability to rheological properties of asphalt. In the study, two samples were taken from each of 12 projects for asphalt extraction and recovery testing. Each of the two samples was taken in opposite lanes of the highway, about 300 ft (91 m) apart, in the outer wheelpath, where there was no obvious contamination from oil or grease. Six of the 12 projects were reported to have had "moderate" to "severe" cracking. Selected test data, reported by Sisko and Brunstrum, are given in Table 22.

The above two sets of data, summarized in Table 22, can be compared to project data, summarized in Table 20. It will be noted that the coefficients of variation for percent passing the No. 8 and No. 200 sieve for the project roadway samples are about twice those reported by Zenewitz and Welborn. The project coefficient of variation for percent asphalt also is about twice that reported by Zenewitz and Welborn, but about the same as reported by Sisko and Brunstrum. A test of the variances using the F-ratio test also indicated that the project roadway data set and the Zenewitz and

Welborn data are from significantly different populations. The same test indicated that the percent asphalt distributions for the Sisko and Brunstrom data may represent a larger percentage of cracked or distressed pavements than the Zenewitz and Welborn data, or other factors may account for the difference. Regardless, the data suggest that distressed pavements, which are candidates for recycling, may have more variable extraction test properties than pavements not in a distressed condition.

Results of tests reported on samples obtained from the roadway have been compared to test results obtained on samples of the same materials that were milled and transported by truck to the job site. In most cases, there were changes noted in properties that may or may not be significant in regard to providing adequate data for mix design or acceptable uniformity of the recycled mix. Average changes are shown in Table 23. Changes in percent passing the No. 8 and No. 200 sieves, asphalt content and penetration were consistent across projects, and may be considered significant. Percent passing the No. 8 and No. 200 sieves increased slightly during the milling process. The average increase was eight percent on the No. 8 sieve and two percent on the No. 200 sieve. Asphalt content either remained the same or decreased slightly, with an average decrease of about 0.2 percentage points. Penetration of the recovered asphalt either remained the same or decreased during the milling process. The average decrease was about 6. Comparisons of viscosities measured on asphalt recovered from roadway samples to viscosities measured on asphalt extracted and recovered from the milled samples were variable, exhibiting both increases and decreases.

Samples of milled material taken from stockpiles, where tests were run on individual samples, exhibited somewhat inconsistent differences. In general, standard deviations for the No. 8 sieve, the No. 200 sieve, and percent asphalt were within the same range for both samples taken from the roadway and samples taken from the stockpiles of milled material. However, standard deviations or coefficients of variation were substantially less for the stockpile samples than for the samples taken from the roadway.

Summary and Conclusions

Plans have been developed for obtaining random samples of asphalt concrete from pavements to be recycled using a hot-recycling process. Sampling plans can be applied to the existing pavement, to milled material samples from trucks or to milled or other material processed and stored in stockpiles. The plans could be modified to include belt sampling and other sources, if desired.

The plans were tested on four actual hot recycling projects in four different states: California, North Carolina, Utah and Virginia. Material for recycling was obtained by milling a portion of the pavement surface. Samples of the material to be recycled were obtained for extraction and recovery testing using some version of the plans developed in the study. All projects, except the New Mexico project, were sampled from the roadway prior to milling. Samples of milled material were obtained from trucks on two projects and from stockpiled milled material in two others. Results of extraction and recovery testing on the samples were analyzed using the procedures outlined for the sampling plans. In addition, the data were analyzed for sample variability in relation to the different variables included in the study.

The following observations are considered pertinent as to how the material to be recycled might affect the final recycled mix.

1. In two projects an analysis of variance indicated that there were significantly different segments of the project that could have been treated differently, if desired. However, the two projects did not display a greater degree of variability than did the other projects for all test variables.

2. Sample variability was high in almost all cases, particularly for penetration and viscosity test results obtained from roadway samples.

3. Comparisons of test variability to ASTM job-mix limits and historical data indicate that the material obtained for recycling on these projects was somewhat more variable than the ASTM limits or historical data on pavements in place would suggest.

4. Where direct comparisons on one project could be made, the milling and hauling process appeared to (1) reduce the variability in the test data; (2) increase the percent passing the No. 8 and No. 200 sieves; (3) reduce slightly the measured percent asphalt; and (4) reduce the penetration of the recovered asphalt. There was no consistent change in viscosity measurements.

Based on the above observations and discussion, samples obtained from the roadway prior to milling or other processing are likely to exhibit highly variable results from penetration and viscosity test measurements. This appears to result from local effects, probably associated with the type or amount of distress. Although Sisko and Brunstrom (13) found a relationship between asphalt hardening and cracking, no attempt was made to document such an observation on this project, and, therefore, their conclusion cannot be substantiated from project data. However, inspection of the data from each project does indicate that variations in penetration and viscosity test measurements on recovered asphalts were randomly located. This observation, and consideration of the large standard deviations associated with these test data, indicated that quite a large number of test locations would be required to discover the extent of pavement having different test properties. In most cases, the amount of testing would be more extensive than most agencies would consider feasible, and would only be of practical use if the more extensive testing program resulted in different mix designs for each section of the project having different test properties.

In general it may be concluded that asphalt pavements that are candidates for recycling can be expected to have a comparatively high level of variability. Some improvement may be obtained during the processing from pavement to plant through a milling operation, or by separating the job into subunits that might have different mix designs.

Recommendations

It is recommended, therefore, that the following procedure be used when sampling asphalt concrete from the roadway prior to milling or other processing: (1) obtain samples and perform extraction tests as outlined in Appendix A, (2) perform the indicated analysis of variance on the test data as outlined in Appendix C, and (3) establish construction units only on the basis of aggregate grading and percent asphalt, unless it can clearly be demonstrated that penetration or viscosity test properties are different.

It is also recommended that, where possible, final mix designs be based on reclaimed and processed pavement material.

TEST METHODS TO CHARACTERIZE THE SALVAGED BINDER

Introduction

Low viscosity grades of asphalt cement and other low viscosity organic recycling agents are used in hot-mix recycling to combine with, and change the aged binder in reclaimed asphalt concrete to have properties similar to new asphalt and to provide the additional binder for any new aggregate used in the mix. When standard specification paving grade asphalt cements are combined, they would not be expected to separate or be altered by chemical interaction. However the use of recycling agents with properties quite different from paving grade asphalt cements introduces uncertainty about the compatibility and durability of the combination of the materials.

Some studies have indicated that various compositional characteristics of asphalts can be related to their physical properties. Other studies have proposed that compositional characteristics of asphalts and recycling agents can be used to assess the compatibility between the materials and the durability of the combined materials.

Corbett (14) (15) related asphaltene, polar aromatic and saturate fractions of asphalts determined by a chromatographic separation method essentially the same as ASTM method D 4124, to certain physical and age hardening properties. Plancher (16) proposed that the settling rate determined by an asphaltene settling test could be used to determine effectiveness of recycling agents as an asphaltene dispersant in aged asphalt. Work reported by Kari (17) proposed that limitations on the saturate content of recycling agents as determined by ASTM D 2007 Clay-Gel chromatographic method would insure sufficient compatibility and solvency of recycling agents when used with aged asphalts.

Davidson (1) proposed that the ratio of N (nitrogen base or polar components) to P (paraffins or saturates) fractions of a recycling agent determined by the Rostler analysis (ASTM Method D 2006 - discontinued) should be less than 1.0 in order to be compatible with aged asphalt. He also proposed that recycling agents should have a composition parameter $(N + A_1) / (P + A_2)$ between 0.4 and 1.0 to improve the durability of the aged asphalts. The A_1 and A_2 fractions are respectively the first and second acidaffins determined by the Rostler method. The fingerprinting studies of asphalts reported by Rostler (18) and Anderson (19) include compositional analysis data determined by the Rostler method for a large number of asphalts.

The physical properties of asphalt cement, primarily consistency and changes in consistency with aging and exposure to heat and air, are the principal properties of asphalt that have been related to pavement construction procedures and to the performance of asphalt in pavements. Specifications for paving asphalts based on their physical properties have been developed through many years of experience. In view of the long proven experience with physical properties and the more recent research on the chemical natures of asphalts, both physical and compositional analysis tests were used in this part of the study to characterize salvaged binders and recycling agents. Because there is little agreement on which of the various compositional analysis tests that have been developed are the most suitable, several of the methods were used.

Study Plans

Four artificially aged asphalts covering a range of consistencies of asphalts found in aged pavements were prepared for evaluations of the various physical and chemical tests. Asphalts for preparing the aged binder samples were selected to represent major crude oil sources in the U.S. Four typical recycling agents were selected and subjected to the same physical and chemical tests as appropriate. Blends of the recycling agents with the four aged asphalts were prepared and subjected to the same physical and chemical tests. Based on results of the artificially aged binder studies, certain of the tests were selected and run on aged asphalt, recycling agents and blends of these materials obtained from sampling five recycling construction projects.

Composition Analysis

Three methods were used for analysis of the composition of aged asphalts, recycling agents and combinations of aged asphalt and recycling agents. Compositional characteristics were determined by ASTM Test Method D 4124 for Separation of Asphalt Into Four Fractions and by ASTM Test Method D 2006 (discontinued) for Characteristic Groups in Rubber Extender and Processing Oils by The Precipitation Method. Saturate fractions were determined by ASTM Test Method D 2007 for Characteristics Groups in Rubber Extender and Processing Oils by the Clay-Gel Adsorption Chromatographic Method. An asphaltene settling test described by Plancher (16) was also used.

Physical Properties

All of the standard tests of the ASTM and AASHTO specifications for paving asphalts were used to determine the properties of original and aged asphalts, recycling agents and combinations of these materials. Viscosities were also determined by ASTM Method D 3205 at a temperature of 77°F (25°C). Ductilities were measured at a temperature of 39.2°F (4°C) in addition to the normal testing temperatures.

Asphalt Cements

The asphalts, their ASTM specification grades, and crude oil sources selected for preparing artificially aged binder samples were as follows:

Asphalt A - AR-16000, Santa Maria

Asphalt B - AC-40, Smackover

Asphalt C - AC-20, Venezuela

Asphalt D - AC-20, Mid-Continent

Physical test properties of the four asphalts before artificial aging are given in Table 24. The temperature susceptibilities of three of the asphalts were about the same. The fourth asphalt was more temperature susceptible. Viscosity temperature susceptibility (VTS) was determined by the following relationship:

$$VTS = \frac{\log \log V_{T_2} - \log \log V_{T_1}}{\log T_1 - \log T_2}$$

where:

V_{T_1} = viscosity, centipoises at temperature T_1

V_{T_2} = viscosity, centipoises at temperature T_2

T_1 = temperature, °K

T_2 = temperature, °K

For viscosities determined at temperatures of 275°F (160°C) and 140°F (60°C), VTS values for asphalts A, B, C and D were respectively 3.50, 3.51, 3.49 and 3.69. The effects of heating on the asphalts as determined by the standard thin film oven varies. Ratios of viscosity at 140°F (60°C) after thin film oven test to viscosity at 140°F (60°C) before thin film oven test ranged from 1.89 for asphalt D to 3.85 for asphalt A.

Compositional characteristics of the four asphalts before artificial aging are given in Table 25. There were considerable differences between the four asphalts in some cases in their various fractions as determined by the different methods. The asphaltene and naphthene fractions later named by ASTM method D 4124 varied widely for the four asphalts. The asphaltene, polar compound, second acidaffin and saturated hydrocarbon fractions determined by ASTM method D 2006 were considerably different for the four asphalts. Asphaltene settling test times differed and ranged from 8 minutes to 71 minutes for the four asphalts.

Results also indicated that the asphaltene fractions differed depending on the test method used. The n-heptane asphaltene fraction by the D 4124 method was substantially less than the n-pentane asphaltene fraction by the D 2006 method. Apart from the asphaltene fractions which differ somewhat, there are no similarities between fractions of asphalts determined by the two methods. Saturated hydrocarbon fractions determined by the ASTM D 2006 method were essentially the same as the saturates fractions determined by ASTM Method D 2007.

Recycling Agents

Typical recycling agents selected for the study were as follows:

Recycling Agent 1 - AC-5 grade asphalt cement, Mid-Continent crude

Recycling Agent 2 - AC-2.5 grade asphalt cement, Smackover crude

Recycling Agent 3 - RA-25 grade, Pacific Coast User Producer Specifications: 3-4

Recycling Agent 4 - RA-5 grade, Pacific Coast User Producer Specifications: 3-4

Physical properties of the recycling agents are given in Table 26. They ranged in viscosity at 140°F (60°C) from about 2 to 500 poises. The AC-5 and AC-2.5 grade asphalt cements were less temperature susceptible with VTS values of 3.44 and 3.43 respectively compared to VTS values of 3.70 and 4.69 respectively for the RA-25 and RA-5 grade recycling agents.

Compositional characteristics of the four recycling agents are given in Table 27. The asphaltene and saturates fractions determined by ASTM Method D 4124 varied considerably for the four recycling agents. Recycling agent 4 contained no asphaltenes. Of the different fractions determined by ASTM Method D 2006 the asphaltenes, second acidaffins and saturated hydrocarbons varied the most for the four recycling agents. Asphaltene settling times for the four recycling agents ranged from zero for recycling agent 4 to 42 for recycling agent 2. As was the case for asphalt cements, saturated hydrocarbons fractions determined by ASTM Method D 2006 were in close agreement with saturate fractions determined by ASTM Method D 2007.

Artificially Aged Asphalts

The asphalts were artificially aged with a controlled flow of 6,000 cm^3 per minute of air and mechanical stirring while heating at a temperature between 325°F and 350°F (163°C to 177°C). The aging of 1300 to 1400 g batch samples was accomplished in from 15 to 35 hours and resulted in viscosities at 140°F (60°C) ranging from about 100,000 to 140,000 poises. Penetrations at 77°F (25°C) ranged from 13 to 23. The physical properties of the artificially aged asphalts are given in Table 28.

Temperature susceptibilities of the aged asphalts followed the same trends as before aging with three asphalts having about the same and one having higher susceptibility. VTS values for artificially aged asphalts A, B, C and D were respectively 3.52, 3.49, 3.46 and 3.76. The effects of heating the artificially aged asphalts as determined by the thin film oven test followed the same trends and were about the same as before aging. Ratios of viscosities before and after the thin film oven tests ranged between 1.89 for Asphalt D to 3.60 for Asphalt A.

The artificial aging resulted in substantial increases in asphaltene fractions of the four asphalts at the expense of varying decreases in one or more other fractions. Polar aromatic fractions determined by ASTM method D 4124 changed very little, as did the second acidaffins and saturated hydrocarbons fractions determined by ASTM Method D 2006. ASTM D 2007 saturates fractions were not changed significantly by the artificial aging. Asphaltene settling test times for the four asphalts increased after artificial aging following the same trends as before aging. The compositional characteristics of the artificially aged asphalts are given in Table 29.

Artificially Aged Asphalt and Recycling Agent Blends

Blends of the four aged asphalts and the four recycling agents were prepared using a viscosity blending chart to obtain a blend viscosity at 140°F (60°C) of 2,000 poises. The blending chart was based on an approximate linear relationship for plots of the log-log viscosity in centipoises at 140°F (60°C) of the aged and of the new asphalt or recycling agent versus percentages of new asphalt or recycling agent in the blend. Blends were prepared by heating the aged asphalt 275°F (135°C) for ten minutes. The blend was removed and stirred for one minute, replaced in the 275°F (135°C) oven for ten minutes, and removed and stirred for one minute.

Asphalt A, the highest viscosity aged asphalt, and asphalt D, the lowest viscosity aged asphalt, were blended with each of the four recycling agents. Aged asphalts B and C having intermediate viscosities were each blended with the highest viscosity recycling agent 1 and the lowest viscosity recycling agent 4. Use of the blending chart for asphalt A and recycling agent 1 to determine blend proportions to obtain a blend viscosity 2,000 poises is shown in Figure 2.

Physical Properties of Artificially Aged Asphalt and Recycling Agent Blends

Viscosities at 140°F (60°C) of ten of twelve blends proportioned according to the blending chart were within the range of 1,600 to 2,400 poises of the viscosity limits for AC-20 grade asphalt. Exceptions were blends of asphalt B with recycling agents 1 and 4 which were slightly lower than indicated by the blending chart. Reductions of about three percent in the amount of recycling agent were made to obtain blend viscosities in the desired range for these two blends.

Blends proportioned using the blending chart to obtain viscosities at 140°F (60°C) of 2,000 poises had penetration test values at 77°F (25°C) ranging from 66 to 116. Viscosity temperature susceptibility (VTS) values of blends fell between VTS values of the components in nearly all cases. In instances where they did not, VTS values of the aged asphalt, recycling agent and blends were so nearly alike that differences were not significant.

The test properties of all blends met ASTM or AASHTO specification requirements for AC-20 viscosity graded asphalt cement except the blend of aged asphalt A and recycling agent 1. Both asphalt A and recycling agent 1 exhibited rather large viscosity changes when subjected to the thin film oven test, and the viscosity of the thin film oven test residue of the blend exceeded the ASTM and AASHTO specification limits for AC-20 grade asphalt cement. The physical properties of artificially aged asphalts and recycling agent blends are given in Tables 30, 32, and 34. Viscosity and penetration test values for all of the blends are summarized in Table 36.

Compositional Characteristics of Blends

The rather wide differences in some fractions for the four aged asphalts were reduced in blends of the aged asphalts and recycling agents that were blended to have viscosities of approximately 2,000 poises at 140°F (60°). Asphaltene fractions by ASTM Method D 4124 for blends of the four aged asphalts and four recycling agents only varied from 15 to 21 percent and naphthene aromatics fraction varied between 26 and 38 percent. Similarly, the differences in asphaltene, polar components and secured acidaffin fractions determined by ASTM Method D 2006 were reduced for all blends compared to wide differences in these fractions for the original aged asphalts. The range in asphaltene settling test times for the blends of aged asphalts and recycling agents was about the same as for the original aged asphalts. About one-half of the time the settling times for the blend did not fall between the settling times for the individual blend components. Compositional characteristics of the aged asphalt and recycling agent blends are given in Tables 31, 33 and 35.

Compositional analysis fractions for the blend of 29 percent Asphalt A and 71 percent recycling agent 1 determined for the blend, and fractions calculated from the amounts of each fraction in asphalt A and recycling agent 1 and blend proportions are given in Table 37. The blend fractions calculated from blend proportions and from the measured amounts of each fraction in the aged asphalts and in the recycling agents were within 1 to 2 percentage points of the measured fractions of the blends. The variations were within the precision of the test method and are not considered significant. Differences between the measured and calculated fractions for all aged asphalt and recycling agent blends were essentially the same as those in Table 37.

Aged Asphalt and Recycling Agents from Five Recycling Construction Projects

Aged asphalts were extracted and recovered from composite samples of cold milled asphalt concrete from the five recycling construction projects that were sampled during the study. The composite cold milled asphalt concrete samples were also used for the mix design studies using Marshall and Hveem apparatus. The consistency of the extracted asphalts from the recycling construction projects varied widely. Viscosities at 140°F (60°C) ranged from about 106,000 poises for the California Highway 97 project to about 6,500 poises for the New Mexico I-40 project. Penetrations at 77°F (25°C) ranged between 7 for the California Highway 97 project and 38 for the New Mexico I-40 project. Temperature susceptibilities of the extracted asphalts varied and were somewhat greater for two projects. The VTS values were 3.89 and 3.86 respectively for the Utah U.S. 89 and California Highway 97 projects. VTS values for extracted asphalts for the North Carolina I-95, Virginia U.S. 220 and New Mexico I-40 projects were respectively 3.66, 3.60 and 3.56. Recycling agents used for the five recycling construction projects included AC 2.5, AC-5, 85-100 penetration, AR 1000 paving grade asphalt cements, RA-500 grade recycling agent (Pacific Coast User Producer specifications) and a low viscosity recycling agent meeting Utah Department of Transportation specifications. The properties of the aged asphalts and recycling agents from the five recycling construction projects in North Carolina, Virginia, New Mexico, Utah and California are given in Tables 38 to 42 along with properties of blends of the aged asphalts and recycling agents.

The viscosity blending chart which produced blends of artificially aged asphalts and recycling agents which generally met standard specification requirements was used for preparing blends of the aged asphalt and recycling agents from the five recycling construction projects. For the North Carolina I-95, Virginia U.S. 220, New Mexico I-40 and Utah 89 projects aged asphalts and recycling agents were blended to obtain a viscosity at 140°F (60°C) of 2,000 poises. The recycling agents and aged asphalt from the California Route 97 project were blended to obtain a viscosity at 140°F (60°C) of 2,667 poises. This target was selected based on an assumption that there would be approximately a threefold increase in viscosity after the thin film oven test. Blends of the North Carolina, Virginia, New Mexico and Utah projects proportioned according to the viscosity blending chart all met AASHTO M 226 and ASTM D 3381 specification requirements for

AC-20 viscosity grade asphalt cement. The blends for the California project met the requirements for AR-8000 viscosity grade asphalt cement except that the blend with the AR-1000 recycling agent was marginal with respect to the viscosity requirements at 275°F (135°C).

Fractions of the aged asphalts, recycling agents and blends of the aged asphalts and recycling agents were determined by ASTM Method D 4124 for the recycling construction project materials. Results were essentially the same as for the artificially aged asphalts with respect to measured fractions in blends and fractions calculated from the blend proportions and the measured amount of the fractions in blend components. The blend fractions calculated from amounts of each fraction in the aged asphalts and in the recycling agents from the recycling construction projects were generally within 1 to 2 percent of the fractions in the blends. No changes due to chemical interactions between various fractions of aged asphalts and recycling agents were indicated.

Summary and Conclusions

Physical and compositional analysis tests were run on artificially aged asphalts prepared from asphalts representing major U.S. crude sources, typical recycling agents, and on blends of the materials. Physical tests and selected compositional analysis tests were run on extracted aged asphalts, recycling agents, and blends of the materials from five recycling construction projects. Test results for the wide range of materials indicated that the viscosity blending chart in Figure 2 could be used to establish proportions of aged asphalts and recycling agents necessary to produce the desired viscosity at 140°F (60°C) of the blend. Blends for essentially all of the materials proportioned according to the blending chart met standard ASTM and AASHTO specification requirements for viscosity graded asphalt cements. In a case where a blend did not meet specification requirements, their film oven residue test results for the blend components indicated that large increases in the viscosity of the blend would also be expected when it was subjected to the thin film oven test.

Viscosity temperature susceptibilities of aged asphalts recycling agents and blends of materials were calculated. Blends of aged asphalts and recycling agents with different viscosity temperature susceptibilities proportioned according to the viscosity blend chart resulted in blends with viscosity temperature susceptibilities between those of the components.

Various fractions of aged asphalts, recycling agents and blends of the materials were determined by ASTM Methods D 4124, D 2006 (discontinued) and D 2007. Percentages of the various fractions in blends calculated from the blend proportions and amounts of the fractions in the aged asphalts and recycling agents were essentially the same and generally within 1 to 2 percent of the fractions measured for the the blends. No alterations due to chemical interactions between the various fractions of the aged asphalts and recycling agents were indicated for blends prepared with the viscosity blending chart.

For mix design purposes, the small deviations of blend viscosity from the viscosity blend chart target viscosity would not be significant. The viscosity blending chart that was used is sufficiently accurate for use in mix design procedures for a wide variety of recycling agents conforming to standard specifications for viscosity graded asphalt cements and conforming to the specifications covering the other recycling agents that were used in the study.

For the wide range of aged asphalts, recycling agents and blends of the materials that were studied, no need was indicated for the compositional analysis test data obtained from ASTM Test Methods D 4124, D 2006 (discontinued) and D 2007 for routine mix design. Similarly no need was indicated for the asphaltene settling test data. While compositional analyses tests might be useful for screening potential new recycling agents, their use in recycling mix design would depend on proven relationships between the various fractions of asphalts, their limiting values and the durability and performance of asphalts in pavements. Such relationships for asphalt fractions determined by the compositional analysis test methods used for the study have not been established.

MOISTURE DAMAGE AND STRIPPING BEHAVIOR OF RECYCLED MIXES

Introduction

Moisture-induced changes in the adhesion of asphalt to aggregate and its effects on the mechanical behavior and the performance of asphalt paving mixes are related to many factors. The type and composition of aggregates, consistency of the asphalt, presence of detrimental fires, density and voids properties of mixes, completeness and thickness of asphalt coatings on aggregate, traffic and environmental conditions are all factors that are related to moisture damage. Although many of the factors and mechanisms involved in moisture damage have been studied extensivel , there has been limited success in the development of widely accepted test methods which can be used to predict moisture damage. Many of the factors involved in stripping, and test methods that have been used to indicate stripping are reviewed in a comprehensive state-of-the-art report on moisture damage to asphalt pavement by Taylor and Khosla (20).

The results of studies on asphalt adhesion and disbonding mechanisms by Scott (21), and the stripping test procedures developed by Lottman (22) to predict moisture damage in paving mixes should be applicable to recycled mixes as well as conventional mixes. However differences in the construction processes, the combination of low viscosity recycling agents and new asphalt with the reclaimed asphalt concrete and new aggregate may result in differences in the moisture-induced damage and stripping behavior of recycled mixes as compared to conventional mixes. Loss or weakening of adhesive bonds between asphalt and aggregate in the presence of water and the resultant moisture damage and stripping behavior may also be affected by the rate and extent the recycling agents combine with and charge the properties of the salvaged binder. In any case the disbonding process in recycled mixes as well as in conventional mixes can result from water entering and penetrating the asphalt-mineral interface at a discontinuity in the asphalt film or by water diffusing through an asphalt film.

The most extensive and best documented studies which have established relationships between the mechanical properties of laboratory conditioned specimens and moisture damage and stripping behavior of in-service pavements are those reported by Lottman (23). Correlation studies by Lottman, extending over a period of 5 years and involving 17 pavements in 14 states, demonstrated that indirect tensile tests and moisture conditioning procedures could be used to make reasonably good predictions of mixtures likely to experience moisture damage. Procedures based on Lottman's work were selected for evaluating moisture damage and stripping behavior of recycled mixes because of the promising results obtained for conventional mixes.

Modified NCHRP Project 4-8(3) Moisture Damage Test System

The NCHRP Project 4-8(3) moisture damage test system developed by Lottman determines the change in the indirect tensile strength and indirect resilient modulus of compacted asphalt paving mixtures resulting from use of a vacuum technique to introduce water into the specimens and freeze-thaw conditioning. A few modifications were made in the moisture damage test system for use with recycled mixes primarily to simplify equipment and procedures and to make the tests easier to run for routine use.

Procedures for preparing standard size Marshall or Hveem test specimens described in the mixture design section of the report were used to prepare recycled mix moisture damage test specimens. The specimens were prepared with compositions specified by the job mix formulas used for the recycling construction projects sampled during the study. Test specimens were prepared with air voids within the range of 5.0 to 9.0 percent to correspond more nearly to pavement air voids immediately after pavement construction.

Only the indirect tensile strength test was used for moisture damage testing because of its simplicity, general availability of test equipment to perform the test and its better precision compared to the indirect resilient modulus test. The latter is an alternate test method in the NCHRP Project 4-8(3). Modifications were made in the indirect tensile strength test to make it easier to run with equipment generally more readily available. A vertical deformation rate of 2 inches (51 mm) per minute, and a testing temperature of 77°F (25°C) instead of 55°F (12.8°C) were used. The modifications which allow use of standard Marshall loading equipment and a standard asphalt cement penetration test water bath were formed by Maupin (24) to result in essentially the same tensile strength ratios as the NCHRP Project 4-8(3) indirect tensile strength test procedures. The measurement and calculations of indirect tensile strength were simplified by use of 1/2-in. (12.7-mm) wide concave surface steel loading strips and the commonly used formula to calculate indirect tensile strength. Standard ASTM test methods were used to determine the bulk specific gravity and percent air voids of compacted specimens. Inclusion of these standard test procedures in the moisture damage test system allowed the calculation of percent air voids in specimens filled with water, and bulk volumes of specimens during the various conditioning procedures. Compacted specimen volume determinations were considered important because of volume changes that can result from certain vacuum saturation procedures and conditions which affect mechanical test properties apart from the effects of water on the adhesion of asphalt to the aggregate. The method of test for the effect of water and freezing and thawing on the indirect tensile strength of compacted recycled mixes, based on the NCHRP Project 4-8(3), "Predicting Moisture-Induced Damage to Asphaltic Concrete," is given in Appendix D.

Moisture Damage Tests On Recycled Mixes

Moisture damage tests were run on compacted recycled mix specimens prepared from materials from the five recycling construction projects listed in Table 1. The tests were run immediately after specimens were prepared, after 1 week and after 4 weeks of aging at room temperature to determine short-term aging effects on moisture damage behavior of recycled mixes.

Materials used for the Virginia (U.S. 220), California (Highway 97), Utah (U.S. 89) and North Carolina (I-95) recycling construction projects were reported as generally not susceptible to moisture damage or stripping. The New Mexico (I-40) recycling project was constructed because of pavement distress due to moisture damage and stripping that occurred soon after the pavement was constructed. The new crushed gravel aggregate used for recycling construction was from a source nearby and similar to that used for the original wearing course. The New Mexico project specimens for the moisture damage contained 1 percent by weight of hydrated lime added to the new aggregate and 1/2 percent of a liquid anti-strip agent added to the new asphalt. These were the same amounts as used for the recycling project construction. New Mexico project mix specimens with the same composition without addition of hydrated lime and the liquid anti-stripping agent were prepared for comparison with specimens containing the anti-stripping agents. The composition of compacted recycled mix specimens used for the moisture damage tests are given in Table 43.

Moisture Damage Test Results

The NCHRP Project 4-8(3) moisture damage test system tensile strength ratio, TSR_1, determined after vacuum saturation conditioning, is considered to be a short-term moisture damage measurement simulating moisture damage when the asphalt pavement approaches saturation. The tensile strength ratio, TSR_2, determined after the accelerated conditioning which includes freezing and thawing after vacuum saturation is considered to be an ultimate or long-term moisture damage measurement.

Unaged Specimens

Short-term TSR_1 ratios for unaged recycled mix specimens for the five recycling construction projects ranged between 0.96 and 1.18. There was little if any effect of vacuum saturation conditioning on indirect tensile strength ratios. The vacuum saturation conditioning for determination of short-term TSR_1 ratios resulted in specimen air voids filled with water ranging from 65 to 92 percentage points.

Long-term TSR_2 ratios for unaged recycled mix specimens for the Virginia project, North Caroline project, and for the New Mexico project containing anti-stripping agents ranged between 0.94 and 1.08 indicating little if any effect of accelerated conditioning on the recycled mix specimens. The long-term TSR_2 ratio for the Utah project was 0.90 indicating a slight effect of the accelerated conditioning.

The long-term TSR_2 ratios for unaged specimens for the New Mexico project not containing anti-stripping agents and the California project were respectively 0.72 and 0.65. Long-term TSR_2 ratios for both projects were below the 0.8 ratio suggested in NCHRP Report 246(23) as the minimum acceptable value for ensuring good performance. There was a significant difference in long-term TSR_2 ratio for the New Mexico project unaged specimens containing anti-stripping agents and not containing anti-stripping agents was 0.94 and without anti-stripping agents was 0.72.

The vacuum saturation and accelerated conditioning for TSR_2 ratio determinations resulted in recycled mix specimens air voids filled with water about 10 percentage points greater than for only vacuum saturation conditioning. Specimen air voids filled with water for accelerated condition and specimens ranged between 74 and 100 percent.

A visual stripping rating of "not discernible" for vacuum saturation conditioned unaged specimens was recorded for all of the recycling construction projects. A visual stripping rating of "not discernible" was also recorded for accelerated conditioned unaged specimens for all projects except for the New Mexico project not containing anti-stripping agents. It was rated "very slight". The visual stripping ratings were not necessarily related to tensile strength ratios for accelerated conditioned specimens. The California project specimens were rated "not discernible" while its TSR_2 ratio was below 0.8 for accelerated conditioned unaged specimens.

Aged Specimens

Short-term TSR_1 ratios for all projects randomly increased and decreased during 4 weeks of aging and ranged between 0.96 and 1.18. The variations were about the same or less than the single-operator standard deviation for indirect tensile strength ratios reported for the method. There was little if any effect of aging on the short-term TSR_1 ratios.

The aging of recycled mix specimens for up to 4 weeks resulted in little if any effect on long term TRS_2 ratios for specimens from the California, New Mexico and North Carolina projects. However, the long-term TSR_2 ratios for the Virginia and Utah projects decreased about 20 percent. The decrease may have in part been caused by an increase of about 10 percent in the indirect tensile strength of subset I dry specimens for the Virginia and Utah projects.

Overall the short-term aging effects on moisture damage test tensile strength ratios were insignificant or relatively small. The results of the moisture damage tests on the recycled asphalt concrete mixes for the five recycling construction project are summarized in Table 44.

Specimen Volume Change

The bulk volumes of short-term moisture damage test specimens were determined after compaction, after vacuum saturation, and after vacuum saturation and 3-hour water soak conditioning. The bulk volumes of long-term moisture damage test specimens were determined at the same stages and also after freeze-thaw and 3-hour water soak conditioning.

Specimen volume changes determined after vacuum saturation which consisted of 30 minutes in water at 77°F (25°C) temperature at atmospheric pressure which followed 30 minutes in water under a partial vacuum of 4 inches (102 mm) Hg absolute pressure were consistent for the five projects. The volumes of all specimens, unaged and aged up to 4 weeks, decreased slightly or remained essentially the same.

Volume change behavior differed for the various projects for short-term TSR_1 specimens subjected to 3-hour water soak after vacuum saturation, and for long-term TSR_2 specimens subjected to freeze-thaw and 3-hour water soaks after the vacuum saturation. Specimen volumes, compared to original volumes after compaction, increased after vacuum saturation and 3-hour water soaking for the Virginia, California and Utah projects, but remained essentially unchanged for the New Mexico and North Carolina projects. This behavior was consistent for unaged specimens and for specimens aged up to 4 weeks. Although the 3-hour water soaking resulted in volume increases for three of the projects, there were no significant or only slight reductions in short-term TSR_1 tensile strength ratios.

Specimen volumes compared to original volumes after compaction increased after the freeze-thaw and 3-hour water soak conditioning for the California project, the Utah project and the New Mexico project not containing anti-stripping agents; specimen volumes remained essentially unchanged for the Virginia project, North Carolina project and the New Mexico project containing anti-stripping agents. This behavior was consistent for unaged specimens and specimens aged up to 4 weeks.

Specimens for the California project, Utah project and New Mexico project not containing anti-stripping agents which increased in volume due to the freeze-thaw and water soak conditioning experienced significant reductions in long-term TSR_2 tensile strength ratios. The tensile strength ratios were reduced to levels below the 0.8 minimum ratio suggested in NCHRP Report 246. This behavior was different than for specimens which increased in volume when subjected only to vacuum saturation and 3-hour water soak. Volume changes and tensile strength ratios obtained from the moisture damage tests for the five recycling construction projects are shown in Figures 3 thru 8.

Summary and Conclusions

The moisture damage and stripping behavior of five recycled mixes were studied using a method of testing for effect of water, freezing, and thawing on indirect tensile strength of compacted recycled asphalt mixtures. The test method was based on the NCHRP Project 4-8(3) "Predicting Moisture-Induced Damage to Asphaltic Concrete." Short-term TSR_1 ratios determined by the test method predicted that no short-term moisture damage would be experienced in the recycled mixtures that were used for five hot-mix recycling projects. Long-term TSR_2 ratios determined by the method predicted that moisture damage would ultimately be experienced in two recycling projects located in California and Utah. Long-term TSR_2 ratios for a New Mexico project recycled mix tested with and without addition of anti-stripping agents predicted moisture damage would ultimately be experienced in the mix not containing the anti-stripping agents. The results indicated ability of the method to differentiate between recycled mixes made with and without anti-stripping agents. The study also indicated that short-term aging of recycled mix test specimens of up to 4 weeks had little if any effect on the moisture damage test results.

Moisture damage has not been reported on any of the projects to date. In general the studies indicated that the method of test should be useful when reclaimed asphalt concrete or aggregates with records of susceptibility to moisture damage are prepared for use in recycled mixes. Future inspection and testing of the two recycling projects where ultimate moisture damages were predicted are recommended to verify the reliability of the modified method of test and the criteria for indirect tensile strength ratios suggested in NCHRP Report 146.

RECYCLED MIX DESIGN CRITERIA

Introduction

One of the study objectives was to develop mix design procedures and criteria for recycled mixes using Marshall and Hveem test apparatus. Modifications in the standard ASTM and AASHTO Marshall and Hveem test methods are necessary to provide for incorporation of reclaimed asphalt concrete and recycling agents or new asphalt cement in specimens prepared for design of recycled mixes. Besides necessary changes in the standard test methods, additional tests are required for the design of recycled mixes. The asphalt content of the reclaimed asphalt concrete, the gradation of the aggregate and properties of the asphalt recovered from the reclaimed asphalt concrete must be determined. Procedures are required for selecting grade of new asphalt or recycling agent for the recycled mix. Also different calculation procedures are required to determine proportions of the materials used to prepare series of test specimens through a range of recycling agent or new asphalt contents. Formulas developed by Folge (25) were used for calculating amounts of the different materials used to prepare specimens.

For convenience in the graphs and figures in this report, new low viscosity paving grade asphalt cements and the other low viscosity recycling agents that were used during the studies are referred to as recycling agents.

Preparation of Marshall and Hveem Test Specimens

The Marshall and Hveem mechanical test properties, particularly Marshall, are affected by mixing and compaction procedures used to prepare test specimens. As few changes as possible were made in the standard procedures for preparing Marshall and Hveem test specimens to minimize these effects on test properties of recycled mix specimens.

Procedures adopted in the study for preparation of Marshall test specimens included the following:

1) Heating the new aggregate 50°F (28°C) above the standard Marshall test mixing temperature (temperature at which the viscosity of the asphalt is 170 ± 20 CSt);

2) Heating the reclaimed asphalt concrete to the standard Marshall compaction temperature (temperature at which the viscosity of the asphalt is 280 ± 30 CSt);

3) Dry mixing the new aggregate and reclaimed asphalt concrete 30 seconds;

4) Adding the new asphalt or recycling agent previously heated to the mixing temperature, to new aggregate and reclaimed asphalt concrete and mixing 60 seconds; and

5) Transferring completed batches of mix to covered tins and placing them in an oven maintained at the compaction temperature for a minimum of one hour and not exceeding two hours prior to compaction of the specimens.

The mixing and compaction temperatures were based on the viscosity of the blend of the recycling agent and/or new asphalt and asphalt extracted and recovered from the reclaimed asphalt concrete. The blend is determined during the mix design.

The mixing and compaction procedures used to prepare Hveem test specimens were identical to those for the Marshall test specimens except temperatures for heating new aggregate, recycling agent, new asphalt and reclaimed asphalt concrete and completed batches of mixture were based on the standard Hveem test mixing and compaction temperatures. The mixtures were also placed in an oven for 1 to 2 hours.

Plans for the Study

Two methods for proportioning mixes for Marshall and Hveem mix design tests were studied. In one method the blend of aggregate recovered from the reclaimed asphalt concrete and the new aggregate is held constant as the amount of recycling agent or new asphalt is varied. The ratio of recycling agent or new asphalt to the aged asphalt then varies. In the other method, the ratio of the recycling agent or new asphalt to the aged asphalt in the recycled mix is maintained constant as the proportion of new aggregate and reclaimed asphalt concrete aggregate is varied.

Marshall and Hveem mix designs were performed for each of the five recycling construction projects listed in Table 1 that were sampled for the statistical sample plan studies. The reclaimed asphalt concrete samples were prepared for Marshall and Hveem mix designs by thoroughly mixing representative portions of the randomly selected samples of processed reclaimed asphalt concrete. Asphalt extraction tests and tests on the recovered asphalts and aggregates were performed on the composite sample using the same test procedures described previously for the statistical sampling plan studies. Marshall and Hveem mix designs were then performed using the following steps.

1) Based on established or proposed proportions of reclaimed asphalt concrete and new aggregate, calculate ratio of new aggregate to aggregate in the reclaimed asphalt concrete and calculate a combined grading meeting specification requirements using gradations of the aggregate from the reclaimed asphalt concrete and the new aggregate;

2) Determine approximate asphalt demand of the combined aggregates by an empirical formula or a centrifuge kerosene equivalent test;

3) Calculate percent of recycling agent required to satisfy asphalt demand, and the ratio of recycling agent to total asphalt as established in steps 1 and 2;

4) Using a viscosity blending chart for reclaimed asphalt and recycling agent and the ratio of recycling agent to total asphalt content, select a recycling agent that produces desired viscosity of the blend of recycling agent and reclaimed asphalt;

5) Keeping the ratio of new aggregate to total aggregate constant, calculate amounts of each ingredient in the mix for the mix design specimens with 0.5 percent increments of recycling agent or new asphalt above and below the estimated amount of recycling agent established in step 3; and

6) Prepare and test specimens using Marshall or Hveem equipment.

Step 5 was changed by calculating amounts of each ingredient keeping the ratio of the recycling agent to the total asphalt content constant during the studies when the alternate method was used for proportioning mixture.

Mix design test data were interpreted, and optimum recycling agent or new asphalt contents were determined insofar as possible in accordance with the Marshall and Hveem methods of mix design and design criteria published by the Asphalt Institute (25). The detailed mix design methods for reclaimed asphalt concrete using Marshall and Hveem apparatus developed and used during the study are given in Appendix E.

Marshall and Hveem Method Mix Designs

Marshall and Hveem method mix design test results for the five recycling projects described in Table 1 were generally similar to results obtained for conventional mixes. However some differences were noted. Stability test levels, particularly Marshall, tended to be higher than for conventional mixes. For some mixes, peaks in Marshall stability versus asphalt recycling agent content curves were not obtained and stabilities decreased with increasing recycling agent content for new mixes.

It is difficult to make accurate specific gravity determinations for reclaimed asphalt concrete aggregates because fine aggregate particles are lost during extraction tests and it is difficult to wet extracted aggregate with water. Therefore maximum specific gravities were determined by ASTM Method D 2041 for each of the different asphalt content mixes during the mix design and these values were used to calculate percent air voids in the compacted specimens. Consequently, the customary percent voids in the mineral aggregates were not considered for the Marshall method mix design. Aggregate gradings used for mix designs for the five recycling projects are given in Table 45.

Marshall specimens were compacted with a mechanical hammer. A check on the calibration of the hammer at the end of the study indicated that 37 blows with the mechanical hammer produced specimen densities approximately the same as standard 50 blow hand hammer compaction. As a result, densities of specimens prepared for the mix design studies may have been slightly higher, and air voids slightly lower than for standard.

Results of the Marshall and Hveem mix designs are described briefly in the following paragraphs.

North Carolina

North Carolina (I-95) recycled mixes were designed with 45 percent reclaimed asphalt concrete which contained 5.7 percent asphalt and 55 percent new aggregate. Properties of the AC 2.5 grade asphalt cement recycling agent used, aged asphalt and a 2,000 poise viscosity target blend of the two are given in Table 38. The mix design viscosity blending chart procedures indicated that the AC 2.5 grade asphalt cement was an appropriate viscosity recycling agent.

An optimum recycling agent content of 2.5 percent by weight of mix was indicated by the Marshall method 50-blow design, using the aggregate blend constant method. However percent air voids were below the recommended 3 percent minimum at this recycling agent content. Selection of a design recycling agent content of 1.9 percent resulted in 4.0 percent air voids, 2700 pounds (12,010 N) stability, and a flow value of 9. Essentially the same optimum recycling agent content was indicated using the asphalt blend constant method. The selection of a design recycling agent content of 2.3 percent produced 4.0 percent air voids, 2700 pounds (12,010 N) stability and flow value of 10. Marshall mix design data for the North Carolina project are given in Table 46 and Marshall test property curves are given in Figure 9 for the aggregate blend constant method. Marshall mix design data for the North Carolina project are given in Table 47 and Marshall test property curves are given in Figure 10 for the asphalt blend constant method.

An optimum recycling agent content of 0.9 percent by weight of mix, 5.0 percent air voids and stabilometer value of 44 was indicated by the Hveem method design using the aggregate blend constant method. An optimum recycling agent content of 2.2 percent by weight of mix, 4.4 percent air voids and stabilometer value of 43 was obtained by the Hveem method design using the asphalt blend constant method. Hveem mix design data for the North Carolina project are given in Table 48 and Hveem mix design test property curves are given in Figure 11 for the aggregate blend constant method.

Virginia

Virginia (U.S. 220) recycled mixes were designed with 40 percent reclaimed asphalt concrete which contained 5.2 percent asphalt and 60 percent new aggregate. Properties of the AC-5 grade asphalt cement recycling agent used, aged asphalt and a 2,000 poise viscosity target blend of the two are given in Table 39. The mix design viscosity blending chart procedures indicated that the AC-5 grade asphalt cement was an appropriate viscosity recycling agent.

Stability decreased with increasing recycling agent contents and a peak was not obtained in the stability curve for the Marshall method 50-blow design using the aggregate blend constant method. A design recycling agent content of 2.7 percent which provided 4.0 percent air voids, indicated 3,100 pounds (13,789 N) stability and a flow value of 13. Marshall method mix design data for the Virginia project are given in Table 49 and Marshall Method design test property curves are given in Figure 12 for the aggregate blend constant method.

An optimum recycling agent content of 2.2 percent by weight of mix was obtained by the Hveem method of mix design using the aggregate blend constant method. The stabilometer value was 42 and percent air voids were 4.6 percent at the optimum recycling agent content. Hveem method mix design data for the Virginia project are given in Table 50 and Hveem method design test properties curves are given in Figure 13 for the aggregate blend constant method.

New Mexico

New Mexico (I-40) recycled mixes were designed with 40 percent reclaimed asphalt concrete containing 4.7 percent asphalt and 60 percent new aggregate. Properties of the 85-100 penetration grade asphalt cement recycling agent used, aged asphalt and a 2,000 poise viscosity target blend of the two are given in Table 42. The mix design viscosity blending chart procedures indicated that the 85-100 penetration grade asphalt cement was an appropriate viscosity recycling agent.

Stability decreased with increasing recycling agent contents and a peak was not obtained for the Marshall method 75-blow design using the aggregate blend constant method. A design recycling agent content of 2.4 percent recycling agent by weight of mix which provided 4.0 percent air voids indicated 3,200 pounds (14,234 N) stability and a flow value of 10. Marshall method mix design data for the New Mexico project are given in Table 51 and Marshall method mix design test property curves are given in Figure 14 for the aggregate blend constant method.

An optimum recycling agent content of 2.4 percent by weight of mix was obtained by the Hveem method of mix design using the aggregate blend constant method. The stabilometer value was 44 and air voids were 4.6 percent at the optimum recycling agent content. Hveem method mix design data for the New Mexico project are given in Table 52 and Hveem method mix design test property curves are given in Figure 15.

California

California (Highway 97) recycled mixes were designed with 52 percent reclaimed asphalt concrete containing 5.2 percent asphalt and 48 percent new aggregate. Properties of aged asphalt and AR 1000 and RA 500 recycling agent and 2,667 poise viscosity target blends are given in Table 40. The mix design viscosity blending chart procedures indicated that the RA 500 recycling agent was an appropriate viscosity recycling agent, and that the AR 1000 grade asphalt cement was slightly high in viscosity and a marginal recycling agent for the California project when 52 percent of reclaimed asphalt concrete was used.

An optimum recycling agent content of 2.1 percent by weight of mix for the RA 500 recycling agent was indicated by the Hveem method of mix design using the aggregate constant method. The stabilometer value was 44 and the air voids were 4.0 percent at the optimum recycling agent content. Hveem mix design data for the California project mix with the RA 500 recycling agent are given in Table 53 and Hveem test property curves are given in Figure 16 for the aggregate blend constant method.

A slighty higher optimum recycling agent content of 2.4 by weight of mix was indicated for the RA 500 recycling agent mix using the asphalt blend constant method. At this recycling agent content a Hveem stabilometer value of 42 and 40 percent air voids were obtained. Hveem mix design data for the California project mix with RA 500 recycling agent are given in Table 54 and Hveem test property curves are given in Figure 17 for the asphalt blend constant method.

An optimum recycling agent content of 2.6 percent by weight of mix for the AR 1000 grade asphalt cement recycling agent was indicated by the Hveem method of mix design using the aggregate grading constant method. The stabilometer value was 40 and air voids were 4.2 percent at the recycling agent content. Hveem mix design data for the California project mix with the AR 1000 recycling agent are given in Table 55 and Hveem test property curves are given in Figure 18 for the aggregate blend constant method.

Stability decreased with increasing recycling agent contents and a peak was not obtained in the stability curve for the Marshall 75-blow design for the California project mix with the AR 1000 recycling agent using the aggregate blend constant method. Selection of a design recycling agent content of 2.3 percent by weight of mix which provided 4.0 percent air voids, indicated 5,000 pounds (22,241 N) stability and a flow value of 12. Marshall method design data for the California project recycled mix containing the AR 1000 recycling agent are given in Table 56 and Marshall method mix design test property curves are given in Figure 19 for the aggregate blend constant method. A slightly higher design recycling agent content of 2.5 percent by weight of mix was indicated by the Marshall

75-blow method design for the California project recycled mix containing AR 1000 recycling agent using the asphalt blend constant method. A stability of 5,000 pounds (22,241 N), 12 flow value and 4.0 percent air voids were indicated for this design recycling agent content. Marshall method design data for the California project recycled mix containing the AR-1000 recycling agent are given in Table 57 and Marshall method design test property curves are given in Figure 20 for the asphalt blend constant method.

Utah

The Utah (U.S. 89) recycled mix was designed with 50 percent reclaimed asphalt concrete containing 6.2 percent asphalt and 50 percent new aggregate. Properties of the AC-5 grade asphalt cement recycling agent, low viscosity (96 cSt) recycling agent and a 2,000 poise viscosity target blend of the three materials are given in Table 41. The mix design viscosity blending chart procedures indicated that the AC-5 grade asphalt cement was an appropriate viscosity recycling agent and that a small amount (1.2 percent of blend) of the low viscosity (96 cSt) recycling agent could be used along with the AC-5 recycling agent to obtain a blend closer to the 2,000 poise target blend.

Stability decreased with increasing recycling agent contents and a peak stability curve was not obtained for the Marshall 50-blow design method for the Utah combined AC-5 grade asphalt cement and low viscosity (96 cSt) recycling agent mix using the aggregate blend constant method. The selection of a design recycling agent content of 2.1 percent recycling agent which provided 4.0 percent air voids indicated 4,200 pounds (18,682 N) stability and a flow value of 13. About the same recycling agent content was indicated using the asphalt blend constant method. Selection of a design recycling agent content of 2.4 percent for the asphalt blend constant method which provided 4.0 percent air voids indicated 3,800 pounds (16,903 N) stability and a flow value of 13. Marshall mix design method data for the Utah recycling project are given in Table 58 and Marshall mix design test property curves are given in Figure 21 for the aggregate blend constant method. Marshall mix design method data for the Utah recycling project are given in Table 59 and Marshall mix design test property curves are given in Figure 22 for the asphalt blend constant method.

Recycled Pavement Cores

Cores were obtained from four of the recycling projects shortly after they were constructed and before they were subjected to appreciable traffic. Ten or more cores were obtained from each project. The coring locations were selected randomly. Relationships between the stability, density, and percent air voids of cores and the same test properties of laboratory prepared and compacted specimens were quite consistent. Test properties of the cores are given in Table 60.

The densities and percent air voids of cores agreed closely with laboratory-prepared specimens compacted with both Marshall and Hveem equipment. The air voids in the laboratory-prepared specimens at design recycling agent contents tended to be within about one percentage point of those in the cores. Marshall and Hveem stabilities of laboratory specimens at design recycling agent contents were always higher and generally about double the stability of cores. Marshall flow values of laboratory specimens at design recycling agent contents were consistently lower than those of cores.

Experience has generally indicated that Marshall and Hveem stabilities of laboratory-prepared specimens of conventional mixes may not agree with stabilities of cores. Pavement cores generally have lower stabilities than laboratory-prepared specimens and part of the difference can be attributed to lower densities of cores compared to laboratory-prepared samples. There appears to be little difference between relationships between stabilities of laboratory-prepared specimens and pavement cores for recycled mixes and those relationships for conventional mixes. However higher levels of stability, particularly Marshall stability, of laboratory-prepared specimens of recycled mixes as compared to conventional mixes were obtained during the studies.

The generally good agreement between the density and voids of laboratory-prepared specimens and the same properties of pavement cores for recycled mixes supports the use of conventional dense graded asphalt concrete Marshall and Hveem air voids mix design criteria for recycled mixes.

Asphalt extraction test results and test properties of extracted aggregate and asphalt for the recycled pavement cores from the four projects are given in Table 61. Aggregate gradations for the core samples indicated slightly larger amounts passing the No. 8 and 200 sieves than for the laboratory mix design specimens. Viscosities and penetrations of the recovered asphalts are typical of those obtained for conventional mixes.

Dynamic modulus, $|E^*|$, tests were also performed on the cores according to ASTM Test Method D 3497, except cores were stacked to obtain required specimen height. Modulus test results are given in Table 62. Comparison of the moduli of cores from the recycled pavements with moduli data reported by Witczak (27) and Shook (28) for a large number of conventional dense-graded asphalt concrete mixes indicates about the same moduli at temperatures of 41°F (5°C) and 77°F (25°C) for the recycled and conventional dense-graded asphalt concrete mixes. Moduli of the recycled asphalt concrete mixes at 104°F (40°C) are slightly less than conventional dense-graded asphalt concrete.

Marshall and Hveem Method Mix Design Study Conclusions

Marshall and Hveem mix design test property curves for the recycled mixes were generally similar to those obtained for dense-graded asphalt concrete made with new aggregate and asphalt. Marshall and Hveem stability levels for recycled mixes were higher than for conventional mixes. The Marshall stability versus asphalt content curves did not peak for some mixes or tended to peak at asphalt contents lower than normally obtained for new materials. In general, the optimum asphalt contents selected from the Marshall mix design curves using average asphalt contents required to produce maximum density, peak stability, and 4 percent air voids were similar to optimum asphalt contents selected to yield 4 percent air voids, and resulted in mix designs meeting the criteria established for new material mixes. Optimum amounts of new asphalt or recycling agent indicated by the Marshall and Hveem designs were generally close to those used for the construction of the field projects sampled for the studies. Also there was reasonably good agreement between optimum recycling agent contents determined using Marshall and Hveem apparatus and design methods.

The measurement of recycled mix design specimen air void contents is more difficult than for specimens made with all new materials. Determining theoretical maximum specific gravity (ASTM Test Method D2041) of mixtures at all asphalt contents, and use of these values for calculating percent air voids provides the most accurate determination of percent air voids in compacted mixtures. The laboratory work in proportioning recycled mixes and calculations of recycled mixture proportions are more time consuming and difficult than for asphalt concrete mix design.

The mix design studies indicated that Marshall and Hveem test properties do vary slightly depending on whether the ratio of the recycling agent to the total asphalt content is maintained constant or is varied. However, the optimum recycling agent contents are similar for both methods of proportioning.

CONCLUSIONS

Conclusions resulting from the study are as follows.

1. Plans that were developed for obtaining random samples of asphalt concrete from pavements to be recycled using a hot-recycling process can be applied to the existing pavement, to milled material samples from trucks or to milled or other material processed and stored in stockpiles. A random sampling plan should be used to obtain reclaimed asphalt concrete samples for laboratory mix design.

2. In general asphalt pavements that are candidates for recycling can be expected to have a comparatively high level of variability. Some improvement may be obtained during the processing from pavement to plant through a milling operation, or by separating the job into subunits that might have different mix designs.

3. A viscosity blending chart based on an approximate linear relationship for plots of the logarithm of the logarithm of viscosity in centipoises at 140°F (60°C) of aged and new asphalt or recycling agent versus percent of new asphalt or recycling agent in the blend was found suitable for establishing proportions of aged asphalt and new asphalt or recycling agents required to obtain a desired blend viscosity.

4. A wide range of aged asphalts and recycling agents proportioned and blended according to the viscosity blending chart met standard ASTM and AASHTO specification requirements for viscosity-graded asphalt cements.

5. Various compositional analysis fractions of blends calculated from blend proportions and from measured amounts of each fraction in the aged asphalt and recycling agent were generally within 1 to 2 percentage points of measured fractions in blends. No alterations due to chemical interactions between the various fractions of the wide range of aged asphalts and recycling agents were indicated for blends prepared with the viscosity blending chart.

6. For the wide range of asphalt materials studied no need was indicated in routine mix design for the asphalt compositional analysis data obtained from ASTM Test Methods D 4124, D 2006 (discontinued) and D 2007. While such data might be useful for screening potential recycling agents, use in recycling mix design would be dependent on the establishment of valid relationships between the various fractions of asphalt of their limiting values and the durability and performance of asphalts in pavements.

7. The method of test used during the study to determine the effect of water, freezing and thawing or indirect tensile strength of recycled asphalt mix, based on NCHRP Project 4-8(3) "Predicting Moisture-Induced Damage to Asphaltic Concrete," differentiated between recycled mixes made with and without anti-stripping agents, and indicated that short-term aging of recycled mix specimens of up to four weeks had little if any effect on moisture damage test results.

8. Study results indicated that the method of test for effect of water, freezing and thawing on the indirect tensile strength of recycled mixes should be useful when reclaimed asphalt concrete or aggregate with records of susceptibility to moisture damage are proposed for use in recycled mixes.

9. Marshall and Hveem mix design test property curves for recycled mixes determined by mix design procedures developed by mix design procedures developed during the study were generally similar to those obtained for dense-graded asphalt concrete made with new aggregate and asphalt. However Marshall stability and Hveem stabilometer value levels for recycled mixes were higher than for conventional mixes, and Marshall stability versus asphalt content curves did not peak for some mixes or tended to peak at asphalt contents lower than normally obtained for new materials.

10. Optimum amounts of new asphalt or recycling agent indicated by Marshall and Hveem designs were generally close to those that were used for the construction of the field projects that were sampled. There was reasonably good agreement between optimum new asphalt recycling agent contents determined using Marshall and Hveem test apparatus and the design method developed during the study.

RECOMMENDATIONS

1. Future inspection and testing of recycling construction projects is recommended to verify the reliability of the test method and proposed criteria for indirect tensile strength ratios.

2. The proportioning method which keeps the aggregate grading constant while the ratio of recycling agent to total asphalt content varies appears to be the most practical. (The method which varies the aggregate grading makes the batching of laboratory specimens more difficult and time-consuming and the grading could go out of specifications.)

3. The optimum new asphalt or recycling agent contents indicated by the test properties and the generally good agreement between the density and percent air voids of the laboratory specimens and the same properties of the recycled mix pavement cores generally support the use of conventional dense-graded asphalt concrete Marshall and Hveem mix design criteria, such as those recommended by The Asphalt Institute (26), for recycled mixes.

4. Use of the conventional criteria are suggested until additional data correlating field performance and the laboratory mix design test properties become available. Although they may be valid, further study is necessary before the percent voids in mineral aggregate requirements used in Marshall design criteria for conventional asphalt concrete are applied to recycled mixes.

5. The final mix design (job mix formula) should be verified using the reclaimed and processed pavement material generated for use on the project.

6. It is recommended that materials having a high level of variability, as indicated by the statistical analyses, be mixed and processed to reduce the variations, or that the job be separated into subunits requiring different mix designs. If the variability cannot be reduced, then the amount of reclaimed material used in the design should be minimized. Analyses can be performed on the combined materials (aged plus virgin) at different proportions to establish an acceptable amount.

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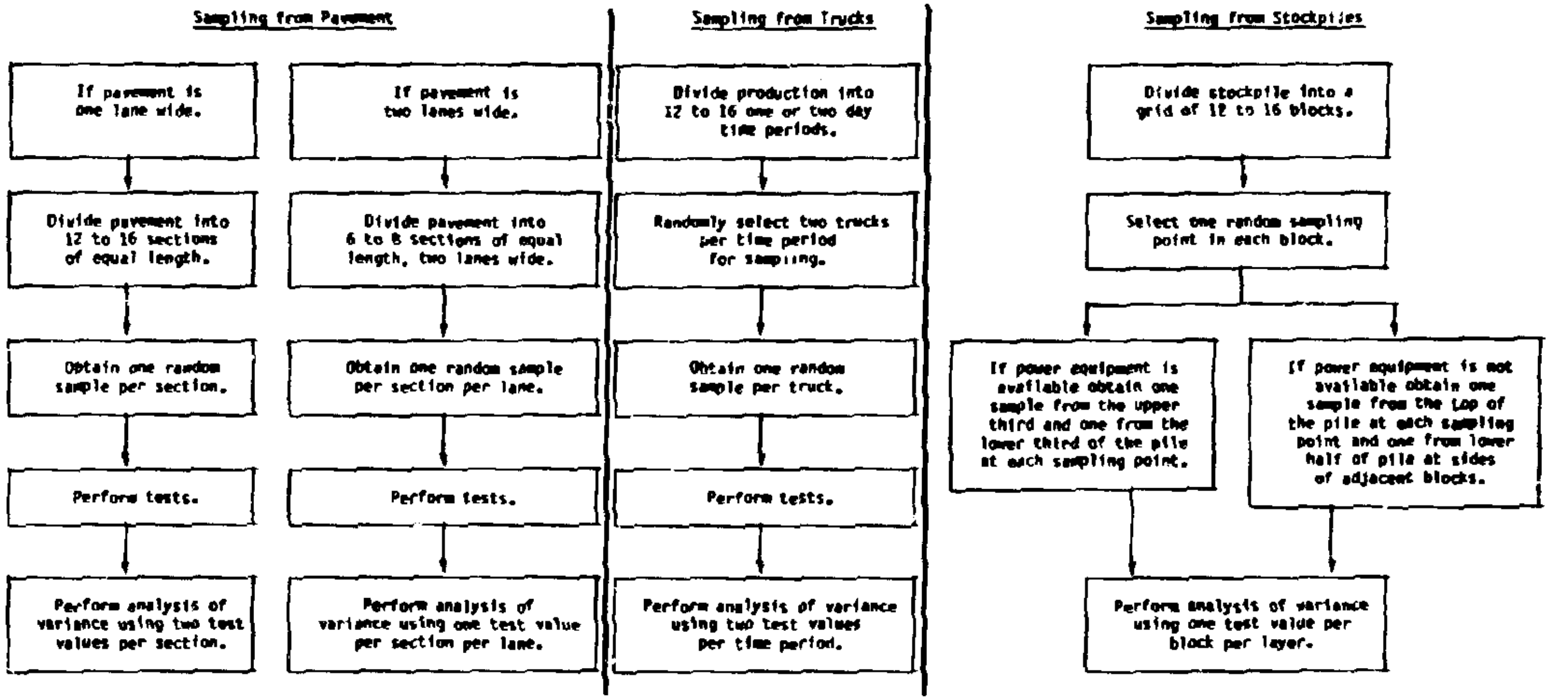

Figure 1 - Flow Chart of Sampling Plans

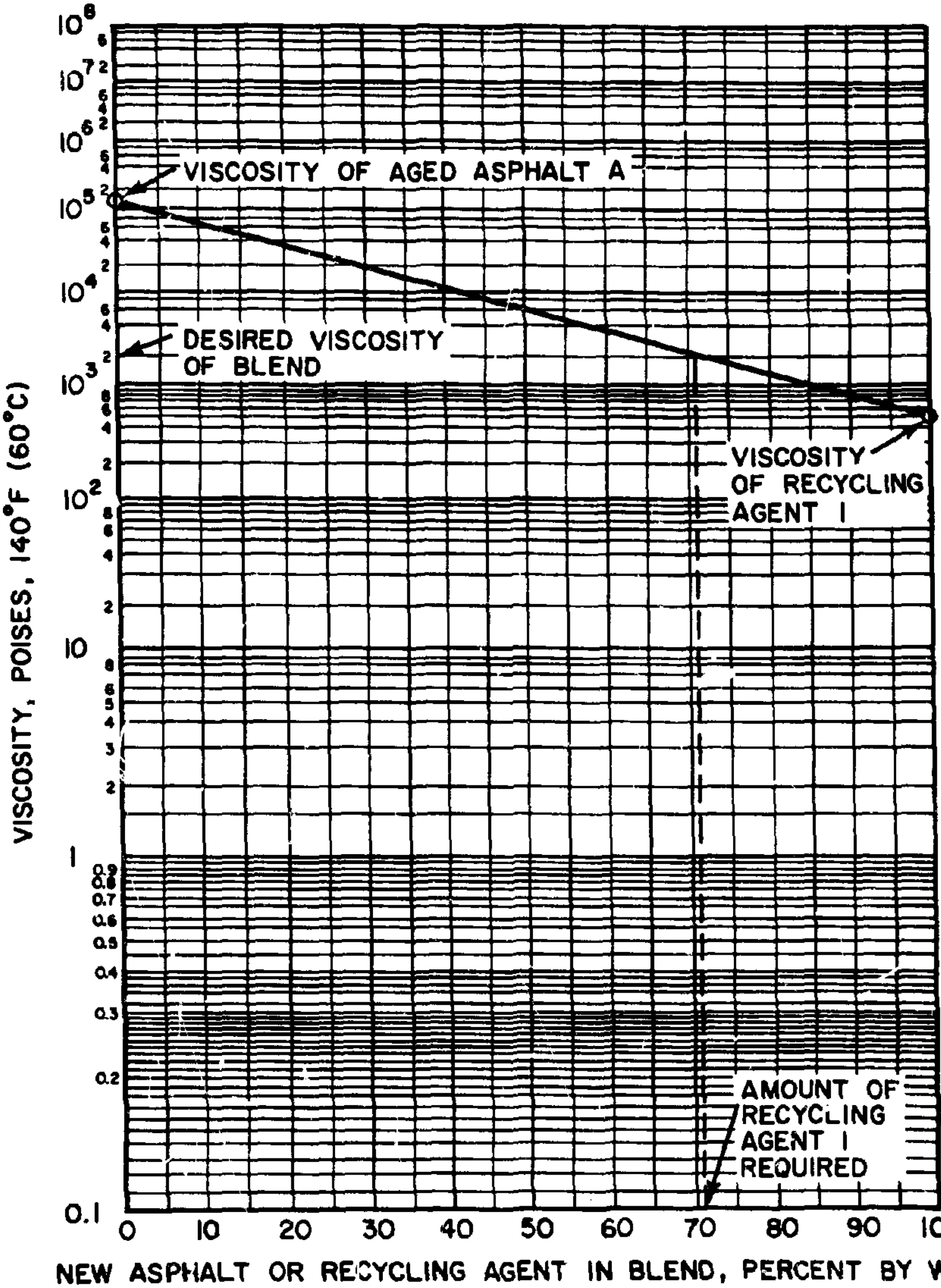

Figure 2 - Use of a viscosity blending chart to determine amount of recycling agent to blend with aged asphalt to obtain a blend viscosity of 2000 poises.

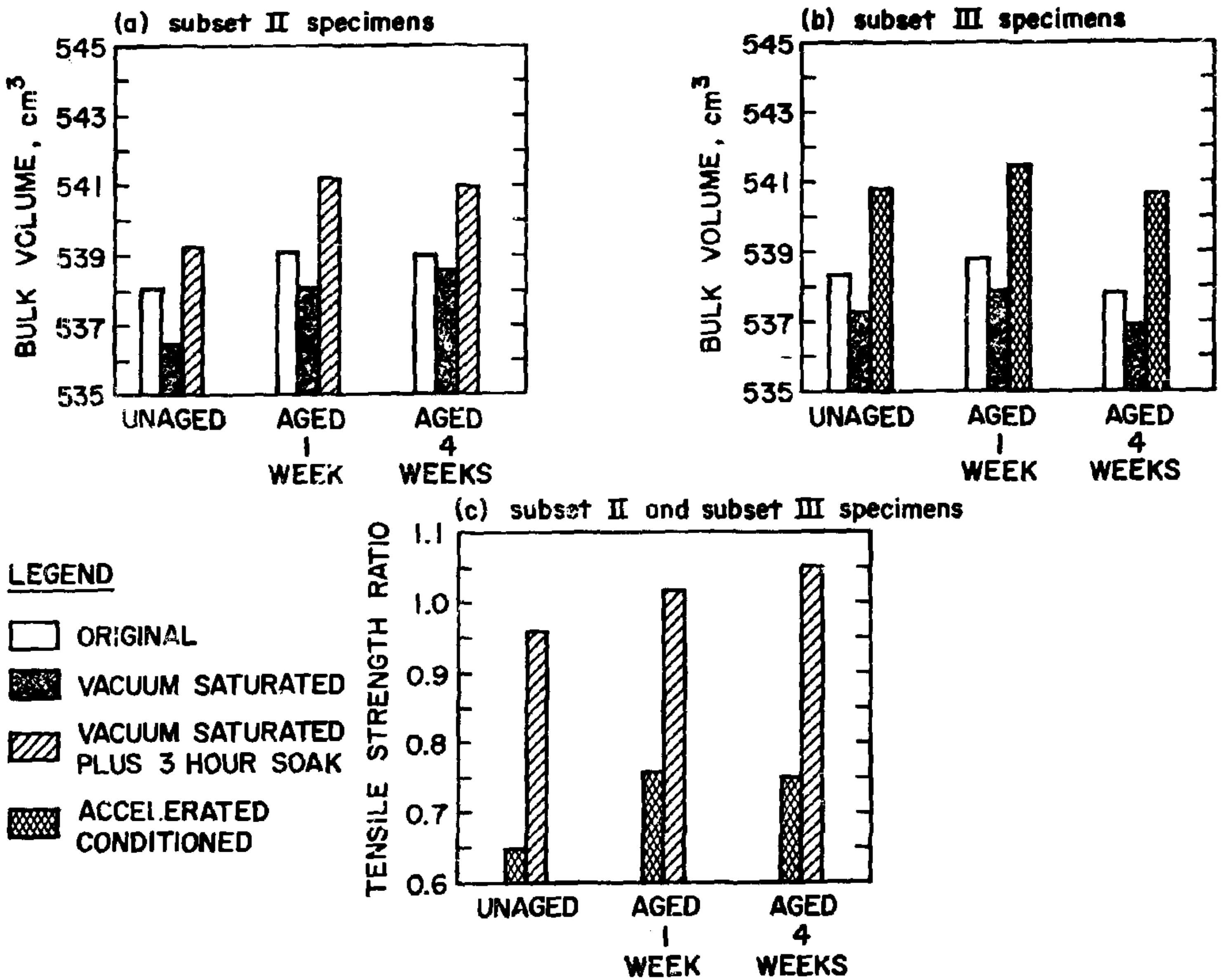

Figure 3 - Volume change and tensile strength ratios for California (Highway 97) recycled mix moisture damage test specimens.

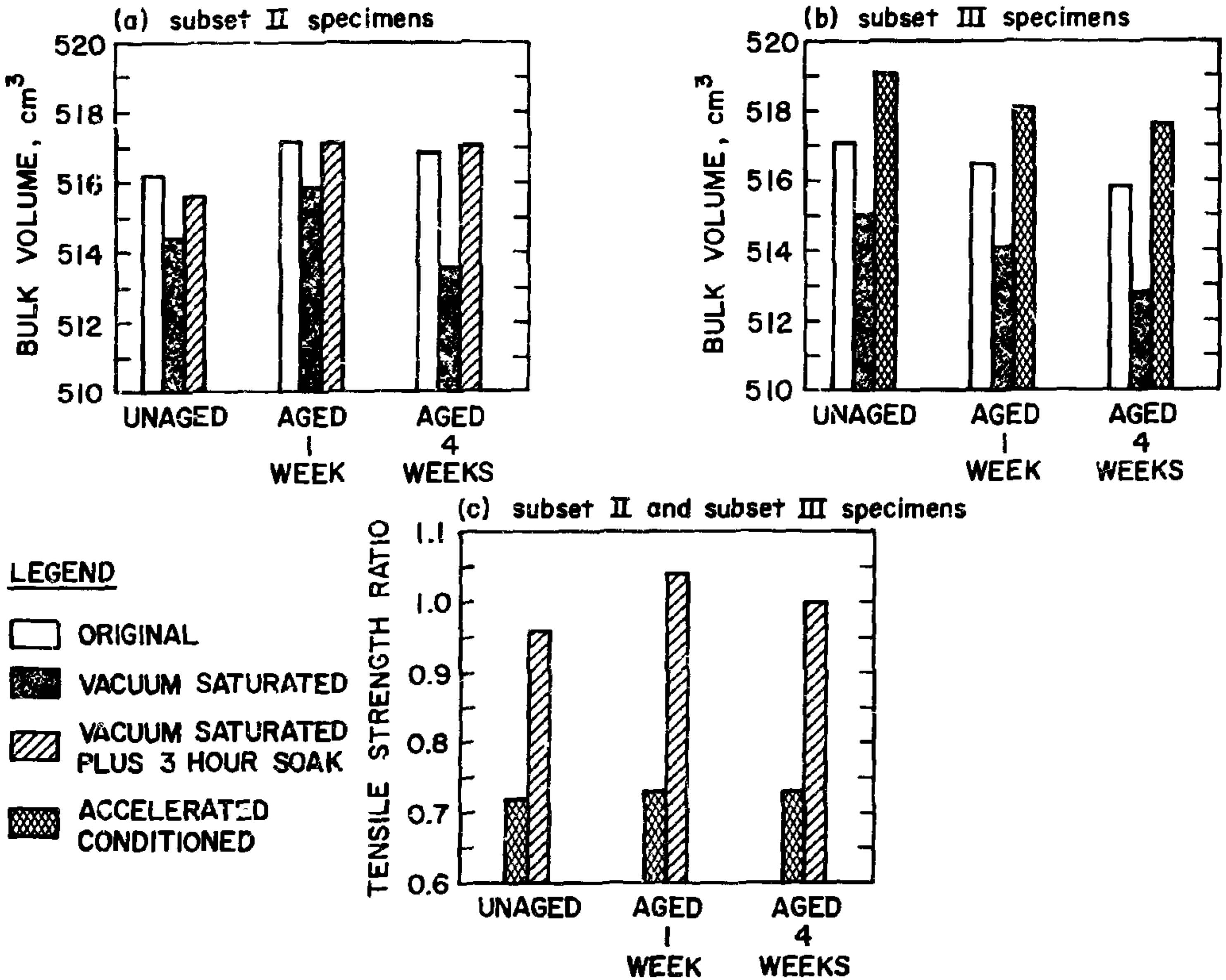

Figure 4 - Volume change and tensile strength ratios for New Mexico (I-40) recycled mix moisture damage test specimens not containing anti-stripping agents.

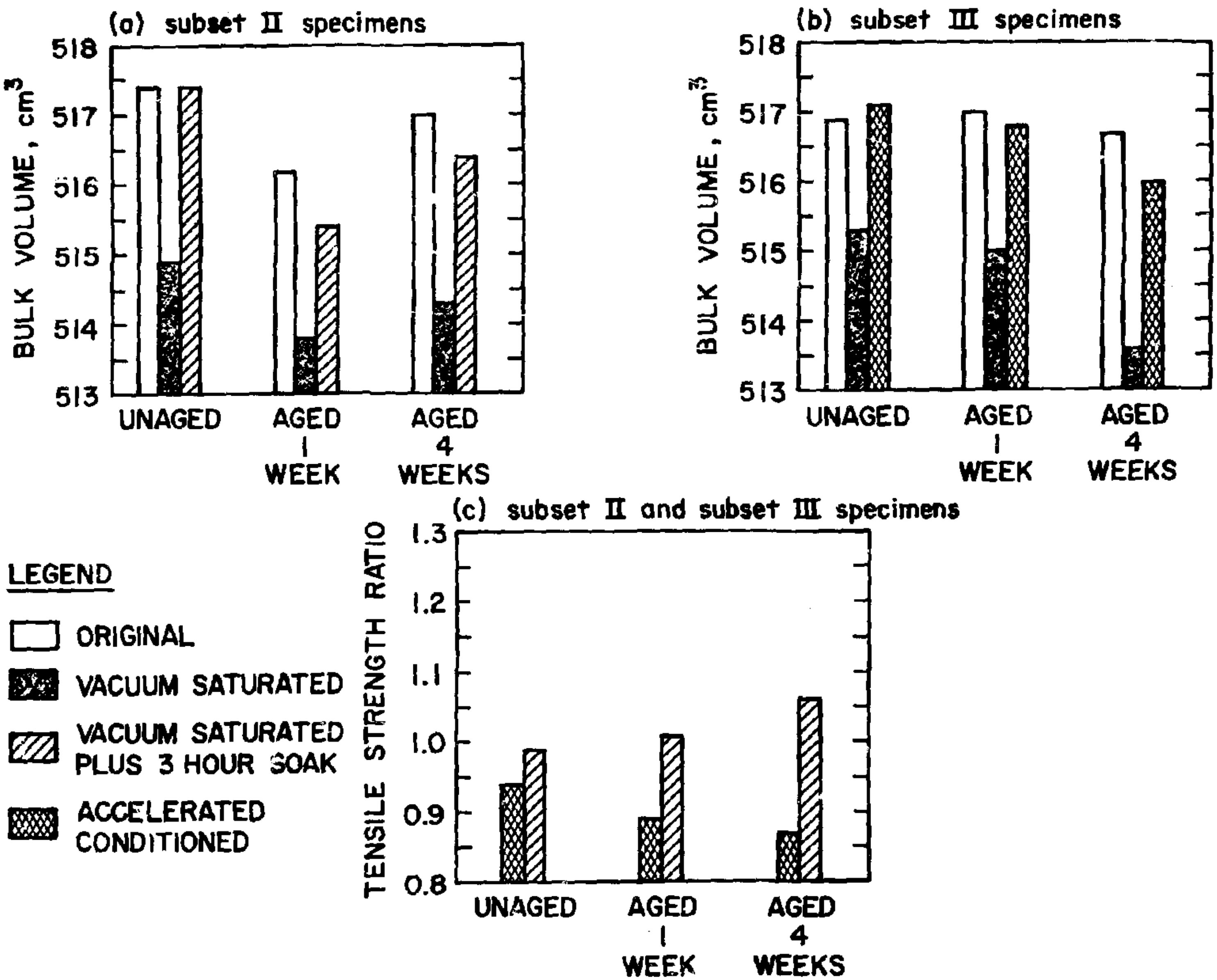

Figure 5 - Volume change and tensile strength ratios for New Mexico (I-40) recycled mix moisture damage test specimens containing anti-stripping agents.

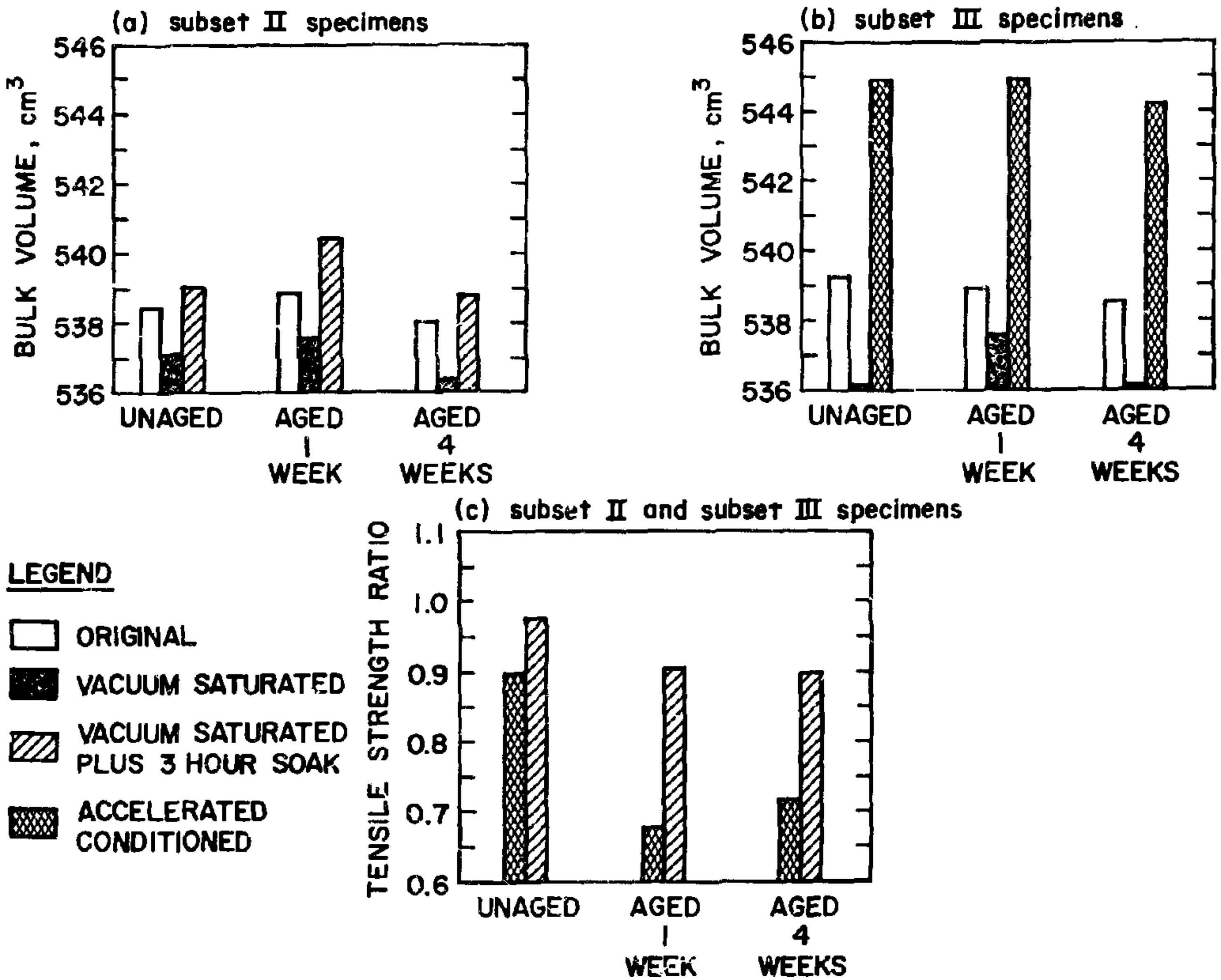

Figure 6 - Volume change and tensile strength ratios for Utah (U.S. 89) recycled mix moisture damage test specimens

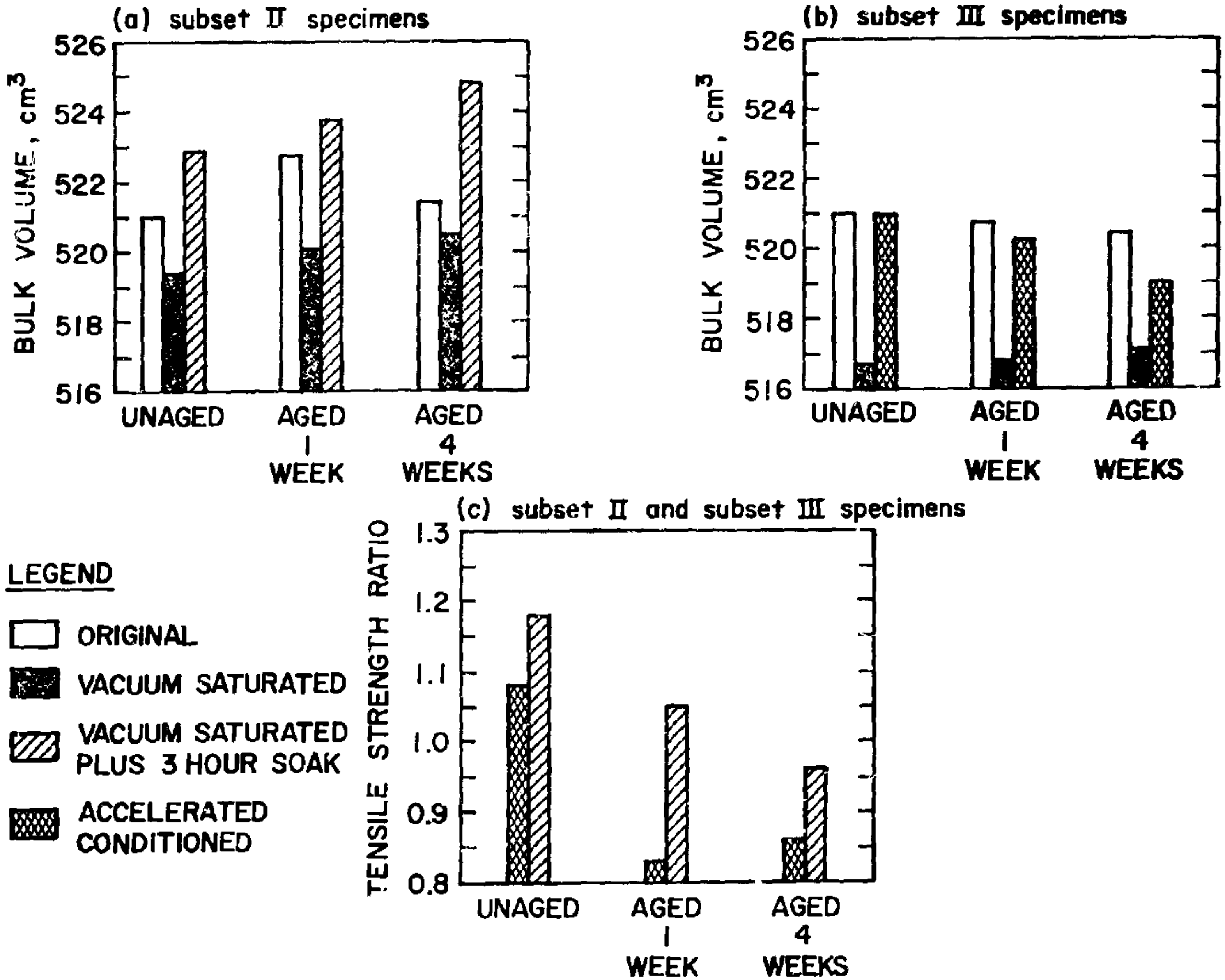

Figure 7 - Volume change and tensile strength ratios for Virginia (U.S. 220) recycled mix moisture damage test specimens.

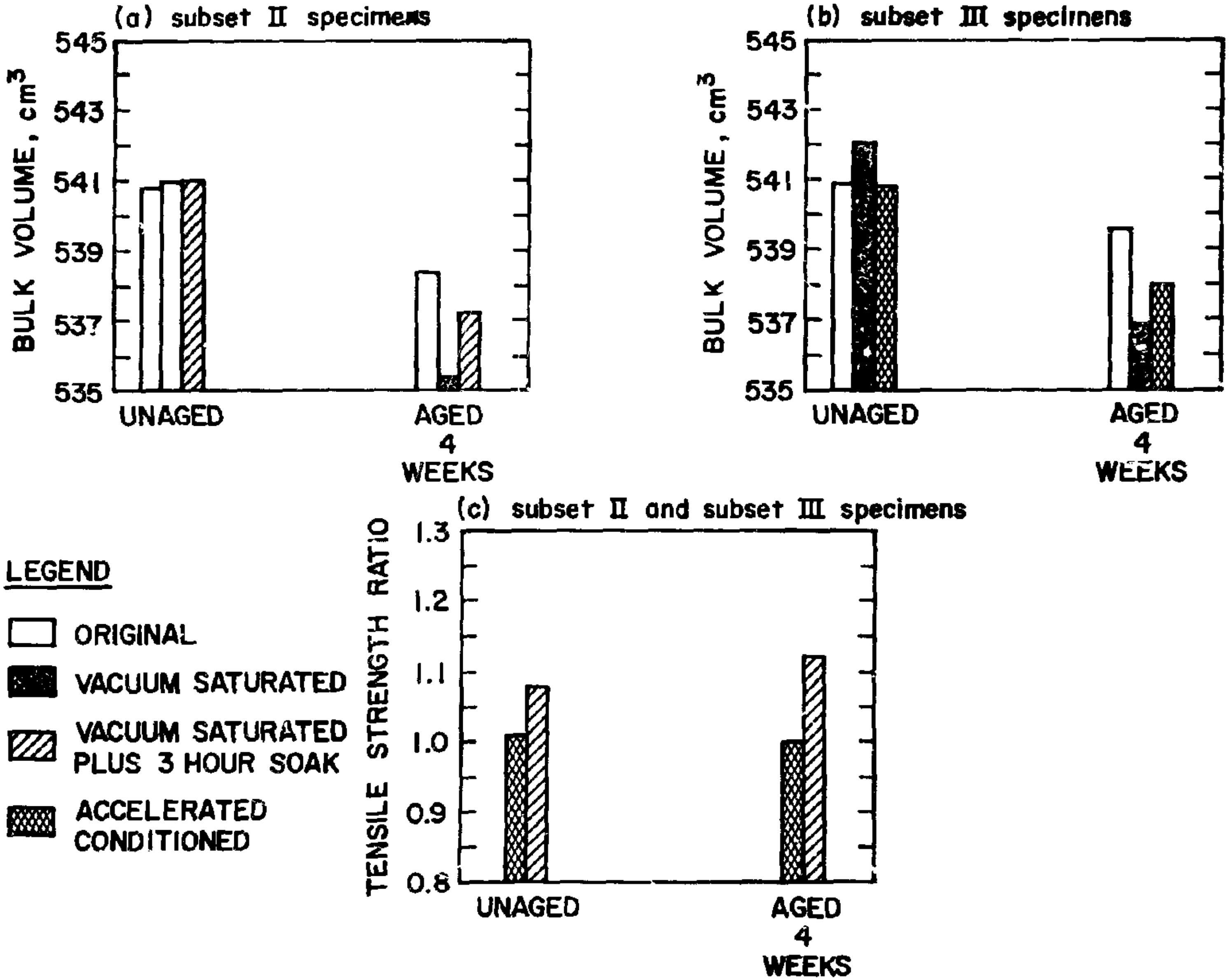

Figure 8 - Volume change and tensile strength ratios for North Carolina (I-95) recycled mix moisture damage test specimens.

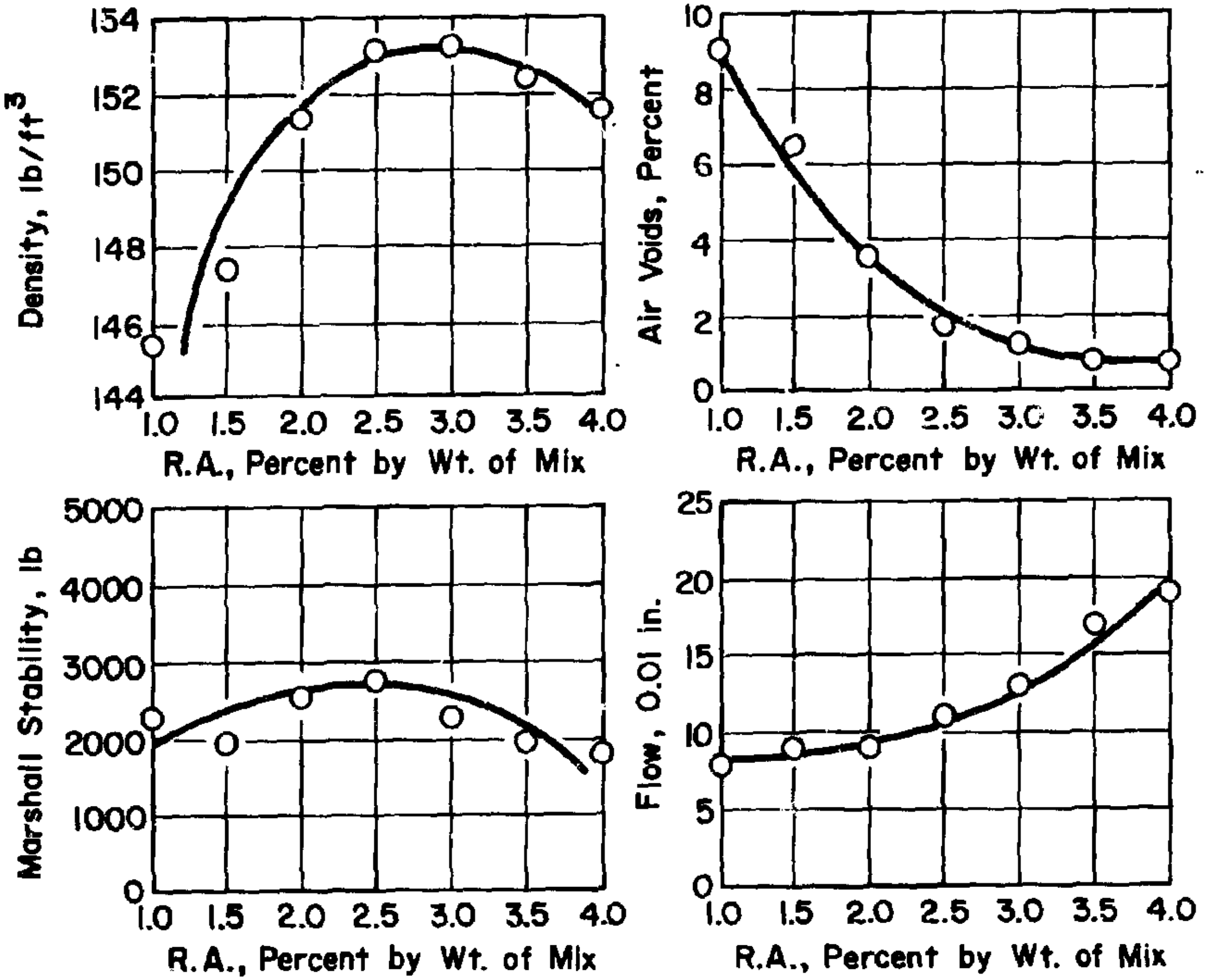

Figure 9 - Marshall Method mix design test property curves for North Carolina (I-95) recycled mix (aggregate blend constant).

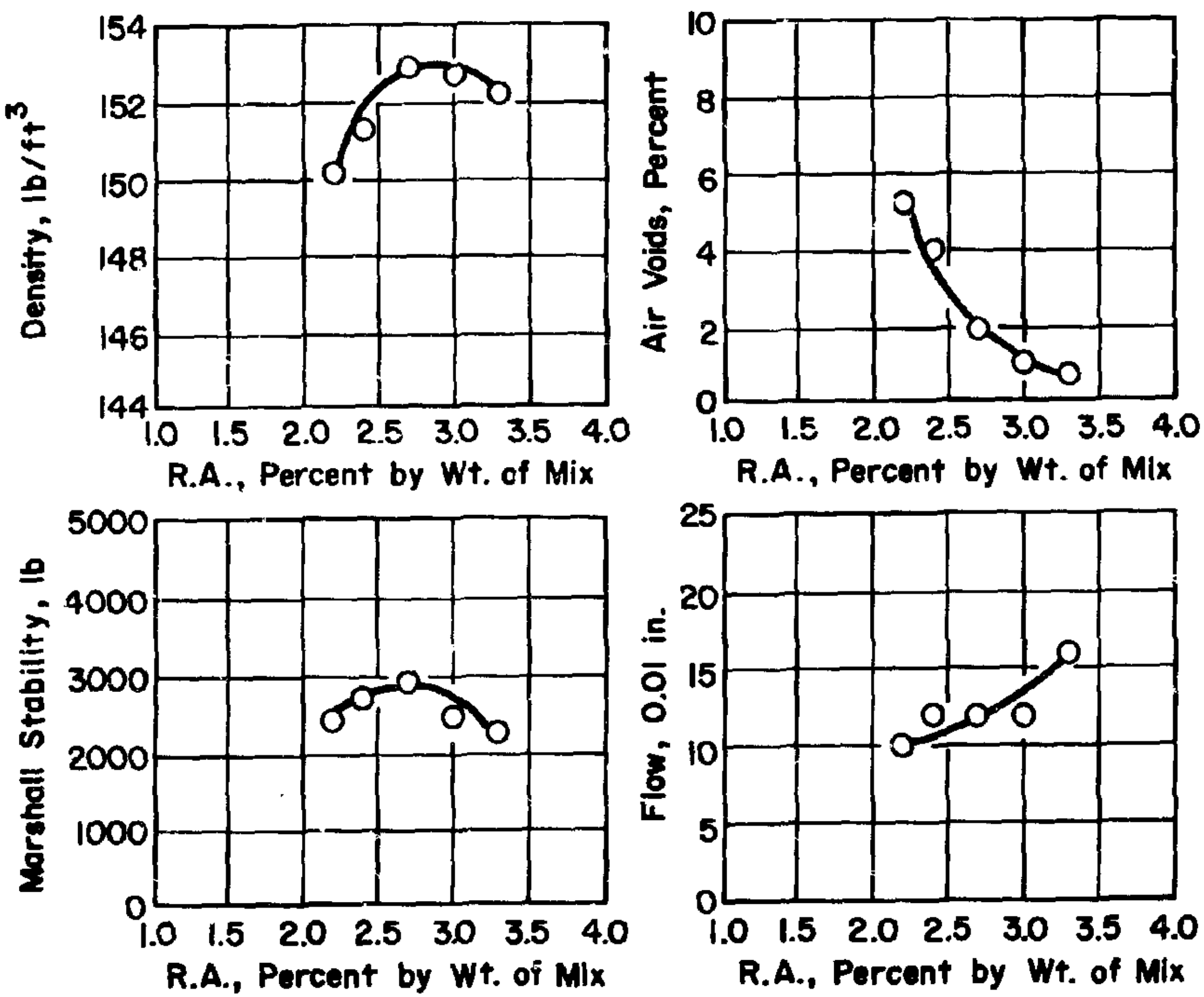

Figure 10 - Marshall Method mix design test property curves for North Carolina (I-95) recycled mix (asphalt blend content).

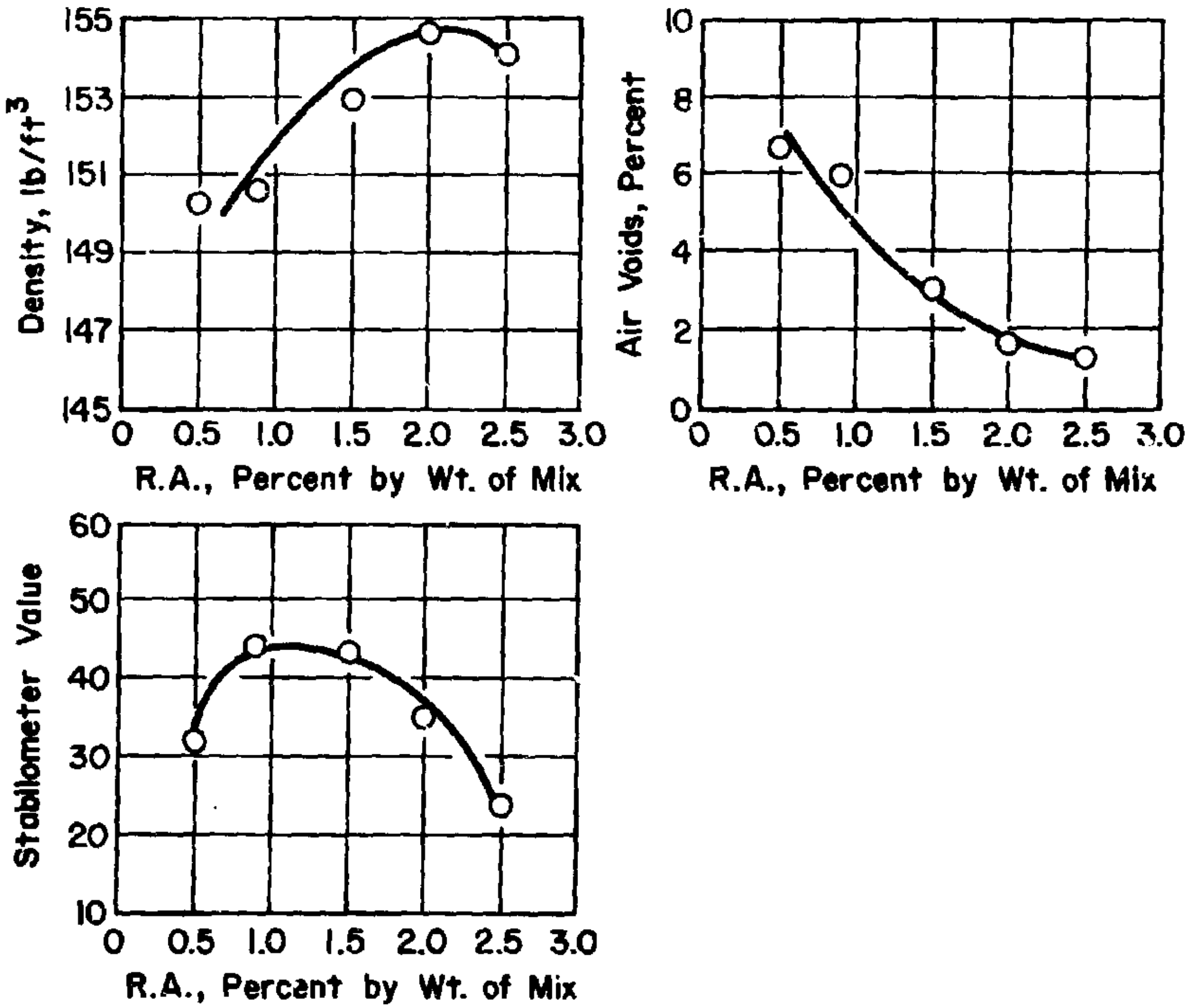

Figure 11 - Hveem Method mix design test property curves for North Carolina (I-95) recycled mix (aggregate blend constant).

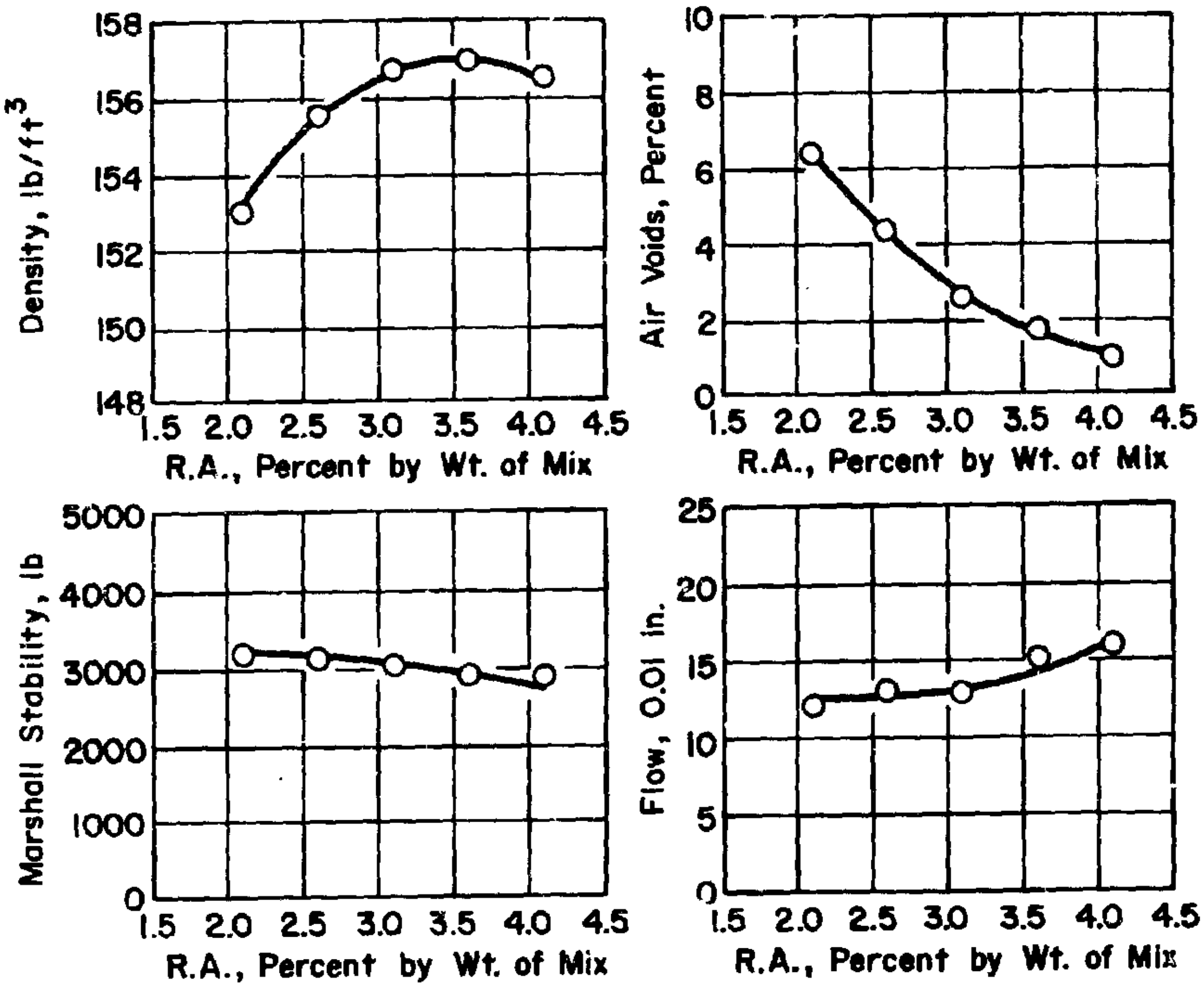

Figure 12 - Marshall Method mix design test property curves for Virginia (U.S. 220) recycled mix (aggregate blend constant).

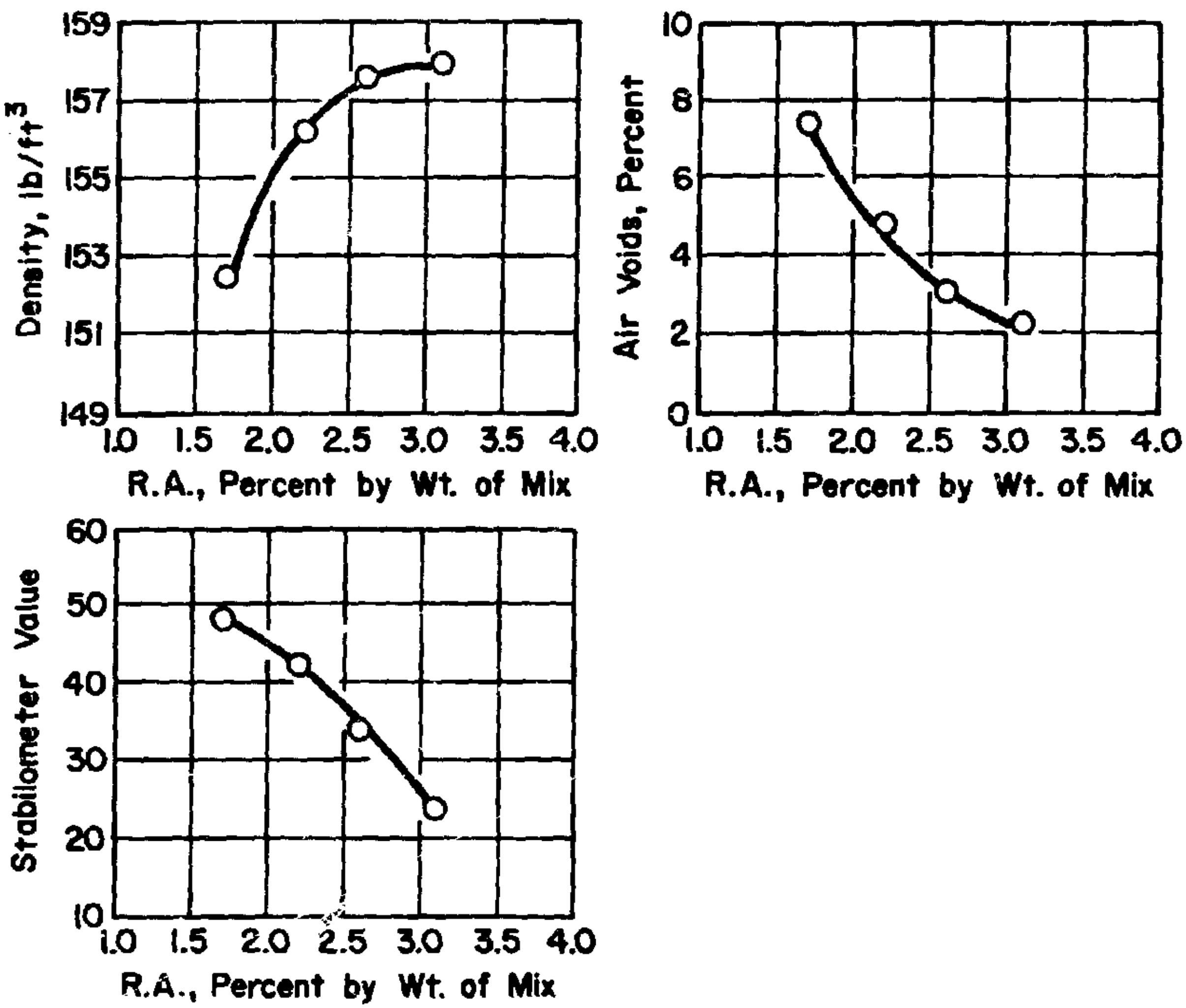

Figure 13 - Hveem Method mix design test property curves for Virginia (U.S. 220) recycled mix (aggregate blend constant).

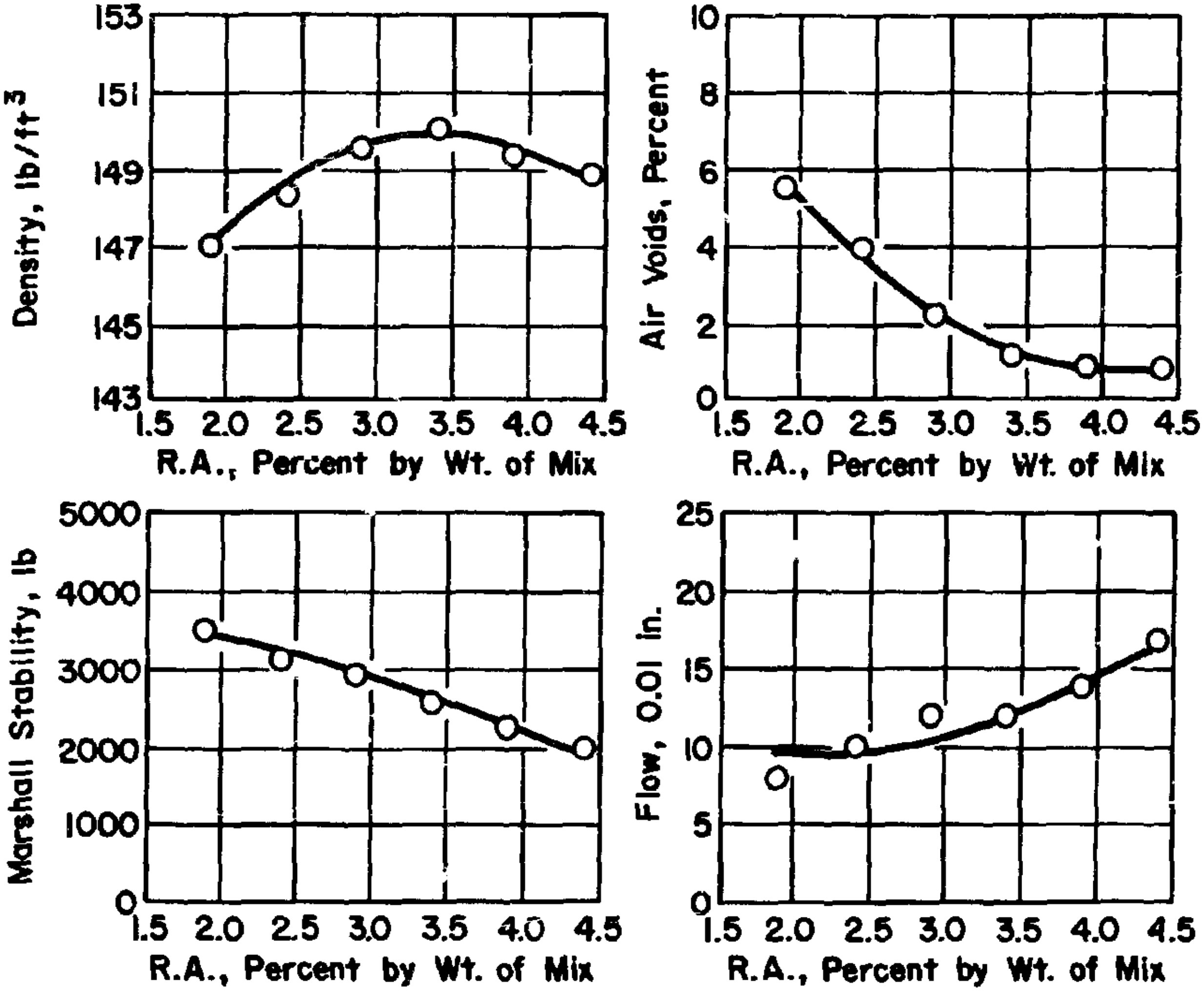

Figure 14 - Marshall Method mix design test property curves for New Mexico (I-40) recycled mix (aggregate blend constant).

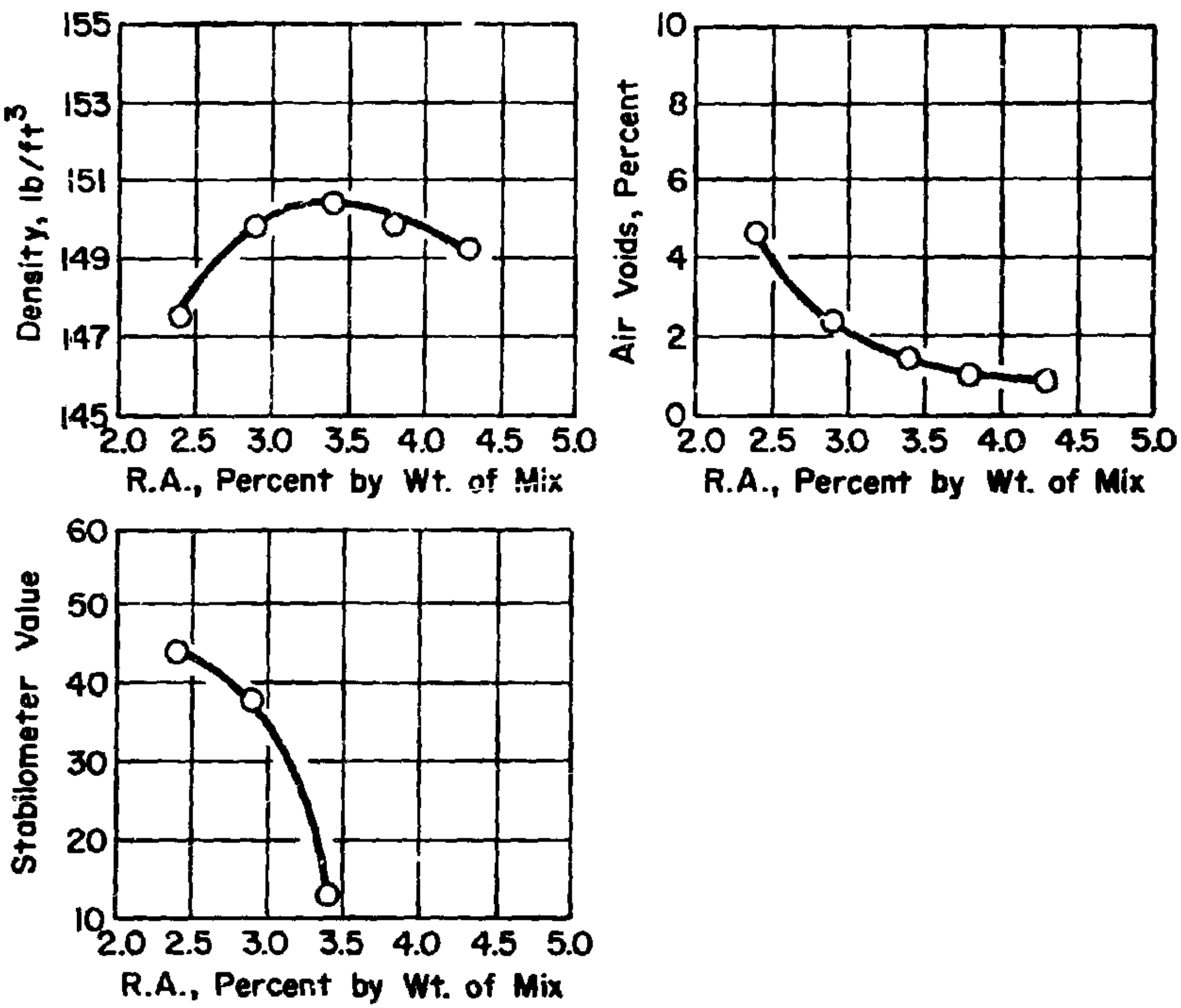

Figure 15 - Hveem Method mix design test property curves for New Mexico (I-40) recycled mix (aggregate blend constant).

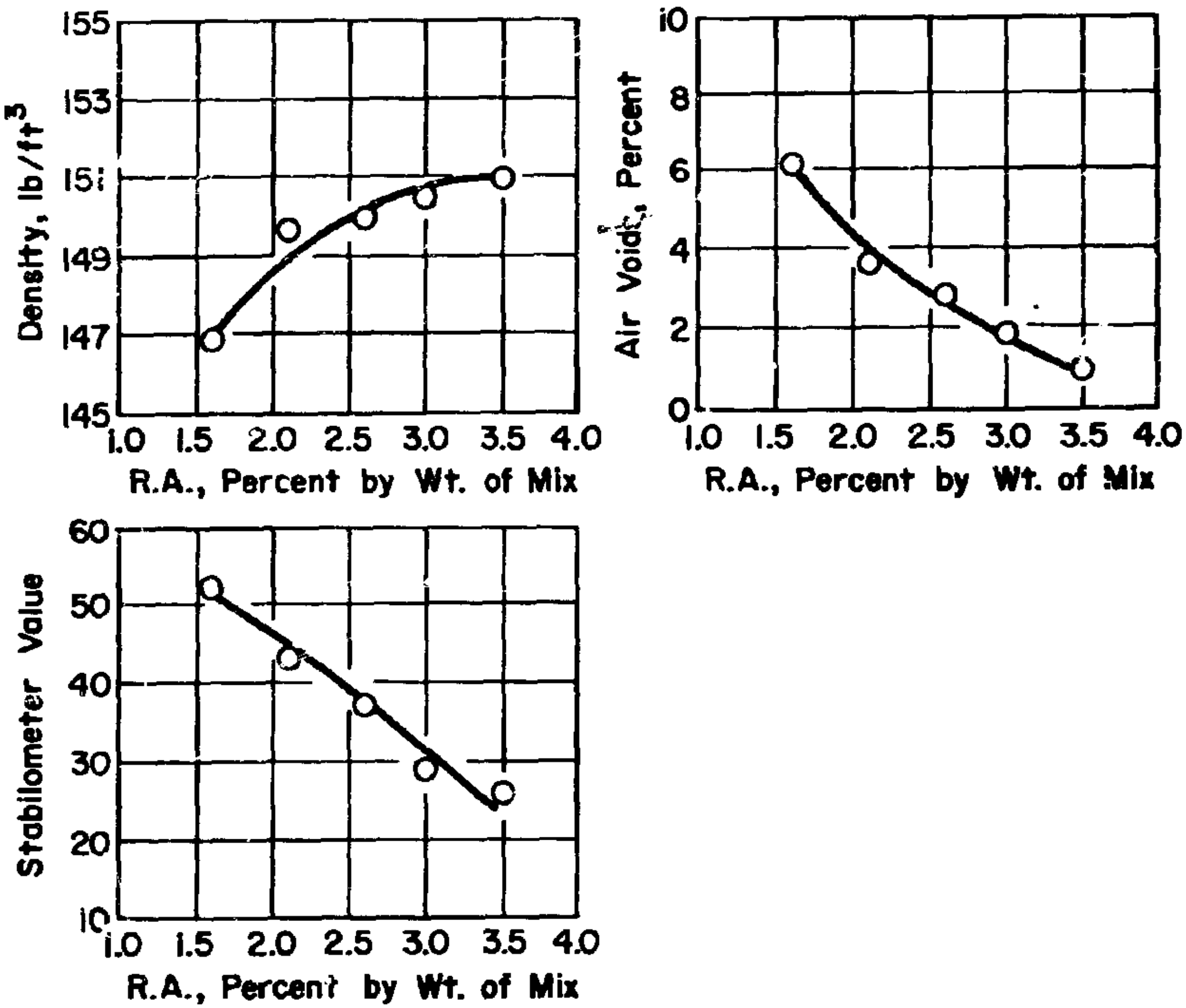

Figure 16 - Hveem Method mix design test property curves for California (Highway 97) recycled mix containing RA 500 recycling agent (aggregate blend constant).

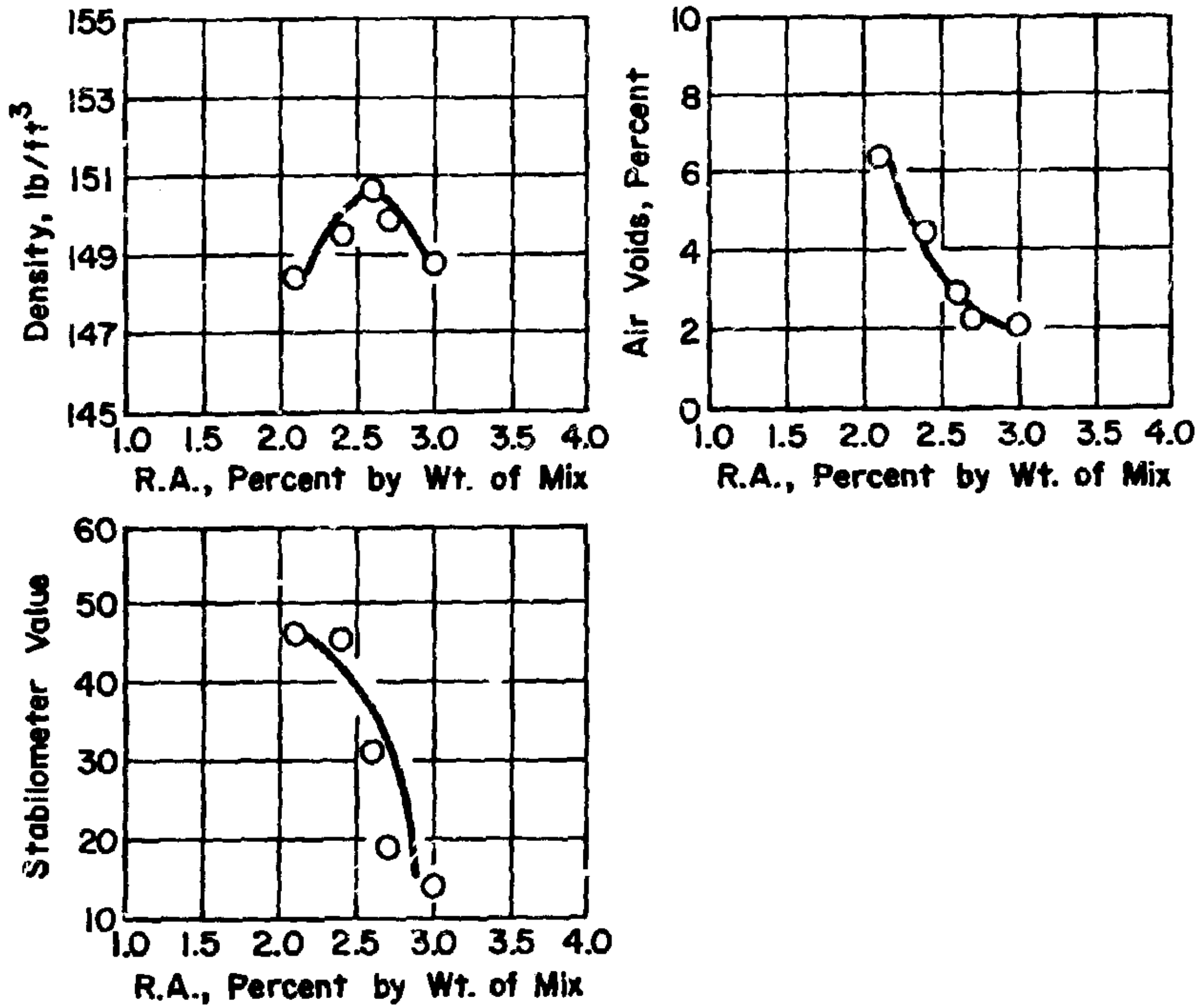

Figure 17 - Hveem Method mix design test property curves for California (Highway 97) recycled mix containing RA 500 recycling agent (asphalt blend constant).

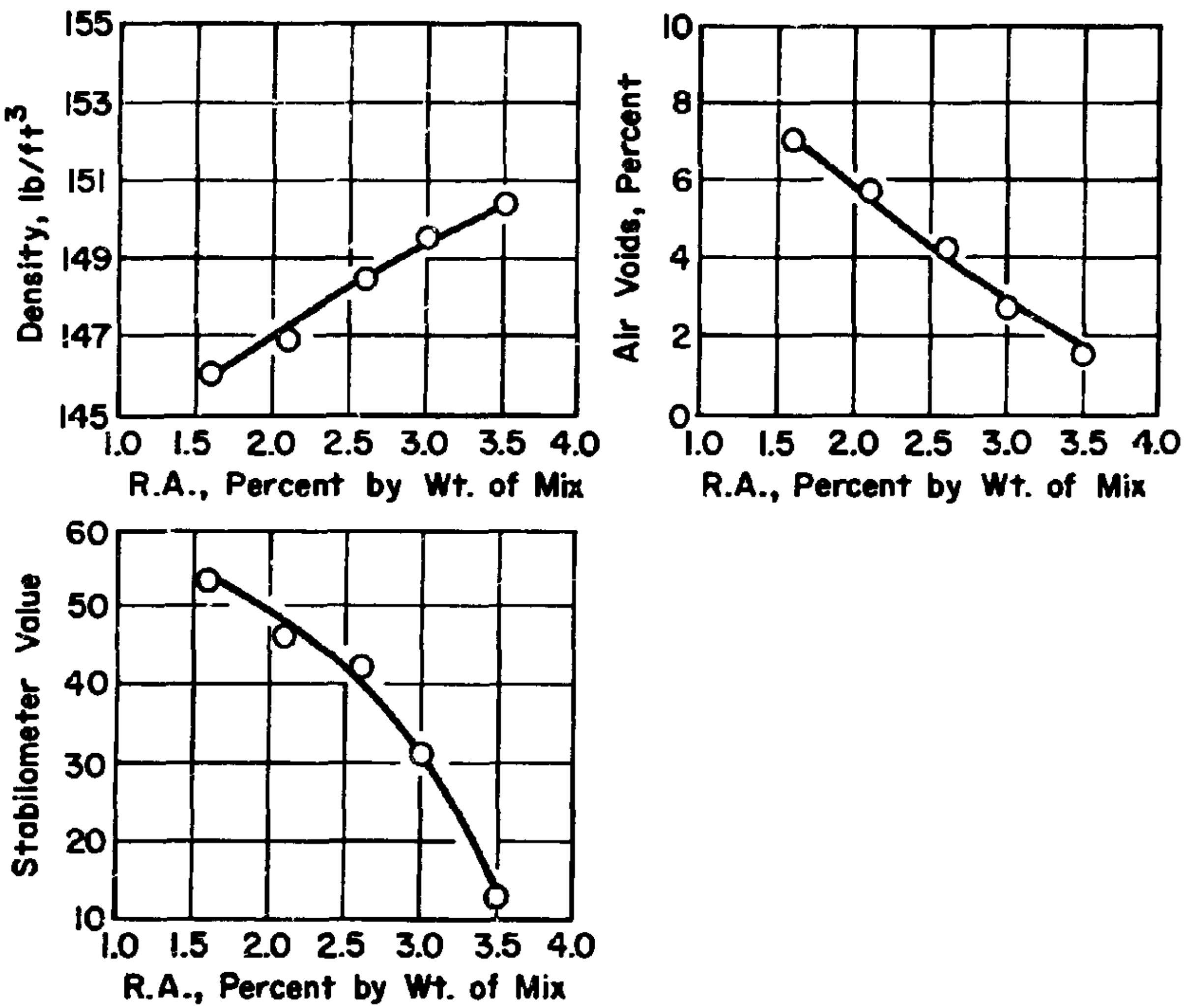

Figure 18 - Hveem Method mix design test property curves for California (Highway 97) recycled mix containing AR 1000 recycling agent (aggregate blend constant).

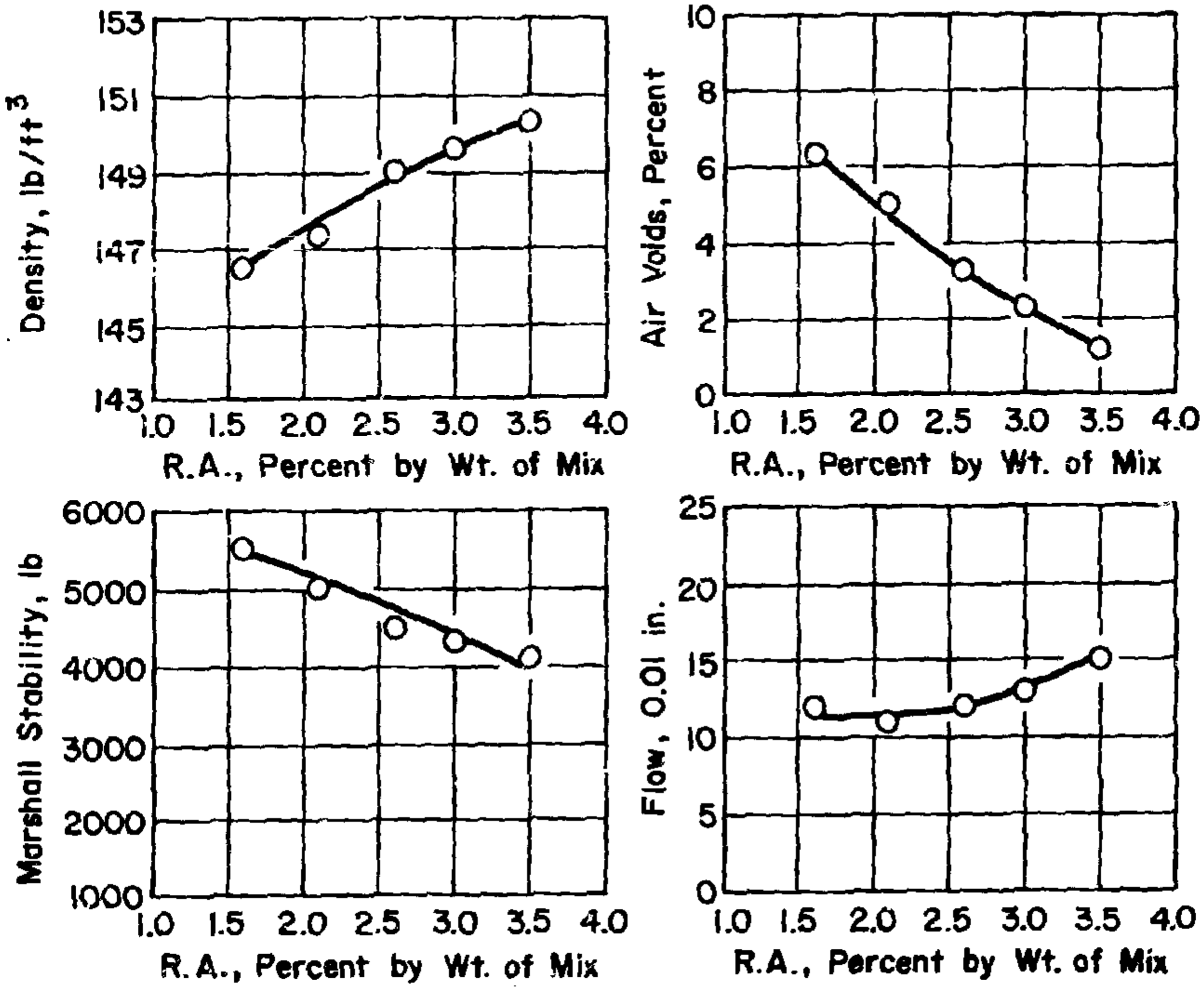

Figure 19 - Marshall Method mix design test property curves for California (Highway 97) recycled mix containing AR 1000 recycling agent (aggregate blend constant).

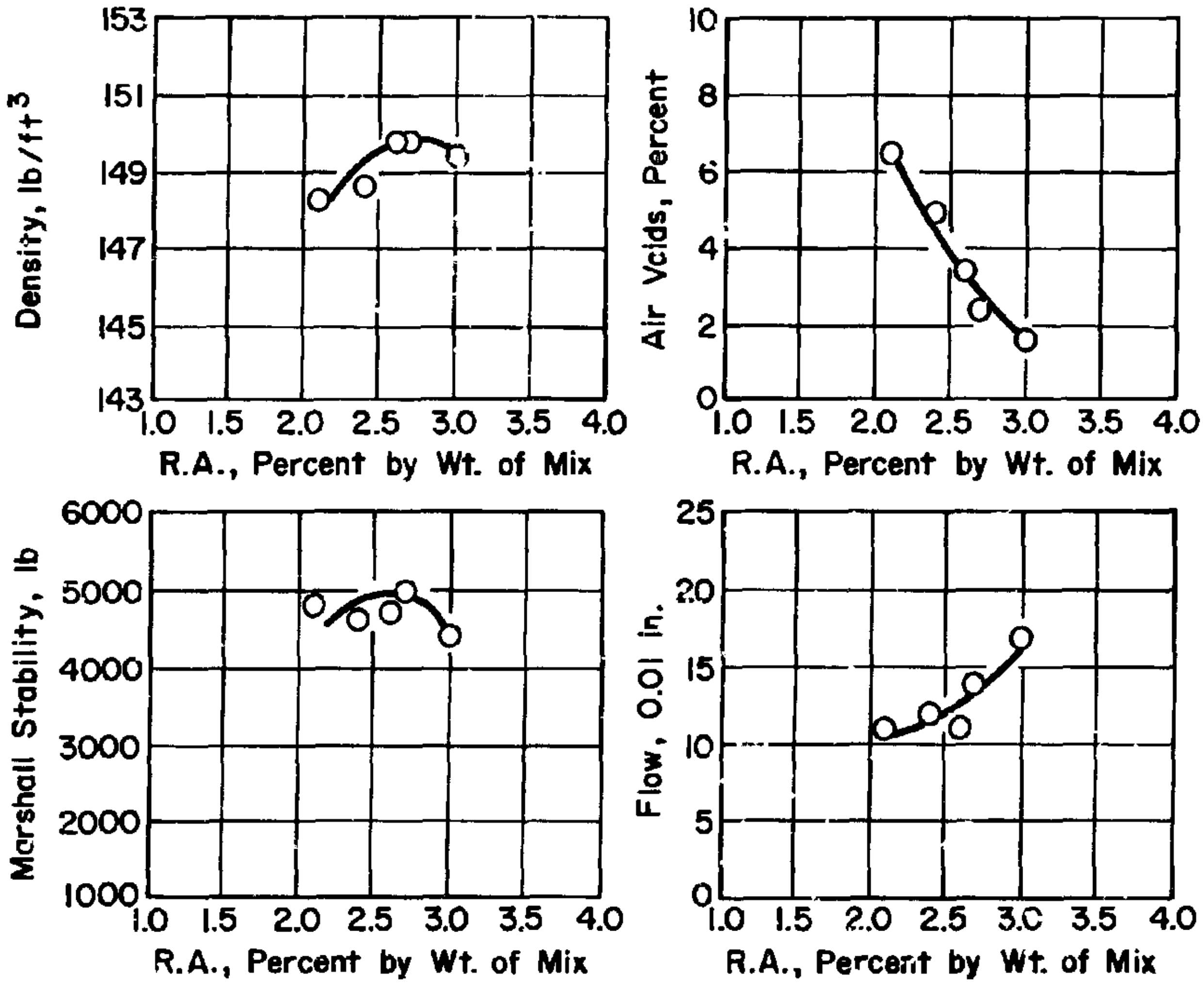

Figure 20 - Marshall Method mix design test property curves for California (Highway 97) recycled mix containing AR 1000 recycling agent (asphalt blend constant).

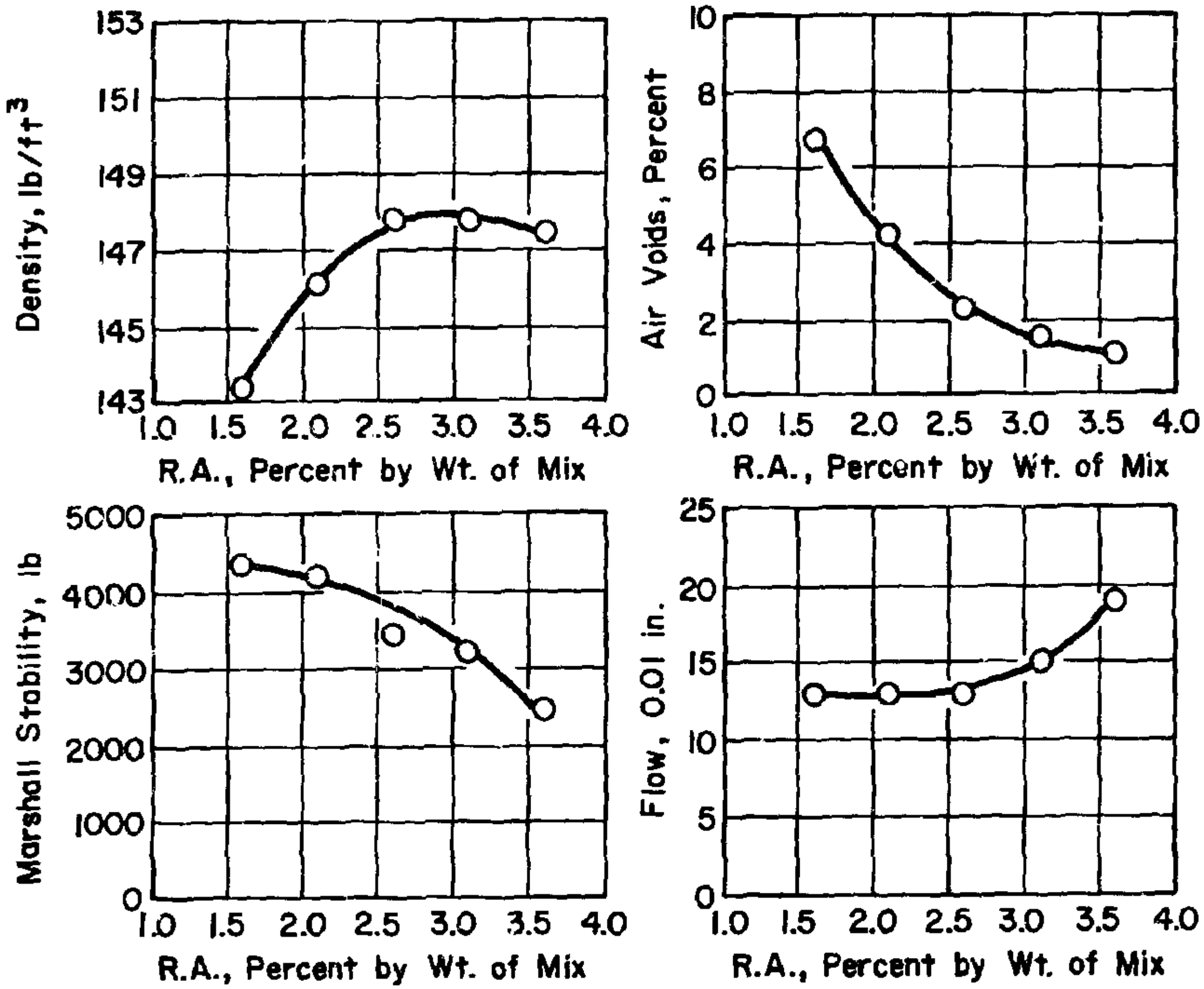

Figure 21 - Marshall Method mix design test property curves for Utah (U.S. 89) recycled mix (aggregate blend constant).

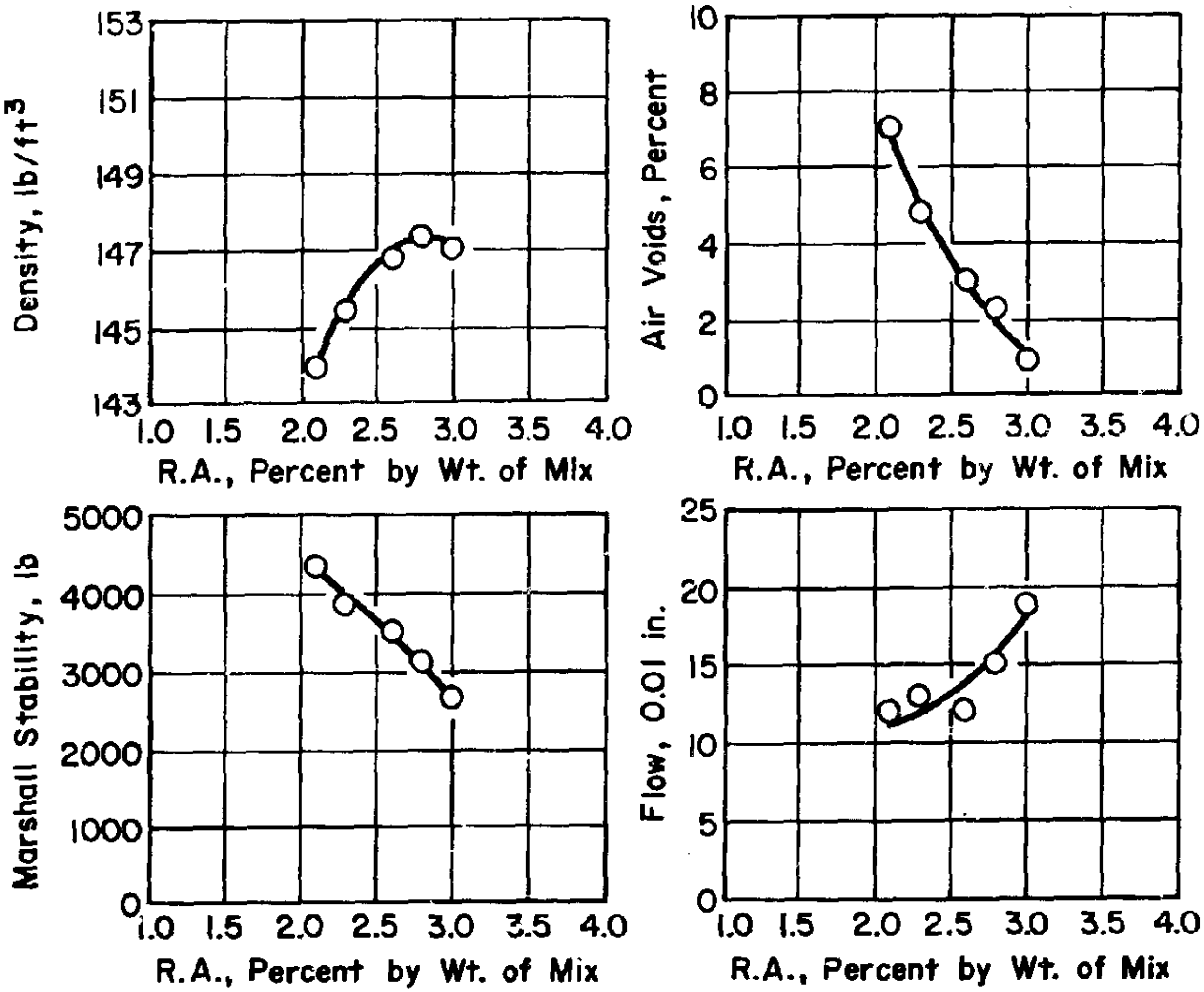

Figure 22 - Marshall Method mix design test property curves for Utah (U.S. 89) recycled mix (asphalt blend constant).

TABLE 1 - RECYCLING PROJECT INFORMATION

PROJECT LOCATION (Agency)	RECLAIMED ASPHALT CONCRETE SAMPLING LOCATION	TYPE OF RECYCLING AGENT
CALIFORNIA (Highway 97)[1]	From pavement and small stockpile	RA-500 grade recycling agent and AR-1000 grade asphalt cement
NEW MEXICO (I-40)[2]	From stockpile[3]	85-100 penetration grade asphalt cement
NORTH CAROLINA (I-95)[4]	From pavement and trucks	AC-2.5 grade asphalt cement
UTAH (U.S. 89)[5]	From pavement and stockpile	Low viscosity recycling agent and AC-5 grade soft asphalt cement
VIRGINIA (U.S. 220)[6]	From pavement and from trucks	AC-5 grade soft asphalt cement

****

[1] Route 97 in Siskiyou County, from Route 265 in Weed to 1.7 mi. S. of Co. Rd. A-12. Project to be constructed with 55% reclaimed asphalt concrete, 45% new aggregate.

[2] I-40 In Quay Co., East of Tucumcari Sta. 210+00 to Sta. 450+00. Project constructed with approximately 50% reclaimed asphalt concrete, 50% new aggregate.

[3] Not used for study of statistical sampling plans.

[4] I-95 in Robeson Co. from U.S. 74 to So. Carolina state line. Project constructed with approximately 50% reclaimed asphalt concrete, 50% new aggregate.

[5] U.S. 89 (Bryce Canyon Junction to Hatch). Project constructed with approximately 50% reclaimed asphalt concrete and 50% new aggregate.

[6] Route 220 in Franklin Co. from 0.23 mi. N. Int. 919 (M.P. 3.07) to 0.20 mi. E. Int. 220 Bus. (M.P. 10.92). Project constructed with approximately 40% reclaimed asphalt concrete, 60% new aggregate.

TABLE 2 - ASPHALT EXTRACTION TESTS AND TESTS ON RECOVERED ASPHALT AND AGGREGATE FROM PAVEMENT CORES (ROUTE 97, SISKIYOU COUNTY, CALIFORNIA)

Section:	1		2		3		4		5		6	
Lane:	1	2	1	2	1	2	1	2	1	2	1	2
Percent by Weight Finer than:												
Sieve Size												
1 in.	-	-	100	-	-	-	-	-	-	-	-	-
3/4 in.	100	100	99	100	100	100	100	-	100	100	100	100
1/2 in.	99	97	96	99	89	87	99	100	98	99	98	99
3/8 in.	96	92	90	92	78	78	96	97	92	95	93	93
No. 4	78	66	70	75	54	55	78	80	71	75	.6	73
No. 8	58	49	51	60	38	38	61	60	55	55	61	58
No. 16	43	37	36	46	28	27	46	45	43	40	48	45
No. 30	32	27	25	34	21	20	36	34	34	29	38	35
No. 50	23	20	16	24	15	14	27	24	24	20	28	26
No. 100	15	15	11	16	10	10	19	17	16	13	19	17
No. 200	10.3	10.3	7.4	10.9	7.0	6.8	12.7	11.1	10.1	8.7	12.3	11.1
Asphalt: Percent by Weight of Total Mix	6.5	5.2	5.3	5.5	4.5	4.4	6.9	5.8	5.3	5.3	5.4	5.2
Recovered Asphalt:												
Pen 77°F, 100g, 5 sec	35	19	12	25	4	2	63	37	7	13	16	17
Vis 140°F, poises	7,600	26,300	105,300	13,900	717,300	968,000	3,140	7,100	271,100	247,800	52,700	52,100
Vis 275°F, cSt	557	1,030	2,480	757	5,130	5,340	392	556	3,350	3,630	1,460	1,540

TABLE 3 - ANALYSIS OF VARIANCE OF EXTRACTION AND RECOVERY TEST DATA FROM PAVEMENT CORES (ROUTE 97, SISKIYOU COUNTY, CALIFORNIA)

	Lane 1		Lane 2		Overall		Sign. Level(1)	
	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Between Lanes	Between Sections
Percent by Weight Finer than:								
Sieve Size								
1 in.								
3/4 in.								
1/2 in.								
3/8 in.								
No. 4								
No. 8	54	8.7	53	8.6	54	8.3	NS	**
No. 16								
No. 30								
No. 50								
No. 100								
No. 200	10.0	2.38	9.8	1.73	9.9	2.01	NS	*
Asphalt: Percent by Weight of Total Mix	5.7	0.88	5.2	0.47	5.4	0.71	*	*
Recovered Asphalt:								
Pen 77°F, 100g, 5 sec	23	22.5	19	11.7	21	17.2	NS	**
Vis 140°F, poises	192,800	275,200	219,200	377,800	206,100	315,500	NS	***
Vis 275°F, cSt	2,230	1,820	2,140	1,920	2,180	1,780		

(1) Statistical significance level:
NS - not significant
* - $1 - \alpha > 0.75$
** - $1 - \alpha > 0.95$
*** - $1 - \alpha > 0.99$

TABLE 4 - ASPHALT EXTRACTION TESTS AND TESTS ON RECOVERED ASPHALT AND AGGREGATE FROM STOCKPILE SAMPLES (ROUTE 97, SISKIYOU, COUNTY CALIFORNIA)

	Test No.					Mean	Std.
	1	2	3	4	5		Dev.
Percent by Weight Finer than:							
Sieve Size							
1 in.							
3/4 in.	100	100	100	100	100		
1/2 in.	96	99	97	96	97		
3/8 in.	89	93	89	88	91		
No. 4	67	74	69	68	69	69	6.5
No. 8	52	58	54	53	54		
No. 16	42	47	44	43	44		
No. 30	34	37	35	35	35		
No. 50	26	28	26	26	26		
No. 100	18	19	18	18	18		
No. 200	11.5	12.5	11.5	11.7	11.8	11.8	0.34
Asphalt: Percent by Weight of Total Mix	5.2	5.3	5.2	5.2	5.2	5.2	0.04
Recovered Asphalt:							
Pen 77°F, 100g, 5 sec	7	7	7	7	7	7	0.0
Vis 140°F, poises	95,200	101,600	96,800	101,400	110,800	101,200	6,100
Vis 275°F, cSt	1,500	1,500	1,580	1,560	1,600	1,550	44

TABLE 5 - COMPARISON OF TEST DATA FROM ROADWAY AND STOCKPILE MATERIAL (ROUTE 97, SISKIYOU COUNTY, CALIFORNIA)

	Roadway Samples			Stockpile Samples		
	No.	Mean	Std. Dev.	No.	Mean	Std. Dev.
Percent by Weight Finer than:						
Sieve Size						
1 in.						
3/4 in.						
1/2 in.						
3/8 in.						
No. 4						
No. 8	12	54	8.3	5	69	6.5
No. 16						
No. 30						
No. 50						
No. 100						
No. 200	12	9.9	2.01	5	11.8	0.34
Asphalt: Percent by Weight of Total Mix	12	5.4	0.71	5	5.2	0.04
Recovered Asphalt:						
Pen 77° F, 100g, 5 sec	12	21	17.2	5	7	0
Vis 140°F, poises	12	206,100	315,500	5	101,200	6,100
Vis 275°F, cSt	12	2,180	1,780	5	1,550	44

TABLE 6 - ASPHALT EXTRACTION TESTS AND TESTS ON RECOVERED ASPHALT AND AGGREGATE FROM PAVEMENT CORES (I-95, ROBESON COUNTY, NORTH CAROLINA)

Section:	1		2		3		4		5		6	
Subsection:	1	2	1	2	1	2	1	2	1	2	1	2
Percent by Weight Finer than:												
Sieve Size												
1 in.	-	-	-	-	-	-	-	-	-	-	-	-
3/4 in.	-	-	100	-	100	100	-	-	-	100	100	-
1/2 in.	100	100	98	100	99	99	100	100	100	98	98	100
3/8 in.	98	98	95	97	95	96	98	98	98	94	94	98
No. 4	83	79	79	79	76	82	78	82	81	75	77	81
No. 8	74	68	69	68	66	73	67	71	71	63	66	70
No. 16	67	59	61	60	58	64	59	63	62	56	59	62
No. 30	48	42	44	43	42	48	44	45	45	42	43	46
No. 50	24	21	24	23	23	28	27	24	25	26	25	26
No. 100	12	10	11	10	11	14	13	11	11	13	12	12
No. 200	7.2	5.7	5.9	5.3	6.1	6.8	6.8	4.9	5.8	6.5	6.2	6.4
Asphalt: Percent by Weight of Total Mix	5.9	5.7	6.0	6.2	5.9	5.6	5.5	5.7	5.4	6.1	5.3	5.6
Recovered Asphalt:												
Pen 77°F, 100g, 5 sec	15	-	21	18	35	17	19	15	8	36	16	34
Vis 140°F, poises	81,200	-	24,400	34,400	10,200	38,800	34,800	74,600	205,600	9,000	41,000	9,300
Vis 275°F, cSt	1,900	-	1,180	1,300	710	1,360	1,320	1,870	3,280	750	1,460	765

TABLE 7 - ANALYSIS OF VARIANCE OF EXTRACTION AND RECOVERY TEST DATA FROM PAVEMENT CORES (I-95, ROBESON COUNTY, NORTH CAROLINA)

	Overall		Sign. Level(1)
	Mean	Std. Dev.	Between Sections
Percent by Weight Finer than:			
Sieve Size			
1 in.			
3/4 in.			
1/2 in.			
3/8 in.			
No. 4			
No. 8	69	3.2	NS
No. 16			
No. 30			
No. 50			
No. 100			
No. 200	6.1	0.66	NS
Asphalt: Percent by Weight of Total Mix	5.7	0.28	NS
Recovered Asphalt:			
Pen 77° F, 100g, 5 sec	22	9.7	NS
Vis 140°F, poises	48,200	58,730	NS
Vis 275°F, cSt	1,410	755	NS

(1) Statistical significance level:
NS - not significant
* - 1 - α > 0.75
** - 1 - α > 0.95
*** - 1 - α > 0.99

TABLE 8 - ASPHALT EXTRACTION TESTS AND TESTS ON RECOVERED ASPHALT AND AGGREGATE FROM COMPOSITE SAMPLE OF MILLED MATERIAL FROM TRUCKS (I-95, ROBESON COUNTY, NORTH CAROLINA)

	Test No.					Mean	Std.
	1	2	3	4	5		Dev.
Percent by Weight Finer than:							
Sieve Size							
1 in.							
3/4 in.	100	100	100	100	100		
1/2 in.	100	100	99	99	100		
3/8 in.	98	99	99	97	98		
No. 4	83	85	84	82	84		
No. 8	72	73	72	70	72	72	0.9
No. 16	63	64	63	62	63		
No. 30	46	47	46	46	47		
No. 50	27	28	27	28	27		
No. 100	15	14	15	15	14		
No. 200	8.1	7.8	8.0	8.0	7.9	8.0	0.11
Asphalt: Percent by Weight of Total Mix	5.7	5.7	5.8	5.5	5.6	5.7	0.11
Recovered Asphalt (Composite Sample of Extracted Asphalt from Above):							
Pen 77°F, 100g, 5 sec	20						
Vis 140°F, poises	33,800						
Vis 275°F, cSt	1,340						

TABLE 9 - COMPARISON BETWEEN ROADWAY AND MILLED MATERIAL FROM TRUCKS (I-95, ROBESON COUNTY, NORTH CAROLINA)

	Roadway			Milled		
	No.	Mean	Std. Dev.	No.	Mean	Std. Dev.
Percent by Weight Finer than:						
Sieve Size						
1 in.						
3/4 in.						
1/2 in.						
3/8 in.						
No. 4						
No. 8	12	69	3.2	5	72	0.9
No. 16						
No. 30						
No. 50						
No. 100						
No. 200	12	6.1	0.66	5	8.0	0.11
Asphalt: Percent by Weight of Total Mix	12	5.7	0.28	5	5.7	0.11
Recovered Asphalt:						
Pen 77°F, 100g, 5 sec	10	22	9.7	1	20	
Vis 140°F, poises	10	48,200	58,730	1	33,800	
Vis 275°F, cSt	10	1,410	755	1	1,340	

TABLE 10 - ASPHALT EXTRACTION TESTS AND TESTS ON RECOVERED ASPHALT AND AGGREGATE FROM PAVEMENT CORES (U.S. 89, BRYCE CANYON JUNCTION-HATCH, UTAH)

Section:	1		2		3		4		5		6	
Lane:	1	2	1	2	1	2	1	2	1	2	1	2
Percent by Weight Finer than:												
Sieve Size												
1 in.	100	100	100	100	100	100	100	100	100	100	100	100
3/4 in.	99	98	98	95	93	96	95	95	95	95	98	92
1/2 in.	90	88	87	84	83	88	84	82	86	89	86	81
3/8 in.	83	82	82	79	77	81	78	74	80	82	79	75
No. 4	66	67	66	62	60	66	60	59	63	65	62	57
No. 8	56	58	55	52	51	56	50	50	52	54	49	44
No. 16	49	52	47	45	44	48	44	43	44	46	41	36
No. 30	41	45	38	38	36	39	37	36	36	38	34	30
No. 50	31	35	28	27	26	23	26	26	26	28	25	23
No. 100	18	23	15	15	14	15	15	15	14	16	17	15
No. 200	8.7	15.4	7.0	7.5	7.2	6.4	7.3	7.8	6.6	8.4	11.5	10.2
Asphalt: Percent by Weight of Total Mix	6.9	6.0	6.9	6.2	6.5	6.6	6.6	6.3	6.4	6.7	6.3	6.2
Recovered Asphalt:												
Pen 77°F, 100g, 5 sec	59	40	40	39	32	27	37	35	31	45	56	51
Vis 140°F, poises	1,530	4,550	4,529	4,430	7,330	11,930	4,900	5,360	7,840	2,710	1,640	2,030
Vis 275°F, cSt	279	381	368	410	452	524	400	442	476	319	272	284

TABLE 11 - ANALYSIS OF VARIANCE OF EXTRACTION AND RECOVERY TEST DATA FROM PAVEMENT CORES (U.S. 89, BRYCE CANYON JUNCTION- HATCH, UTAH)

	Lane 1		Lane 2		Overall		Sign. Level (1)	
	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Between Lanes	Between Sections
Percent by Weight Finer than:								
Sieve Size								
1 in.								
3/4 in.								
1/2 in.								
3/8 in.								
No. 4								
No. 8	52	2.7	52	5.0	52	3.6	NS	*
No. 16								
No. 30								
No. 50								
No. 100								
No. 200	8.0	1.83	9.3	3.25	8.7	2.60	NS	*
Asphalt: Percent by Weight of Total Mix	6.6	0.25	6.3	0.27	6.5	0.28	*	NS
Recovered Asphalt:								
Pen 77°F, 100g, 5 sec	42	12.1	40	8.2	41	10.0	NS	*
Vis 140°F, poises	4,630	2,690	5,170	3,540	4,900	3,010	NS	*
Vis 275°F, cSt	374	856	393	864	384	82.6	NS	*

(1) Statistical significance level:
NS - not significant
* - 1 - α > 0.75
** - 1 - α > 0.95
*** - 1 - α > 0.99

TABLE 11 - ANALYSIS OF VARIANCE OF EXTRACTION AND RECOVERY TEST DATA FROM PAVEMENT CORES (U.S. 89, BRYCE CANYON JUNCTION- HATCH, UTAH)

	Lane 1		Lane 2		Overall		Sign. Level(1)	
	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Between Lanes	Between Sections
Percent by Weight Finer than:								
Sieve Size								
1 in.								
3/4 in.								
1/2 in.								
3/8 in.								
No. 4								
No. 8	52	2.7	52	5.0	52	3.8	NS	*
No. 16								
No. 30								
No. 50								
No. 100								
No. 200	8.0	1.83	9.3	3.25	8.7	2.60	NS	*
Asphalt: Percent by Weight of Total Mix	6.6	0.25	6.3	0.27	6.5	0.28	*	NS
Recovered Asphalt:								
Pen 77°F, 100g, 5 sec	42	12.1	40	8.2	41	10.0	NS	*
Vis 140°F, poises	4,630	2,690	5,170	3,540	4,900	3,010	NS	*
Vis 275°F, cSt	374	856	393	864	384	82.6	NS	*

(1) Statistical significance level:
NS - not significant
* - 1 - α > 0.75
** - 1 - α > 0.95
*** - 1 - α > 0.99

TABLE 12 - ASPHALT EXTRACTION TESTS AND TESTS ON RECOVERED ASPHALT AND AGGREGATE FROM SAMPLES FROM STOCKPILE NO. 1 (U.S. 89, BRYCE CANYON JUNCTION, HATCH, UTAH)

	Sample No. 1	2	3	Mean	Std. Dev.
Percent by Weight Finer than:					
Sieve Size					
1 in.	100	100	100		
3/4 in.	94	98	98		
1/2 in.	86	89	91		
3/8 in.	80	80	84		
No. 4	67	62	68		
No. 8	56	52	58	55	2.9
No. 16	48	45	49		
No. 30	37	37	41		
No. 50	25	28	31		
No. 100	18	16	19		
No. 200	9.3	8.6	10.0	9.3	0.70
Asphalt: Percent by Weight of Total Mix	5.4	5.9	6.7	6.0	0.66
Recovered Asphalt:					
Pen 77°F, 100g, 5 sec	30	32	38	33	4.2
Vis 140°F, poises	9,130	7,640	5,660	7,480	1,740
Vis 275°F, cSt	500	458	411	456	44.5

TABLE 13 - ASPHALT EXTRACTION TESTS AND TESTS ON RECOVERED ASPHALT AND AGGREGATE FROM SEPARATE SAMPLES FROM STOCKPILE NO. 2 (U.S. 89, BRYCE CANYON JUNCTION-HATCH, UTAH)

Section:	1		2		3		4		5	
Sub-section:	1	2	1	2	1	2	1	2	1	2
Percent by Weight Finer than:										
Sieve Size										
1 in.	100	100	100	100	100	100	100	-	100	100
3/4 in.	98	99	98	96	96	99	96	100	99	98
1/2 in.	90	93	90	90	87	91	88	93	96	94
3/8 in.	84	86	83	84	79	86	82	87	93	87
No. 4	69	67	66	69	64	70	69	69	76	70
No. 8	58	55	56	58	55	60	58	57	65	58
No. 16	50	48	48	50	47	51	50	49	56	50
No. 30	42	40	40	42	40	43	42	42	47	42
No. 50	32	29	29	31	29	31	31	31	36	32
No. 100	19	17	17	18	17	18	18	19	22	19
No. 200	10.4	8.9	8.8	9.6	9.1	9.4	9.7	10.0	12.8	9.9
Asphalt: Percent by Weight of Total Mix	5.6	6.4	6.0	6.0	5.7	6.7	6.0	6.7	6.6	6.8
Recovered Asphalt:										
Pen 77° F, 100g, 5 sec	30	33	33	31	37	34	30	32	35	41
Vis 140°F, poises	9,610	7,150	6,900	8,430	4,590	7,370	9,060	6,610	5,555	3,460
Vis 275°F, cSt	530	480	450	480	400	440	510	460	430	380

TABLE 14 - ANALYSIS OF VARIANCE OF EXTRACTION AND RECOVERY TEST DATA FROM SEPARATE SAMPLES FROM STOCKPILE NO. 2 (U.S. 89, BRYCE CANYON JUNCTION - HATCH, UTAH)

	Sub-section 1		Sub-section 2		Overall		Sign. Level(1)	
	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Between Sub-sections	Between Sections
Percent by Weight Finer than:								
Sieve Size								
1 in.								
3/4 in.								
1/2 in.								
3/8 in.								
No. 4								
No. 8	58	3.9	58	1.6	58	2.8	NS	NS
No. 16								
No. 30								
No. 50								
No. 100								
No. 200	10.2	1.60	9.6	0.44	9.9	1.15	NS	NS
Asphalt: Percent by Weight of Total Mix	6.0	0.39	6.5	0.33	6.2	0.44	**	NS
Recovered Asphalt:								
Pen 77°F, 100g, 5 sec	33	3.1	34	4.0	34	3.4	NS	*
Vis 140°F, poises	7,140	2,170	6,600	1,880	6,870	1,940	NS	NS
Vis 275°F, cSt	466	53.3	447	41.9	457	46.3	NS	*

(1) Statistical significance level:
NS - not significant
* - $1 - \alpha > 0.75$
** - $1 - \alpha > 0.95$
*** - $1 - \alpha > 0.99$

TABLE 15 - COMPARISON OF TEST DATA FROM ROADWAY AND STOCKPILE MATERIAL (U.S. 89, BRYCE JUNCTION, HATCH, UTAH)

	Roadway			Stockpile No. 1			Stockpile No. 2		
	No.	Mean	Std. Dev.	No.	Mean	Std. Dev.	No.	Mean	Std. Dev.
Percent by Weight Finer than:									
Sieve Size									
1 in.									
3/4 in.									
1/2 in.									
3/8 in.									
No. 4									
No. 8	12	52	3.8	3	55	2.9	10	58	2.8
No. 16									
No. 30									
No. 50									
No. 100									
No. 200	12	8.7	2.60	3	9.3	0.70	10	9.9	1.15
Asphalt: Percent by Weight of Total Mix	12	6.5	0.28	3	6.0	0.66	10	6.2	0.44
Recovered Asphalt:									
Pen 77°F, 100g, 5 sec	12	41	10.0	3	33	4.2	10	34	3.4
Vis 140°F, poises	12	4,900	3,010	3	7,480	1,740	10	6,870	1,940
Vis 275°F, cSt	12	384	82.6	3	456	44.0	10	457	46.3

TABLE 16 - ASPHALT EXTRACTION TESTS AND TESTS ON RECOVERED ASPHALT AND AGGREGATE FROM PAVEMENT SAMPLES (U.S. 220, ROANOKE, VIRGINIA)

Section:	1		2		3		4		5		6	
Lane:	1	2	1	2	1	2	1	2	1	2	1	2
Percent by Weight Finer than:												
Sieve Size												
1 in.	-	-	-	-	-	-	-	-	-	-	-	-
3/4 in.	100	-	100	100	100	100	100	100	100	100	100	-
1/2 in.	92	100	96	96	96	98	97	98	97	98	96	100
3/8 in.	83	93	88	89	89	92	90	91	91	86	88	92
No. 4	58	57	63	60	60	61	55	62	58	55	57	58
No. 8	40	41	43	44	40	42	39	44	39	39	38	43
No. 16	28	32	30	33	30	30	30	32	28	28	26	33
No. 30	21	24	21	24	21	21	22	23	20	20	19	25
No. 50	16	18	16	17	15	16	16	17	14	15	15	19
No. 100	12	14	12	13	12	12	12	13	11	12	12	14
No. 200	10.1	10.5	9.9	10.4	9.0	9.1	8.7	10.0	8.5	9.5	10.1	11.1
Asphalt: Percent by Weight of Total Mix	5.1	4.8	5.5	5.5	5.3	5.3	5.3	5.2	5.4	5.4	5.5	5.2
Recovered Asphalt:												
Pen 77°F, 100g, 5 sec	12	4	29	19	22	17	25	19	19	18	19	6
Vis 140°F, poises	83,400	658,300	14,500	44,200	37,500	50,300	17,700	58,800	24,800	37,000	24,200	247,000
Vis 275°F, cSt	1,780	5,120	721	1,160	959	1,140	835	1,190	959	1,100	1,010	2,800

TABLE 17 - ANALYSIS OF VARIANCE OF EXTRACTION AND RECOVERY TESTS DATA FROM PAVEMENT SAMPLES (U.S. 220, ROANOKE, VIRGINIA)

	Lane 1		Lane 2		Overall		Sign. Level(1)	
	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Between Lanes	Between Sections
Percent by Weight Finer than:								
Sieve Size								
1 in.								
3/4 in.								
1/2 in.								
3/8 in.								
No. 4								
No. 8	40	1.9	4[illegible]	1.7	41	2.1	**	*
No. 16								
No. 30								
No. 50								
No. 100								
No. 200	9.4	0.73	10.1	0.72	9.7	0.79	**	**
Asphalt: Percent by Weight of Total Mix	5.3	0.15	5.2	0.24	5.3	0.20	*	**
Recovered Asphalt:								
Pen 77°F, 100g, 5 sec	21	5.6	14	6.9	17	7.2	***	**
Vis 140°F, poises	34,200	26,750	182,600	246,400	108,400	184,170	*	NS
Vis 275°F, cSt	1,040	374	2,080	1,627	1,560	1,250	*	*

(1) Statistical significance level:
NS - not significant
* - 1 - α > 0.75
** - 1 - α > 0.95
*** - 1 - α > 0.99

TABLE 18 - ASPHALT EXTRACTION TESTS AND TESTS ON RECOVERED ASPHALT AND AGGREGATE FROM COMPOSITE SAMPLE OF MILLED MATERIAL FROM TRUCKS (U.S. 220, ROANOKE, VIRGINIA)

	Test No.						Mean	Std.
	1	2	3	4	5	6		Dev.
Percent by Weight Finer than:								
Sieve Size								
1 in.								
3/4 in.	100	100	100	100	100	100		
1/2 in.	100	99	98	99	100	99		
3/8 in.	95	95	93	95	95	94		
No. 4	72	74	70	72	71	72		
No. 8	53	52	50	51	51	52	52	1.0
No. 16	38	38	36	37	37	38		
No. 30	28	27	26	27	26	27		
No. 50	21	20	20	20	20	21		
No. 100	16	16	16	16	16	16		
No. 200	13.2	13.1	12.5	13.1	12.8	13.3	13.0	0.30
Asphalt: Percent by Weight of Total Mix	5.3	5.3	5.0	5.2	5.2	5.3	5.2	0.12
Recovered Asphalt (Composite Sample of Extracted Asphalt from Above):								
Pen 77°F, 100g, 5 sec	17							
Vis 140°F, poises	46,100							
Vis 275°F, cSt	1,690							

TABLE 19 - COMPARISON BETWEEN ROADWAY AND MILLED MATERIAL FROM TRUCK. (U.S. 220, ROANOKE, VIRGINIA)

	Roadway			Milled		
	No.	Mean	Std. Dev.	No.	Mean	Std. Dev.
Percent by Weight Finer than:						
Sieve Size						
1 in.						
3/4 in.						
1/2 in.						
3/8 in.						
No. 4						
No. 8	12	41	2.1	6	52	1.1
No. 16						
No. 30						
No. 50						
No. 100						
No. 200	12	9.7	0.79	6	13.0	0.30
Asphalt: Percent by Weight of Total Mix	12	5.3	0.20	6	5.2	0.12
Recovered Asphalt:						
Pen 77°F, 100g, 5 sec	12	17	7.2	1	17	
Vis 140°F, poises	12	108,400	184,170	1	46,100	
Vis 275°F, cSt	12	1,560	1,250	1	1,690	

Table 20 - POOLED RESULTS - VARIABILITY OF RESULTS FROM ASPHALT EXTRACTION TESTS AND TESTS ON RECOVERED ASPHALT

	Roadway Samples (1)				Individual Samples from Stockpiles (2)				Composite Samples From Trucks (3) and Stockpile (4)			
	df	Mean	Std. Dev.	Coeff. Var.	df	Mean	Std. Dev.	Coeff. Var.	df	Mean	Std. Dev.	Coeff. Var.
Percent by Weight Finer than:												
Sieve Size												
1 in.												
3/4 in.												
1/2 in.												
3/8 in.												
No. 4												
No. 8	44	54	4.9	9	11	57	2.8	5	13	64	3.7	6
No. 16												
No. 30												
No. 50												
No. 100												
No. 200	44	8.6	1.7	20	11	9.8	1.1	11	13	11.0	0.3	6
Asphalt: Percent by Weight of Total Mix	44	5.7	0.41	7	11	6.2	0.49	8	13	5.3	0.10	2
Recovered Asphalt:												
Pen 77°F, 100g, 5 sec	42	25	11.8	47	11	34	3.6	11	4 (5)	7	0	0
Vis 140°F, poises	42	93,800	189,150	202	11	7010	1905	27	4 (5)	101,200	6,100	6
Vis 275°F, cSt	42	1,380	1,170	85	11	457	46.0	10	4 (5)	1,550	44	3

(1) All projects.
(2) Utah project.
(3) North Carolina and Virginia projects.
(4) California project.
(5) California project only.

TABLE 21 - COMPARISON OF LIMITS - RESULTS FROM ASPHALT EXTRACTIONS TESTS

		Roadway Samples				Individual Samples From Stockpiles (2)				Composite Samples from Trucks (3) and Stockpile (4)			
	ASTM D 3515	Std. Dev.	1.96σ Limits(5)	Sampling Limits(6)	No. Req'd(7)	Std. Dev.	1.96σ Limits(5)	Sampling Limits(6)	No. Req'd(7)	Std. Dev.	1.96σ Limits(5)	Sampling Limits (6)	No. Req'd(7)
Percent by Weight Finer than:													
Sieve Size													
1 in.													
3/4 in.													
1/2 in.													
3/8 in.													
No. 4													
No. 8	± 5	4.9	± 9.6	± 15.5	-	2.8	± 5.5	± 8.9	23	3.7	± 7.3	± 11.7	130
No. 16													
No. 30													
No. 50													
No. 100													
No. 200	± 3	1.7	± 3.3	± 5.4	24	1.1	± 2.2	± 3.5	19	0.3	± 0.6	± 0.9	4
Asphalt: Percent by Weight of													
Total Mix	± 0.5	0.41	± 0.8	± 2.5	130	0.49	± 0.96	± 1.5	-	0.10	± 0.2	± 0.3	5
Recovered Asphalt:													
Pen 77°F, 100g, 5 sec													
Vis 140°F, poises													
Vis 275°F, cSt													

(1) All projects.
(2) Utah project.
(3) North Carolina and Virginia projects.
(4) California project.
(5) Based on normal distribution: $\mu \pm 2\sigma$.
(6) Based on the probability that 95% of the time, 95% of the tests in a sample of N = 12 will be within the limits shown: $\mu \pm ks$.
(7) Number of tests required in one sample to produce the probability that 99 percent of the time the ASTM limits will include 75 percent of the test values.

TABLE 22 - ASPHALT EXTRACTION TESTS AND TESTS ON RECOVERED ASPHALT ON PAVEMENT CORES BY THREE AGENCIES (REFERENCES (11), (12), and (13)

	North Carolina DOT				Zenewitz and Welborn				Sisko and Brunstrum			
	No.	Mean	Std. Dev.	Coeff. Var.	No.	Mean	Std. Dev.	Coeff. Var.	No.	Mean	Std. Dev.	Coeff. Var.
Percent by Weight Finer than:												
Sieve Size												
1 in.												
3/4 in.												
1/2 in.												
3/8 in.												
No. 4												
No. 8	10	68	1.90	2.8	(1)	53	2.4	4.5				
No. 16												
No. 30												
No. 50												
No. 100												
No. 200	10	5.2	0.73	13.9	(1)	6.9	0.79	11.4				
Asphalt: Percent by Weight of Total Mix	10	5.7	0.38	6.7	(1)	6.0	0.22	3.7	12(2)	4.9	0.32	6.5
Recovered Asphalt:												
Pen 77°F, 100g, 5 sec									12(2)	32	7.4	23
Vis 140°F, poises									11(2)	65,800	159,000	241
									11(3)	65,800	78,400	119
Vis 275°F, cSt									11(2)	1,232	338	27
									11(3)	1,232	236	19

(1) Standard deviations were obtained by averaging pooled standard deviations having from 6 to 36 degrees of freedom from 34 projects. For example, 7 samples and 6 sites from one project would be 36 degrees of freedom.
(2) Values obtained by pooling the results of two tests from each of the number of projects indicated.
(3) Values obtained by averaging the results of two tests from each of the number of projects indicated.

Table 23 - COMPARISON - BEFORE AND AFTER MILLING

	California (1)			North Carolina (2)			Utah (3)			Virginia (4)			Average Difference (5)
	Before Milling	After Milling	Difference (5)	Before Milling	After Milling	Difference (5)	Before Milling	After Milling	Difference (5)	Before Milling	After Milling	Difference (5)	
Percent by Weight Finer than:													
Sieve Size													
1 in.													
3/4 in.													
1/2 in.													
3/8 in.													
No. 4													
No. 8	54	69	+15	69	72	+3	52	56	+4	41	52	+11	+8
No. 16													
No. 30													
No. 50													
No. 100													
No. 200	9.9	11.8	+1.9	6.1	8.0	+1.9	8.7	9.6	+0.9	9.7	13.0	+3.3	+2
Asphalt: Percent by Weight of Total Mix	5.4	5.2	-0.2	5.7	5.7	0	6.5	6.1	-0.4	5.3	5.2	-0.1	-0.2
Recovered Asphalt:													
Pen 77°F, 100g, 5 sec	21	7	-14	22	20	-2	41	34	-7	17	17	0	-6
Vis 140°F, poises	206,100	101,200	-104,900	48,200	33,800	-14,400	4,900	7,180	+2280	108,400	46,100	-62,300	
Vis 275°F, cSt	2,180	1,550	-630	1,410	1,340	-70	384	456	+72	1,560	1,690	+130	

(1) From Table 5.
(2) From Table 9.
(3) From Table 15, both, stockpiles averaged.
(4) From Table 19.
(5) Difference: after milling - before milling.

TABLE 24 - PROPERTIES OF ORIGINAL ASPHALTS

Asphalt Cement Asphalt Grade Crude Oil Source	A AR-16000 St. Maria, CA	B AC-40 Smackover, AR	C AC-20 Venezuela	D AC-20 Mid-Continent
Properties of Original Asphalt:				
Viscosity				
140°F (60°C), Poises	4,028	4,024	2,141	1,921
275°F (135°C), cSt	593	588	438	330
77°F (25°C), kP	3,170	4,623	1,125	2,445
Penetration				
77°F (25°C), (100g, 5s), 0.1 mm	63	52	90	58
Ductility				
77°F (25°C), (5cm/min), cm	150+	150+	150+	150+
39.2°F (4°C) (5cm/min), cm	6.0	2.75	10.7	0.0
Flash Point, Cleveland Open Cup, °F	485	665	510	660
Solubility in Trichloroethylene, Percent	99.94	99.84	99.90	99.82
Specific Gravity at 77°F (25°C)	1.033	1.025	1.034	1.033
Spot Test	Neg.	Neg.	Neg.	Neg.
Viscosity Temperature Susceptibility, VTS	3.50	3.51	3.49	3.69
Properties of Thin Film Oven Test Residue:				
Mass Change, Percent	-0.993	+0.059	-0.589	+0.001
Viscosity				
140°F (60°C), Poises	15,496	8,311	7,106	3,625
275°F (135°C), cSt	1,059	795	794	408
77 °F (25°C), kP	20,529	17,067	6,425	7,022
Viscosity at 140°F (60°C) after thin film oven test / Viscosity at 140°F (60°C) before thin film oven test	3.85	2.07	3.32	1.89
Penetration				
77°F (25°C) (100g, 5s), 0.1 mm	35	37	51	39
Retained Penetration, Percent	55.6	71.2	56.7	67.2
Ductility				
77°F (25°C) (5cm/min), cm	150+	150+	150+	150+
39.2°F (4°C) (5cm/min), cm	1.9	2.9	4.5	0.0

TABLE 25 - COMPOSITIONAL CHARACTERISTICS OF ORIGINAL ASPHALTS

Asphalt Cement Asphalt Grade Crude Oil Source	A AR-16000 St. Maria, CA	B AC-40 Smackover, AR	C AC-20 Venezuela	D AC-20 Mid-Continent
Asphalt Composition Analysis (ASTM D 4124)				
Asphaltenes (n-Heptane), percent	22.29	13.25	19.19	11.47
Saturates, percent	7.99	7.64	6.80	6.87
Naphthene Aromatics, percent	24.56	40.14	26.96	39.03
Polar Aromatics, percent	43.62	38.27	44.37	41.98
Characteristic Groups by Precipitation (ASTM D 2006 Discontinued)				
Asphaltenes (n-Pentane), percent	30.84	23.93	28.47	20.06
Polar Compounds, percent	28.04	16.25	27.50	23.59
First Acidaffins, percent	19.37	21.02	15.16	19.27
Second Acidaffins, percent	13.19	24.21	21.37	24.10
Sat. Hydrocarbons, percent	8.56	14.59	7.50	12.98
Test for Saturates (ASTM D 2007)				
Saturates, percent	8.89	15.64	8.30	13.30
Asphaltene Settling Test				
Settling Time, minutes	8	71	29	55

TABLE 26 - PROPERTIES OF RECYCLING AGENTS

Asphalt Agent	1	2	3	4
Asphalt Agent Grade	AC-5	AC-2.5	RA-25	RA-5
Properties of Recycling Agents:				
Viscosity				
140°F (60°C), Poises	502	272	36	2.2
275°F (135°C), cSt	227	170	50	8.4
77°F (25°C), kP	113	87	19	0.086
Penetration				
77°F (25°C), (100g, 5s), 0.1 mm	262	290	380+	380+
Ductility				
77°F (25°C), (5cm/min), cm	150+	150+	150+	150+
39.2°F (4°C), (5cm/min), cm	150+	150+	150+	150+
Flash Point, Cleveland Open Cup, °F	450	640	525	445
Solubility in Trichloroethylene, Percent	99.86	99.81	99.89	99.99
Specific Gravity at 77°F (25°C)	1.025	1.008	0.989	0.983
Viscosity Temperature Susceptibility, VTS	3.44	3.43	3.70	4.69
Spot Test	Neg.	Neg.	Neg.	Neg.
Properties of Thin Film Oven Test Residue:				
Mass Change, Percent	-2.094	+0.078	-0.612	-2.200
Viscosity				
140°F (60°C), Poises	2,199	442	63	2.8
275°F (135°C), cSt	428	183	66	9.2
77 °F (25°C), kP	1,425	245	362	0.15
Viscosity at 140°F (60°C) after thin film oven test / Viscosity at 140°F (60°C) before thin film oven test	4.38	1.63	1.75	1.27
Penetration				
77°F (25°C), (100g, 5s), 0.1 mm	105	175	380+	380+
Retained Penetration, Percent	40.5	60.3	-	-
Ductility				
77°F (25°C) (5cm/min), cm	150+	150+	150+	150+
39.2°F (4°C) (5cm/min), cm	15.8	35.8	130.5	150+

TABLE 27 - COMPOSITIONAL CHARACTERISTICS OF RECYCLING AGENTS

Recycling Agent Recycling Agent Grade	1 AC-5	2 AC-2.5	3 RA-25	4 RA-5
Asphalt Composition Analysis (ASTM D 4124)				
Asphaltenes (n-Heptane), percent	16.71	8.54	7.01	0.00
Saturates, percent	8.54	10.54	16.35	34.77
Naphthene Aromatics, percent	30.88	39.69	36.48	41.42
Polar Aromatics, percent	42.05	39.51	38.01	21.74
Characteristic Groups by Precipitation (ASTM D 2006 Discontinued)				
Asphaltenes (n-Pentane), percent	24.73	16.51	14.11	0.57
Polar Compounds, percent	25.04	17.03	24.91	18.06
First Acidaffins, percent	20.96	19.30	15.59	16.35
Second Acidaffins, percent	19.35	27.53	23.57	40.43
Sat. Hydrocarbons, percent	9.92	19.63	21.82	24.59
Test for Saturates (ASTM D 2007)				
Saturates, percent	10.82	20.66	23.27	26.25
Asphaltene Settling Test				
Settling Time, minutes	16	42	23	0

TABLE 28 - PROPERTIES OF AGED ASPHALTS

Aged Asphalts Original Asphalt Grade Crude Oil Source	A AR-16000 St. Maria, CA	B AC-40 Smackover, AR	C AC-20 Venezuela	D AC-20 Mid-Continent
Properties of Aged Asphalt:				
Viscosity				
140°F (60°C), Poises	142,619	111,312	119,031	101,831
275°F (135°C), cSt	3,290	3,080	3,311	1,905
77°F (25°C), kP	200,916	318,133	167,151	514,071
Penetration				
77°F (25°C), (100g, 5s), 0.1 mm	19	19	23	13
Ductility				
77°F (25°C), (5cm/min), cm	14.6	6.4	14.3	6.7
39.2°F (4°C), (5cm/min), cm	0.0	0.0	0.0	0.0
Flash Point, Cleveland Open Cup, °F	525	665	515	640
Solubility in Trichloroethylene, Percent	99.94	99.93	99.92	99.86
Specific Gravity at 77°F (25°C)	1.040	1.030	1.042	1.044
Spot Test	Neg.	Neg.	Neg.	Neg.
Temperature Susceptibility, VTS	3.52	3.49	3.46	3.77
Properties of Thin Film Oven Test Residue:				
Mass Change, Percent	-0.583	+0.030	-0.399	+0.002
Viscosity				
140°F (60°C), Poises	512,746	239,200	378,704	192,097
275°F (135°C), cSt	6,671	3,268	6,676	2,401
77 °F (25°C), kP	769,077	796,919	787,406	1,264,512
Viscosity at 140°F (60°C) after thin film oven test / Viscosity at 140°F (60°C) before thin film oven test	3.60	2.15	3.18	1.89
Penetration				
77°F (25°C) (100g, 5s), 0.1 mm	15	18	18	11
Retained Penetration, Percent	78.9	94.7	78.3	84.6
Ductility				
77°F (25°C) (5cm/min), cm	4.9	5.0	6.8	5.6
39.2°F (4°C) (5cm/min), cm	0.0	0.0	0.0	0.0

TABLE 29 - COMPOSITIONAL CHARACTERISTICS OF AGED ASPHALTS

Asphalt Cement	A	B	C	D
Asphalt Grade	AR-16000	AC-40	AC-20	AC-20
Crude Oil Source	St. Maria, CA	Smackover, AR	Venezuela	Mid-Continent
Asphalt Composition Analysis (ASTM D 4124)				
Asphaltenes (n-Heptane), percent	28.37	19.80	28.40	21.70
Saturates, percent	7.49	5.79	5.83	7.38
Naphthene Aromatics, percent	19.78	34.65	26.53	31.90
Polar Aromatics, percent	42.05	37.84	37.07	37.17
Characteristic Groups by Precipitation (ASTM D 2006 Discontinued)				
Asphaltenes (n-Pentane), percent	40.41	31.74	37.19	31.57
Polar Compounds, percent	21.80	9.33	19.40	17.35
First Acidaffins, percent	17.33	21.19	19.61	14.28
Second Acidaffins, percent	12.42	23.64	16.60	24.06
Sat. Hydrocarbons, percent	8.04	14.10	7.20	12.74
Test for Saturates (ASTM D 2007)				
Saturates, percent	8.45	14.28	8.04	12.89
Asphaltene Settling Test				
Settling Time, minutes	19	120	33	82

TABLE 30 - PROPERTIES OF AGED ASPHALT A AND RECYCLING AGENT BLENDS

Aged Asphalt	A	A	A	A
Recycling Agent	1	2	3	4
Recycling Agent Grade	AC-5	AC-2.5	RA-25	RA-5
Percent Recycling Agent	71	62	41	25
Properties of Original Asphalt:				
Viscosity				
140°F (60°C), Poises	2,078	2,206	2,496	2,100
275°F (135°C), cSt	453	430	429	398
77°F (25°C), kP	1,141	2,440	3,117	1,341
Penetration				
77°F (25°C), (100g, 5s), 0.1 mm	108	77	80	110
Ductility				
77°F (25°C), (5cm/min), cm	150+	150+	150+	150+
39.2°F (4°C), (5cm/min), cm	13.8	5.3	5.5	12.6
Flash Point, Cleveland Open Cup, °F	460	590	515	475
Solubility in Trichloroethylene, Percent	99.87	99.85	99.90	99.94
Specific Gravity at 77°F (25°C)	1.029	1.018	1.019	1.025
Spot Test	Neg.	Neg.	Neg.	Neg.
Viscosity Temperature Susceptibility, VTS	3.45	3.51	3.57	3.50
Properties of Thin Film Oven Test Residue:				
Mass Change, Percent	-1.762	-0.170	-0.619	-1.180
Viscosity				
140°F (60°C), Poises	10,531	5,384	7,137	6,169
275°F (135°C), cSt	991	586	659	636
77 °F (25°C), kP	9,492	10,694	10,349	4,616
Viscosity at 140°F (60°C) after thin film oven test / Viscosity at 140°F (60°C) before thin film oven test	5.07	2.44	2.86	2.94
Penetration				
77°F (25°C) (100g, 5s), 0.1 mm	52	52	53	67
Retained Penetration, Percent	48.1	67.5	66.3	60.9
Ductility				
77°F (25°C) (5cm/min), cm	150+	150+	91.0	150+
39.2°F (4°C) (5cm/min), cm	44	3.7	3.9	5.4

TABLE 31 - COMPOSITIONAL CHARACTERISTICS OF AGED ASPHALT A AND RECYCLING AGENT BLENDS

Aged Asphalt	A	A	A	A
Recycling Agent	1	2	3	4
Recycling Agent Grade	AC-5	AC-2.5	RA-25	RA-5
Percent Recycling Agent	71	62	41	25
Asphalt Composition Analysis (ASTM D 4124)				
Asphaltenes (n-Heptane), percent	20.86	16.49	18.69	21.16
Saturates, percent	7.91	8.74	12.21	14.48
Naphthene Aromatics, percent	26.08	33.31	25.93	23.33
Polar Aromatics, percent	43.79	40.55	41.67	37.47
Characteristic Groups by Precipitation (ASTM D 2006 Discontinued)				
Asphaltenes (n-Pentane), percent	27.74	23.44	28.51	29.49
Polar Compounds, percent	27.96	21.63	25.84	19.54
First Acidaffins, percent	17.17	16.41	15.72	20.31
Second Acidaffins, percent	16.71	23.16	16.43	18.48
Sat. Hydrocarbons, percent	10.42	15.36	13.50	12.18
Test for Saturates (ASTM D 2007)				
Saturates, percent	10.29	15.61	15.08	13.01
Asphaltene Settling Test				
Settling Time, minutes	30	38	33	33

TABLE 32 - PROPERTIES OF AGED ASPHALT D AND RECYCLING AGENT BLENDS

Aged Asphalt	D	D	D	D
Recycling Agent	1	2	3	4
Recycling Agent Grade	AC-5	AC-2.5	RA-25	RA-5
Percent Recycling Agent	70	60	39	20
Properties of Original Asphalt:				
Viscosity				
140°F (60°C), Poises	1,655	1,987	1,742	1,960
275°F (135°C), cSt	386	382	321	318
77°F (25°C), kP	1,000	2,780	3,554	2,406
Penetration				
77°F (25°C), (100g, 5s), 0.1 mm	100	66	68	71
Ductility				
77°F (25°C), (5cm/min), cm	150+	150+	150+	150+
39.2°F (4°C), (5cm/min), cm	10.7	4.3	4.5	5.2
Flash Point, Cleveland Open Cup, °F	525	635	560	530
Solubility in Trichloroethylene, Percent	99.34	99.75	99.78	99.77
Specific Gravity at 77°F (25°C)	1.030	1.021	1.021	1.030
Spot Test	Neg.	Neg.	Neg.	Neg.
Viscosity Temperature Susceptiblity, VTS	3.49	3.58	3.67	3.73
Properties of Thin Film Oven Test Residue:				
Mass Change, Percent	-1.411	+0.021	-0.295	-0.560
Viscosity				
140°F (60°C), Poises	5,048	3,566	3,545	3,607
275°F (135°C), cSt	631	482	410	397
77 °F (25°C), kP	4,502	6,546	7,532	5,187
Viscosity at 140°F (60°C) after thin film oven test / Viscosity at 140°F (60°C) before thin film oven test	3.05	1.79	2.04	1.84
Penetration				
77°F (25°C) (100g, 5s), 0.1 mm	57	49	49	51
Retained Penetration, Percent	57.0	74.2	72.1	71.8
Ductility				
77°F (25°C) (5cm/min), cm	150+	150+	150+	150+
39.2°F (4°C) (5cm/min), cm	4.3	1.3	3.4	4.0

TABLE 33 - COMPOSITIONAL CHARACTERISTICS OF AGED ASPHALT D AND RECYCLING AGENT BLENDS

Aged Asphalt	D	D	D	D
Recycling Agent	1	2	3	4
Recycling Agent Grade	AC-5	AC-2.5	RA-25	RA-5
Percent Recycling Agent	70	60	39	20
Asphalt Composition Analysis (ASTM D 4124)				
Asphaltenes (n-Heptane), percent	18.37	14.45	16.75	18.70
Saturates, percent	6.39	8.19	11.30	11.20
Naphthene Aromatics, percent	30.58	38.68	32.01	32.37
Polar Aromatics, percent	44.09	37.68	39.93	37.40
Characteristic Groups by Precipitation (ASTM D 2006 Discontinued)				
Asphaltenes (n-Pentane), percent	25.20	23.03	24.27	24.7n
Polar Compounds, percent	24.52	19.69	23.86	20.55
First Acidaffins, percent	17.34	13.88	11.13	14.18
Second Acidaffins, percent	21.10	27.01	22.83	24.34
Sat. Hydrocarbons, percent	11.84	16.39	17.91	16.23
Test for Saturates (ASTM D 2007)				
Saturates, percent	11.86	17.17	17.42	16.10
Asphaltene Settling Test				
Settling Time, minutes	60	75	110	110

TABLE 34 - PROPERTIES OF AGED ASPHALTS B AND C, AND RECYCLING AGENT BLENDS

Aged Asphalt	B	B	C	C
Recycling Agent	1	4	1	4
Recycling Agent Grade	AC-5	RA-5	AC-5	RA-5
Percent Recycling Agent	67	18	70	23
Properties of Original Asphalt:				
Viscosity				
140°F (60°C), Poises	1,756	2,331	1,883	2,072
275°F (135°C), cSt	435	430	460	430
77°F (25°C), kP	999	2,058	922	1,179
Penetration				
77°F (25°C), (100g, 5s), 0.1 mm	108	84	116	115
Ductility				
77°F (25°C), (5cm/min), cm	150+	150+	150+	150+
39.2°F (4°C), (5cm/min), cm	9.9	5.8	26.2	17.4
Flash Point, Cleveland Open Cup, °F	495	555	475	480
Solubility in Trichloroethylene, Percent	99.85	99.87	99.92	99.93
Specific Gravity at 77°F (25°C)	1.027	1.021	1.030	1.027
Spot Test	Neg.	Neg.	Neg.	Neg.
Viscosity Temperature Susceptiblity, VTS	3.42	3.54	3.40	3.50
Properties of Thin Film Oven Test Residue:				
Mass Change, Percent	-1.302	-0.508	-1.426	-0.850
Viscosity				
140°F (60°C), Poises	6,006	4,560	6,724	4,424
275°F (135°C), cSt	671	519	794	571
77 °F (25°C), kP	4,985	4,937	5,228	2,971
Viscosity at 140°F (60°C) after thin film oven test / Viscosity at 140°F (60°C) before thin film oven test	3.42	1.96	3.57	2.14
Penetration				
77°F (25°C) (100g, 5s), 0.1 mm	58	59	63	82
Retained Penetration, Percent	53.7	70.2	54.3	71.3
Ductility				
77°F (25°C) (5cm/min), cm	150+	150+	150+	150+
39.2°F (4°C) (5cm/min), cm	4.5	4.3	5.1	7.5

TABLE 35 - COMPOSITIONAL CHARACTERISTICS OF AGED ASPHALTS B AND C AND RECYCLING AGENT BLENDS

Aged Asphalt	B	B	C	C
Recycling Agent	1	4	1	4
Recycling Agent Grade	AC-5	RA-5	AC-5	RA-5
Percent Recycling Agent	67	18	70	23
Asphalt Composition Analysis (ASTM D 4124)				
Asphaltenes (n-Heptane), percent	19.91	18.06	21.65	21.30
Saturates, percent	6.13	8.46	8.99	11.30
Naphthene Aromatics, percent	30.40	30.40	26.48	28.78
Polar Aromatics, percent	41.60	36.04	41.05	36.91
Test for Saturates (ASTM D 2007)				
Saturates, percent	12.02	17.40	9.62	12.43
Asphaltene Settling Test				
Settling Time, minutes	35	91	17	30

TABLE 36 - VISCOSITY AND PENETRATION OF AGED ASPHALT AND RECYCLING AGENT BLENDS

Aged Asphalt		Recycling Agent		Blended to obtain a desired Viscosity of 2000 poises at 140°F		
Ident.	Viscosity at 140°F (60°C), Poises	Ident.	Viscosity at 140°F (60°C), Poises	Recycling Agent Content, percent	Viscosity of blend @ 140°F (60°C), Poises	Penetration of blend @ 77°F (25°C), dmm
A	142,619	1	502	71	2,078	108
A	142,619	2	272	62	2,206	77
A	142,619	3	36	41	2,496	80
A	142,619	4	2.2	25	2,100	110
B	111,312	1	502	67	1,756	108
B	111,312	4	2.2	18	2,331	84
C	119,031	1	502	70	1,883	116
C	119,031	4	2.2	23	2,072	115
D	101,831	1	502	70	1,655	100
D	101,831	2	272	60	1,987	66
D	101,831	3	36	39	1,742	68
D	101,831	4	2.2	20	1,960	71

Table 37 - CALCULATED AND MEASURED COMPOSITIONAL ANALYSIS FRACTIONS FOR BLEND OF 29 PERCENT AGED ASPHALT A AND 71 PERCENT RECYCLING AGENT 1

Fraction	Calculated from measured fractions in each component, percent	Measured fractions in blend, percent
	ASTM Method D 4124	
Asphaltenes (n-Heptane)	20.09	20.86
Saturates	8.24	7.91
Naphthene Aromatics	27.66	26.08
Polar Aromatics	42.05	43.79
	ASTM Method D 2006 (discontinued)	
Asphaltenes (n-Pentane)	26.50	27.74
Polar Compounds	25.91	27.06
First Acidaffins	20.49	17.17
Second Acidaffins	17.56	15.71
Sat. Hydrocarbons	9.52	10.42
	ASTM Method D 2007	
Saturates	10.29	11.00

TABLE 38 - PROPERTIES OF NORTH CAROLINA (I-95) EXTRACTED ASPHALT, RECYCLING AGENT AND EXTRACTED ASPHALT BLEND

Material	Extracted Asphalt	Recycling Agent	Blend
Grade	-	AC-2.5	-
Percent Recycling Agent	-	-	52
Properties of Original Material:			
Viscosity			
140°F (60°C), Poises	33,768	300	2,139
275°F (135°C), cSt	1,335	167	411
77°F (25°C), kP	124,751	53	1,367
140°F, (60°C), cSt	-	-	-
Penetration			
77°F (25°C), (100g, 5s), 0.1 mm	20	362	89
Ductility			
77°F (25°C), (5cm/min), cm	28.7	150+	150+
39.2°F (4°C), (5cm/min), cm	0.0	150+	9.1
Flash Point, Cleveland Open Cup, °F	-	470	515
Solubility in Trichloroethylene, Percent	99.83	99.95	99.86
Specific Gravity at 77°F (25°C)	1.061	1.018	1.038
Spot Test	Pos.	Neg.	Pos.
Viscosity Temperature Susceptibility, VTS	3.66	3.49	3.55
Asphalt Composition Analysis (ASTM D 4124):			
Asphaltenes (n-heptane), percent	25.65	14.62	19.9
Saturates, percent	9.17	12.95	8.8
Naphthene Aromatics, percent	26.06	27.40	28.63
Polar Aromatics, percent	38.31	43.86	41.39
Test for Saturates (ASTM 2007):			
Saturates, percent	13.28	13.36	13.35
Properties of Thin Film Oven Test Residue:			
Mass Change, Percent	-0.787	-1.821	-1.232
Viscosity			
140°F (60°C), Poises	145,357	957	6,512
275°F (135°C), cSt	2,597	284	670
77 °F (25°C), kP	507,424	371	7,719
140°F, (60°C), cSt	-	-	-
Viscosity at 140°F (60°C) after thin film oven test / Viscosity at 140°F (60°C) before thin film oven test	4.30	3.19	3.0
Penetration			
77°F (25°C) (100g, 5s), 0.1 mm	15	152	51
Retained Penetration, Percent	75.0	42.0	57.3
Ductility			
77°F (25°C) (5cm/min), cm	7.1	150+	150+
39.2°F (4°C) (5cm/min), cm	0.0	65.7	4.2

- PROPERTIES OF VIRGINIA (U.S. 220) EXTRACTED ASPHALT, RECYCLING AGENT, AND EXTRACTED ASPHALT AND RECYCLING AGENT BLEND

	Extracted Asphalt	Recycling Agent AC-5	Blend
	-		-
lecycling Agent	37	-	63
ıs of Original Material:			
ty			
(60°C), Poises	46,149	502	2,181
(135°C), cSt	1,688	229	407
(25°C), kP	232,843	209	2,204
, (60°C), cSt	-	-	-
tion			
(25°C), (100g, 5s), 0.1 mm	17	206	72
ty			
(25°C), (5cm/min), cm	10.6	150+	150+
F (4°C), (5cm/min), cm	0.0	85.2	5.1
oint, Cleveland Open Cup, °F	-	590	590
ity in Trichloroethylene, Percent	99.85	99.83	99.83
c Gravity at 77°F (25°C)	1.042	1.023	1.028
st	Neg.	Neg.	Neg.
ty Temperature Susceptibility, VTS	3.60	3.43	3.56
on Characteristics Comp. Analysis (ASTM Prop.)			
enes (n-heptane), percent	23.35	14.29	16.98
es, percent	9.82	8.49	10.94
ne Aromatics, percent	25.58	35.00	31.57
romatics, percent	39.52	41.90	40.10
Saturates (ASTM 2007)			
es, percent	16.26	13.93	14.48
of Thin Film Oven Test Residue:			
inge, Percent	-	-0.483	-0.468
y			
(60°C), Poises	-	1,202	4,865
(135°C), cSt	-	317	574
(25°C), kP			
(60°C), cSt	-	814	6,635
y at 140°F (60°C) in film oven test / y at 140°F (60°C) hin film oven test	-	2.39	2.23
ion			
25°C) (100g, 5s), 0.1 mm	-	116	48
Penetration, Percent	-	56.3	66.7
y			
25°C) (5cm/min), cm	-	150+	150+
(4°C) (5cm/min), cm	-	10.1	3.6

TABLE 40 - PROPERTIES OF CALIFORNIA (HIGHWAY 97) EXTRACTED ASPHALT, RECYCLING AGENTS, AND EXTRACTED ASPHALT AND RECYCLING AGENT BLENDS

Material	Extracted Asphalt	Recycling Agent	Recycling Agent	Blend	Blend
Grade	-	AR-1000	RA500	AR-1000	RA500
Percent Recycling Agent	-	-	-	65	58
Properties of Original Material:					
Viscosity					
140°F (60°C), Poises	105,763	537	396	2,723	2,885
275°F (135°C), cSt	1,672	138	113	292	298
77°F (25°C), kP	1,500,000	400	260	4,300	4,300
140°F, (60°C), cSt	-	-	-	-	-
Penetration					
77°F (25°C), (100g, 5s), 0.1 mm	7	142	169	45	42
Ductility					
77°F (25°C), (5cm/min), cm	6.4	150+	150+	150+	150+
39.2°F (4°C), (5cm/min), cm	0.0	150+	150+	0.0	0.0
Flash Point, Cleveland Open Cup, °F	-	570	560	555	565
Solubility in Trichloroethylene, Percent	99.98	99.96	99.98	94.95	99.99
Specific Gravity at 77°F (25°C)	-	1.002	1.010	1.027	1.028
Spot Test	Pos.	Neg.	Neg.	Pos.	Pos.
Viscosity Temperature Susceptibility, VTS	3.86	3.95	4.02	3.93	3.94
Composition Characteristics Comp. Analysis (ASTM Prop.)					
Asphaltenes (n-heptane), percent	26.06	4.71	4.92	12.23	12.70
Saturates, percent	8.86	15.68	14.24	7.63	11.58
Naphthene Aromatics, percent	16.52	27.16	30.67	28.36	24.92
Polar Aromatics, percent	46.76	52.44	50.00	50.42	50.72
Test for Saturates (ASTM 2007)					
Saturates, percent	9.91	15.63	17.08	13.61	14.09
Properties of Thin Film Oven Test Residue:					
Mass Change, Percent	-	-0.77	-0.237	-1.02	-0.746
Viscosity					
140°F (60°C), Poises	-	1,125	703	6,437	6,474
275°F (135°C), cSt	-	188	148	389	414
77 °F (25°C), kP	-	2,200	540	9,200	17,600
140°F, (60°C), cSt	-	-	-	-	-
Viscosity at 140°F (60°C) after thin film oven test / Viscosity at 140°F (60°C) before thin film oven test	-	2.09	1.78	2.36	2.24
Penetration					
77°F (25°C) (100g, 5s), 0.1 mm	-	81	110	26	26
Retained Penetration, Percent	-	58.7	65.1	57.8	61.9
Ductility					
77°F (25°C) (5cm/min), cm	-	150+	150+	150+	150+
39.2°F (4°C) (5cm/min), cm	-	0.25	14.25	0.0	0.0

TABLE 41 - PROPERTIES OF UTAH (U.S. 89) EXTRACTED ASPHALT, RECYCLING AGENTS, AND EXTRACTED ASPHALT AND RECYCLING AGENT BLENDS

Material	Extracted Asphalt	Recycling Agent	Recycling Agent	Blend
Grade	-	AC-5	(1)	-
Percent Recycling Agent	-	-	-	(2)
Properties of Original Material:				
Viscosity				
140°F (60°C), Poises	7,002	613	-	1,673
275°F (135°C), cSt	472	222	-	309
77°F (25°C), kP	52,000	560	0.0353	3,500
140°F, (60°C), cSt	-	-	96	-
Penetration				
77°F (25°C), (100g, 5s), 0.1 mm	32	127	380+	62
Ductility				
77°F (25°C), (5cm/min), cm	80.5	150+	-	150+
39.2°F (4°C), (5cm/min), cm	0.0	8.0	-	0.0
Flash Point, Cleveland Open Cup, °F	-	520	345	560
Solubility in Trichloroethylene, Percent	99.66	99.91	99.98	99.86
Specific Gravity at 77°F (25°C)	1.041	1.019	1.013	1.028
Spot Test	Pos.	Neg.	Pos.	Pos.
Viscosity Temperature Susceptibility, VTS	3.89	3.55	-	3.69
Composition Characteristics Comp. Analysis (ASTM Prop.)				
Asphaltenes (n-heptane), percent	25.13	12.98	1.18	18.14
Saturates, percent	19.95	13.72	17.87	14.81
Naphthene Aromatics, percent	23.21	32.16	50.31	28.23
Polar Aromatics, percent	31.71	41.13	25.72	38.41
Test for Saturates (ASTM 2007)				
Saturates, percent	21.70	17.79	9.87	19.78
Properties of Thin Film Oven Test Residue:				
Mass Change, Percent	-	-0.77	-8.16	-0.81
Viscosity				
140°F (60°C), Poises	-	1,525	-	4,172
275°F (135°C), cSt	-	327	-	414
77 °F (25°C), kP	-	3,302	0.383	13,000
140°F, (60°C), cSt	-	-	310	-
Viscosity at 140°F (60°C) after thin film oven test / Viscosity at 140°F (60°C) before thin film oven test	-	2.49	3.23	2.49
Penetration				
77°F (25°C) (100g, 5s), 0.1 mm	-	65	-	42
Retained Penetration, Percent	-	51.2	-	67.7
Ductility				
77°F (25°C) (5cm/min), cm	-	150+	-	150+
39.2°F (4°C) (5cm/min), cm	-	3.75	-	0.0

(1)Utah softening agent specifications.

(2)43.8 percent AC-5, 1.2 percent softening agent, 55 percent extracted asphalt

Table 42 - PROPERTIES OF NEW MEXICO (I-40) EXTRACTED ASPHALT, RECYCLING AGENT AND EXTRACTED ASPHALT AND RECYCLING AGENT BLEND

Material Grade Percent Recycling Agent	Extracted Asphalt -	Recycling Agent 85-100	Blend - 78
Properties of Original Material:			
Viscosity			
140°F (60°C), Poises	6532	716	868
275°F (135°C), cSt	696	209	265
77°F (25°C), kP	45,500	1,100	1,650
140°F (60°C), cSt			
Penetration			
77°F (25°C), (100g, 5s), 0.1 mm	38	96	76
Ductility			
77°F (25°C), (5cm/min), cm	33	150+	150+
39.2°F (4°C), (5cm/min), cm	0.0	4.7	3.8
Flash Point, Cleveland Open Cup, °F	655	645	645
Solubility in Trichloroethylene, Percent	99.95	99.97	99.97
Specific Gravity at 77°F (25°C)	1.015	1.017	1.017
Spot Test	pos	pos	pos
Viscosity Temperature Susceptibility, VTS	3.56	3.68	3.55
Composition Characteristics			
Comp. Analysis (ASTM Prop.)			
Asphaltenes (n-Heptane),	-	-	-
Saturates, percent	-	-	-
Naphthene Aromatics, percent	-	-	-
Polar Aromatics, percent	-	-	-
Test for Saturates (ASTM 2007)			
Saturates, percent	-	-	-
Properties of Thin Film Oven Test Residue:			
Mass Change, Percent		+0.0502	+0.0628
Viscosity			
140°F (60°C), Poises		1592	2372
275°F (135°C), cSt		276	356
77°F (25°C), kP		4050	8400
140°F (60°C), cSt			
Viscosity @ 140°F (60°C) after TFOT / Viscosity @ 140°F (60°C) after TFOT		2.22	2.73
Penetration, 77°F (25°C) (100g, 5s), 0.1 mm		57	49
Retained Penetration, Percent		59.4	64.5
Ductility, 77°F (25°C) (5cm/min), cm		150+	150+
39.2°F (4°C) (5cm/min), cm		3.2	2.7

Table 43 - COMPOSITION OF COMPACTED RECYCLED MIX SPECIMENS FOR MOISTURE DAMAGE TESTS

Recycling Construction Project	California (Highway 97)	New Mexico (I-40) (1)	New Mexico (I-40) (2)	North Carolina (I-95)	Utah (U.S. 89) (3)	Virginia (U.S. 220)
Percent by weight finer than: Sieve Size						
1 in.	100	100	100	100	100	100
3/4 in.	99	100	100	97	100	100
1/2 in.	86	85	84	75	87	81
3/8 in.	72	69	68	66	74	64
No. 4	47	45	44	48	51	40
No. 8	35	32	31	37	40	28
No. 16	28	25	25	32	33	21
No. 30	23	21	21	24	27	15
No. 50	17	17	16	14	21	10
No. 100	12	11	10	8	13	8
No. 200	7.6	7.1	6.2	4.3	7.6	6.1
Recycling Agent: Percent by total weight of mix	1.9	2.3	2.3	2.2	3.1	2.5
Reclaimed Asphalt Concrete: Percent	45.0	50.0	50.0	49.6	50	40.0
Recycling Agent: Type and Grade	Asphalt Cement AR-1000	Asphalt Cement 85-100	Asphalt Cement 85-100	Asphalt Cement AC-20	Asphalt Cement AC-5	Asphalt Cement AC-5

1) The new aggregate contained 1 percent hydratal lime and the new asphalt cement contained 1/2 percent liquid antistripping agent.
2) Recycled mix contained no hydratal lime or liquid antistripping agent.
3) The new aggregate contained 1 percent of hydratal lime and the recycled mix contained 0.08 percent of Utah specification low viscosity recycling agent.

Table 44 - SUMMARY OF MOISTURE DAMAGE TEST FOR FIVE RECYCLING CONSTRUCTION PROJECTS

Specimen Age	Air Voids %	Air Voids Filled With Water[1], %		Indirect Tensile Strength[1], PSI			Indirect Tensile Strength Ratio[1]		Visual Rating of Stripping[2]	
		Subset II	Subset III	Subset I	Subset II	Subset III	TSR_1	TSR_2	Subset II	Subset III
				VIRGINIA (U.S. 220)						
unaged	7.3	69.3	71.3	94.3	111.7	102.1	1.18	1.08	N.D.	N.D.
1 week	7.3	79.8	78.2	113.0	118.5	93.9	1.05	0.83	N.D.	N.D.
4 weeks	7.3	72.5	78.4	111.7	106.7	95.5	0.96	0.86	N.D.	N.D.
				CALIFORNIA (HIGHWAY 97)						
unaged	7.6	89.0	97.9	317.5	298.7	204.0	0.96	0.65	N.D.	N.D.
1 week	7.6	88.4	94.9	282.5	288.6	216.0	1.02	0.76	N.D.	N.D.
4 weeks	7.6	92.2	100.2	295.8	311.4	221.6	1.05	0.75	N.D.	N.D.
				NEW MEXICO (I 40), WITHOUT ANTISTRIPPING AGENT						
unaged	5.6	80.7	90.3	123.9	118.8	89.8	0.96	0.72	N.D.	V.S.
1 week	5.5	83.5	90.7	123.5	128.1	89.7	1.04	0.73	N.D.	V.S.
4 weeks	5.5	78.6	89.2	122.3	122.4	88.9	1.00	0.73	N.D.	V.S.
				NEW MEXICO (I 40), WITH ANTISTRIPPING AGENT						
unaged	5.3	72.2	85.3	131.7	131.0	123.2	0.99	0.94	N.D.	N.D.
1 week	5.3	76.1	88.9	130.0	131.6	115.0	1.01	0.89	N.D.	V.S.
4 weeks	5.2	80.5	86.0	123.6	130.6	107.2	1.06	0.87	N.D.	V.S.
				UTAH (U.S. 89)						
unaged	7.6	81.5	89.6	94.1	91.0	84.4	0.97	0.90	N.D.	N.D.
1 week	7.7	89.9	96.8	122.1	111.4	82.6	0.91	0.68	N.D.	N.D.
4 weeks	7.6	86.0	102.8	113.8	102.4	81.4	0.90	0.72	N.D.	N.D.
				NORTH CAROLINA (I 95)						
unaged	5.4	65.1	74.5	100.4	108.8	101.0	1.08	1.01	N.D.	N.D.
1 week	-	-	-	-	-	-	-	-	-	-
4 weeks	5.4	71.6	74.3	110.6	124.1	110.8	1.12	1.00	N.D.	S.

[1] Test values are averages for three specimens.
[2] N.D. (not discernible)
V.S. (very slight)
S. (slight)

Table 45 - AGGREGATE GRADINGS FOR FIVE RECYCLING PROJECT MIX DESIGNS

Sieve Size	Percent Passing				
	North Carolina (I-95)	Virginia (U.S. 220)	New Mexico I-40	California (Highway 97)	Utah (U.S. 89)
1 in.	100	100		100	
3/4 in.	96.4	99.9	100	99.1	100
1/2 in.	72.2	82.2	86.1	81.7	86.5
3/8 in.	62.4	66.7	66.7	71.0	73.9
No. 4	43.6	43.6	45.4	45.5	50.8
No. 8	32.8	31.7	30.9	33.4	39.9
No. 16	28.2	23.5	24.3	27.2	33.1
No. 30	20.8	16.0	20.2	21.9	27.1
No. 50	12.5	10.8	15.8	16.6	20.5
No. 100	6.7	7.9	10.5	11.4	13.2
No. 200	3.8	6.0	6.5	7.4	7.6

TABLE 46 - MARSHALL METHOD MIX DESIGN DATA FOR NORTH CAROLINA (I-95) RECYCLED MIX (AGGREGATE BLEND CONSTANT)

Total Binder % by Wgt. of Mix	RA by Wgt. of Mix, %	Mass, g In Air	Mass, g In Water	Mass, g Sat. Sur. Dry	Bulk Vol., cm3	Bulk S.G.	Theo. Max. S.G.	Air Voids %	Density, lb/ft3	Stability, lbf Meas.	Stability, lbf Adjust.	Flow 0.01 in.
3.5 A	1.0	1,24[illegible].3	723.6	1,255.8	532.2	2.336	-	-	-	2,414	2,317	7
B	-	1,244.0	727.7	1,261.0	533.3	2.333	-	-	-	2,155	2,069	9
C	-	1,247.0	730.1	1,266.5	536.4	2.325	-	-	-	2,567	2,464	9
Avg.	-	-	-	-	-	2.331	2.563	9.1	145.5	-	2,283	8
4.0 A	1.5	1,[illegible]5.4	726.7	1,252.0	525.3	2.371	-	-	-	2,062	1,980	10
B	-	1,243.2	724.6	1,252.8	528.2	2.354	-	-	-	2,082	1,999	8
C	-	1,249.1	726.8	1,254.5	527.7	2.367	-	-	-	2,047	1,965	9
Avg.	-	-	-	-	-	2.364	2.528	6.5	147.5	-	1,981	9
4.5 A	2.0	1,246.3	733.4	1,247.6	514.2	2.424	-	-	-	2,667	-	9
B	-	1,249.5	735.9	1,252.4	516.5	2.419	-	-	-	2,461	-	9
C	-	1,246.1	736.1	1,248.1	512.0	2.434	-	-	-	2,564	-	8
Avg.	-	-	-	-	-	2.426	2.517	3.6	151.4	2,564	-	9
5.0 A	2.5	1,243.1	738.8	1,244.2	505.4	2.460	-	-	-	2,496	2,596	10
B	-	1,244.3	737.3	1,244.5	507.2	2.453	-	-	-	2,747	2,857	13
C	-	1,245.9	738.4	1,246.4	508.0	2.453	-	-	-	2,768	2,879	11
Avg.	-	-	-	-	-	2.455	2.500	1.8	153.2	-	2,777	11
5.5 A	3.0	1,242.8	735.9	1,242.8	506.9	2.452	-	-	-	2,280	2,371	12
B	-	1,237.8	733.4	1,237.8	504.4	2.454	-	-	-	2,165	2,252	14
C	-	1,238.5	735.5	1,238.5	503.0	2.462	-	-	-	2,152	2,238	13
Avg.	-	-	-	-	-	2.456	2.485	1.2	153.3	-	2,287	13
6.0 A	3.5	1,235.4	730.0	1,235.4	505.4	2.444	-	-	-	1,702	1,770	15
B	-	1,240.1	733.3	1,240.1	506.8	2.4[illegible]	-	-	-	2,067	2,150	15
C	-	1,230.7	726.6	1,230.7	504.1	2.441	-	-	-	1,863	1,938	21
Avg.	-	-	-	-	-	2.444	2.464	0.8	152.5	-	1,953	17
6.5 A	4.0	1,226.4	722.4	1,226.4	504.0	2.433	-	-	-	1,817	1,890	16
B	-	1,226.2	722.3	1,226.2	504.0	2.433	-	-	-	1,549	1,611	18
C	-	1,230.6	723.3	1,230.6	507.3	2.426	-	-	-	1,906	1,982	22
Avg.	-	-	-	-	-	2.431	2.449	0.7	151.7	-	1,828	19

Mg/m^3 = 0.01618 lb/ft^3
N = 4.448 lbf

TABLE 47 - MARSHALL METHOD MIX DESIGN DATA FOR NORTH CAROLINA (I-95) RECYCLED MIX (ASPHALT BLEND CONSTANT)

Total Binder % by Wgt. of Mix	RA by Wgt. of Mix, %	Mass, g			Bulk Vol., cm^3	Bulk S.G.	Theo. Max. S.G.	Air Voids %	Density, lb/ft^3	Stability, lbf		Flow 0.01 in.
		In Air	In Water	Sat. Sur. Dry						Meas.	Adjust.	
4.0 A	2.2	1,244.0	733.0	1,247.8	514.8	2.416	-	-	150.8	2,478	-	9
B	-	1,249.3	734.3	1,254.9	520.6	2.400	-	-	149.8	2,390	-	10
C	-	1,236.4	728.6	1,243.2	514.6	2.403	-	-	149.9	2,487	-	11
Avg.	-	-	-	-	-	2.406	2.541	5.3	150.2	2,452	-	10
4.5 A	2.4	1,248.1	731.4	1,250.3	518.9	2.405	-	-	150.1	2,681	-	12
B	-	1,247.2	736.7	1,248.2	511.5	2.438	-	-	152.1	2,963	-	12
C	-	1,247.1	735.6	1,248.9	513.3	2.430	-	-	151.6	2,538	-	12
Avg.	-	-	-	-	-	2.424	2.524	4.0	151.3	2,727	-	12
5.0 A	2.7	1,247.2	740.8	1,247.5	506.7	2.461	-	-	153.6	2,889	3,004	11
B	-	1,249.3	741.6	1,249.7	508.1	2.459	-	-	153.4	2,936	3,053	12
C	-	1,248.8	737.0	1,249.4	512.4	2.437	-	-	152.1	2,781	2,781	12
Avg.	-	-	-	-	-	2.452	2.499	1.9	153.0	-	2,946	12
5.5 A	3.0	1,244.2	736.2	1,244.5	508.3	2.448	-	-	152.8	2,272	2,363	12
B	-	1,244.4	736.3	1,244.5	508.2	2.449	-	-	152.8	2,402	2,498	12
C	-	1,245.8	737.5	1,246.0	508.5	2.450	-	-	152.9	2,531	2,632	12
Avg.	-	-	-	-	-	2.449	2.477	1.1	152.8	-	2,498	12
6.0 A	3.3	1,239.4	731.3	1,239.4	508.1	2.439	-	-	152.2	2,176	2,263	17
B	-	1,241.9	733.0	1,242.0	509.0	2.440	-	-	152.3	2,305	2,305	16
C	-	1,237.6	731.3	1,237.8	506.5	2.443	-	-	152.4	2,214	2,303	15
Avg.	-	-	-	-		2.441	2.459	0.7	152.3	-	2,290	16

$Mg/m^3 = 0.01618\ lb/ft^3$
N = 4.488 lbf

TABLE 48 - HVEEM METHOD MIX DESIGN DATA FOR NORTH CAROLINA (I-95) RECYCLED MIX (AGGREGATE BLEND CONSTANT)

Total Binder % by Wgt. of		RA Wgt., %		Mass, g			Bulk Vol., cm^3	Bulk S.G.	Theo. Max. S.G.	Air Voids %	Density, lb/ft^3	Stabilometer Value
Mix	Agg.	of Mix	of Agg.	In Air	In Water	Sat. Sur. Dry						
3.0	3.1	0.5	0.5	1,256.3	741.1	1,262.5	521.4	2.409	2.578	6.6	150.3	32
3.5	3.6	0.9	0.9	1,253.8	741.0	1,260.8	519.8	2.412	2.563	5.9	150.5	44
4.0	4.2	1.5	1.5	1,253.7	744.0	1,255.5	511.5	2.451	2.528	3.0	152.9	43
4.5	4.7	2.0	2.0	1,250.8	747.0	1,252.0	505.0	2.477	2.517	1.6	154.6	35
5.0	5.3	2.5	2.6	1,250.2	744.6	1,250.8	506.2	2.470	2.500	1.2	154.1	24

Mg/m^3 = 0.01618 lb/ft^3
N = 4.448 lbf

TABLE 49 - MARSHALL METHOD MIX DESIGN DATA FOR VIRGINIA (U.S. 220)
RECYCLED MIX (AGGREGATE BLEND CONSTANT)

Total Binder % by Wgt. of Mix		RA by Wgt. of Mix, %	Mass, g			Bulk Vol., cm^3	Bulk S.G.	Theo. Max. S.G.	Air Voids %	Density, lb/ft^3	Stability, lbf		Flow 0.01 in.
			In Air	In Water	Sat. Sur. Dry						Meas.	Adjust.	
4.1	A	2.1	1,274.3	759.7	1,277.6	517.9	2.461	-	-	153.6	3,044	-	12
	B	-	1,273.4	759.2	1,270.9	520.0	2.449	-	-	152.8	3,200	-	12
	C	-	1,277.5	762.3	1,283.1	520.8	2.453	-	-	153.1	3,220	-	12
	Avg.	-	-	-	-	-	2.454	2.623	6.4	153.1	3,181	-	12
4.6	A	2.6	1,273.8	765.3	1,276.0	510.7	2.494	-	-	155.6	3,401	-	14
	B	-	1,269.9	761.7	1,271.6	509.9	2.490	-	-	155.4	3,010	-	13
	C	-	1,273.8	765.3	1,275.6	510.3	2.496	-	-	155.8	3,061	-	12
	Avg.	-	-	-	-	-	2.493	2.605	4.3	155.6	3,157	-	13
5.1	A	3.1	1,269.0	765.7	1,269.8	504.1	2.517	-	-	157.1	2,902	3,018	13
	B	-	1,274.4	768.4	1,275.0	506.6	2.516	-	-	157.0	2,969	3,088	14
	C	-	1,270.5	764.3	1,271.4	507.1	2.505	-	-	156.3	2,945	3,063	11
	Avg.	-	-	-	-	-	2.513	2.580	2.6	156.8		3,056	13
5.6	A	3.6	1,267.0	763.4	1,267.4	504.0	2.514	-	-	156.9	2,785	2,896	14
	B	-	1,265.9	763.9	1,266.2	502.3	2.520	-	-	157.2	2,777	2,888	14
	C	-	1,269.7	766.1	1,270.2	504.1	2.519	-	-	157.2	2,825	2,938	18
	Avg.	-	-	-	-	-	2.518	2.562	1.7	157.1		2,907	15
6.1	A	4.1	1,271.1	764.7	1,271.4	506.7	2.509	-	-	156.6	2,975	3,094	16
	B	-	1,266.4	762.2	1,266.7	504.5	2.510	-	-	156.6	2,697	2,805	14
	C	-	1,266.0	762.4	1,266.4	504.0	2.512	-	-	156.7	2,749	2,859	17
	Avg.	-	-	-	-	-	2.510	2.536	1.0	156.6	-	2,919	16

$Mg/m^3 = 0.01618\ lb/ft^3$
$N = 4.448\ lbf$

TABLE 50 - HVEEM METHOD MIX DESIGN DATA FOR VIRGINIA (U.S. 220) RECYCLED MIX (AGGREGATE BLEND CONSTANT)

Total Binder % by Wgt. of Mix	Total Binder % by Wgt. of Agg.	RA Wgt., % of Mix	RA Wgt., % of Agg.	Mass, g In Air	Mass, g In Water	Mass, g Sat. Sur. Dry	Bulk Vol., cm3	Bulk S.G.	Theo. Max. S.G.	Air Voids %	Density, lb/ft3	Stabilometer Value
3.7	3.8	1.7	1.7	1,278.7	765.3	1,288.9	523.6	2.442	2.638	7.4	152.4	48
4.1	4.3	2.2	2.2	1,283.0	774.0	1,286.6	512.6	2.503	2.627	4.7	156.2	42
4.6	4.8	2.6	2.7	1,282.7	776.0	1,284.0	508.0	2.525	2.603	3.0	157.6	34
5.0	5.3	3.1	3.2	1,282.1	776.5	1,283.3	506.7	2.530	2.586	2.2	157.9	24

Mg/m3 = 0.01618 lb/ft3
N = 4.448 lbf

CKE. 2.2
Percent Oil Retained. 2.8
Surface Area. 25.84
K_f. 0.9
K_c. 1.3
K_m. 1.0
Approximately Asphalt Content by CKE Method . 4.3

TABLE 51 - MARSHALL METHOD MIX DESIGN FOR NEW MEXICO (1-40)
RECYCLED MIX (AGGREGATE BLEND CONSTANT)

Total Binder % by Wgt. of Mix		RA by Wgt. of Mix, %	Mass, g In Air	Mass, g In Water	Mass, g Sat. Sur. Dry	Bulk Vol., cm^3	Bulk S.G.	Theo. Max. S.G.	Air Voids %	Density, lb/ft^3	Stability, lbf Meas.	Stability, lbf Adjust.	Flow 0.01 in.
3.7	A	1.9	1236.7	719.0	1242.9	523.9	2.361			147.3	3902	3745	9
	B		1229.1	712.7	1233.7	521.0	2.359			147.2	3419	3419	8
	C		1241.6	719.4	1246.9	527.5	2.354			146.9	3642	3496	8
	Avg.						2.358	2.496	5.5	147.1	--	3553	8
4.2	A	2.4	1235.3	719.0	1237.4	518.4	2.383			148.7	2978		10
	B		1236.1	720.9	1239.0	518.1	2.386			148.9	3237		10
	C		1235.7	717.8	1240.5	522.7	2.364			147.5	3145		9
	Avg.						2.378	2.477	4.0	148.4	3120		10
4.7	A	2.9	1237.5	722.9	1238.9	516.0	2.398			146.9	3009		11
	B		1233.9	721.1	1235.0	513.9	2.400			149.8	2849		13
	C		1236.9	722.2	1238.2	516.0	2.397			149.6	3018		11
	Avg.						2.398	2.455	2.3	149.6	2959		12
5.2	A	3.4	1231.6	719.0	1232.0	513.0	2.401			149.8	2595		12
	B		1232.0	720.9	1232.4	511.5	2.409			150.3	2521		12
	C		1232.4	721.1	1232.7	511.6	2.409			150.3	2703		13
	Avg.						2.406	2.438	1.3	150.1	2606		12
5.7	A	3.9	1232.7	719.0	1233.1	514.1	2.398			149.6	2084		14
	B		1231.7	717.2	1232.1	514.9	2.392			149.6	2392		15
	C		1228.9	716.5	1229.2	512.7	2.397			149.6	2424		12
	Avg.						2.396	2.418	0.9	149.5	2300		14
6.2	A	4.4	1227.7	714.1	1228.3	514.2	2.388			149.0	2306		16
	B		1223.8	711.9	1224.3	512.4	2.388			149.0	1837		18
	C		1226.5	713.2	1226.7	513.5	2.386			148.9	1983		18
	Avg.						2.387	2.408	0.9	148.9	2042		17

Mg/m^3 = 0.01618 lb/ft^3
N = 4.448 lbf

TABLE 52 - HVEEM METHOD MIX DESIGN DATA FOR NEW MEXICO (I-40)
RECYCLED MIX (AGGREGATE BLEND CONSTANT)

Total Binder % by Wgt. of		RA Wgt., %		Mass, g			Bulk Vol., cm^3	Bulk S.G.	Theo. Max. S.G.	Air Voids %	Density, lb/ft^3	Stabilometer Value
Mix	Agg.	of Mix	of Agg.	In Air	In Water	Sat. Sur. Dry						
4.2	4.4	2.4	2.5		715.9	1,238.3	522.4	2.363	2.477	4.6	147.5	44
4.7	4.9	2.9	3.0		723.7	1,238.5	514.8	2.401	2.458	2.3	149.8	38
5.1	5.4	3.4	3.5		724.7	1,237.8	513.1	2.411	2.444	1.4	150.4	13
5.6	5.9	3.8	4.0		717.6	1,229.1	511.5	2.402	2.425	0.9	149.9	-
6.0	6.4	4.3	4.5		711.9	1,223.5	511.6	2.391	2.410	0.8	149.2	-

Mg/m^3 = 0.01618 lb/ft^3
N = 4.448 lbf

CKE	3.8
Percent Oil Retained	2.9
Surface Area	30.4
K_f	1.05
K_c	1.30
K_m	1.15
Approximate Asphalt Content by CKE Method	5.4

TABLE 53 - HVEEM METHOD MIX DESIGN DATA FOR CALIFORNIA (HIGHWAY 97)
RECYCLED MIX CONTAINING RA 500 RECYCLING AGENT (AGGREGATE BLEND CONSTANT)

Total Binder % by Wgt. of Mix	Total Binder % by Wgt. of Agg.	RA Wgt., % of Mix	RA Wgt., % of Agg.	Mass, g In Air	Mass, g In Water	Mass, g Sat. Sur. Dry	Bulk Vol., cm^3	Bulk S.G.	Theo. Max. S.G.	Air Voids %	Density, lb/ft^3	Stabilometer Value
4.3	4.5	1.6	1.7	1,233.2	716.0	1,240.3	524.3	2.352	2.506	6.1	146.8	52
4.8	5.0	2.1	2.2	1,232.5	722.6	1,236.7	514.1	2.397	2.487	3.6	149.6	43
5.2	5.5	2.6	2.7	1,229.4	721.5	1,233.4	511.9	2.402	2.472	2.8	149.9	37
5.7	6.0	3.0	3.2	1,231.5	721.5	1,232.5	511.0	2.410	2.453	1.8	150.4	29
6.1	6.5	3.5	3.7	1,233.3	724.2	1,234.0	509.8	2.419	2.438	0.8	150.9	26

Mg/m^3 = 0.01618 lb/ft^3
N = 4.448 lbf

TABLE 54 - HVEEM METHOD MIX DESIGN DATA FOR CALIFORNIA (HIGHWAY 97)
RECYCLED MIX CONTAINING RA 500 RECYCLING AGENT (ASPHALT BLEND CONSTANT)

Total Binder % by Wgt. of Mix	Total Binder % by Wgt. of Agg.	RA Wgt., % of Mix	RA Wgt., % of Agg.	Mass, g In Air	Mass, g In Water	Mass, g Sat. Sur. Dry	Bulk Vol., cm3	Bulk S.G.	Theo. Max. S.G.	Air Voids %	Density, lb/ft3	Stabilometer Value
4.3	4.5	2.1	2.2	1,234.9	727.1	1,246.2	519.1	2.379	2.540	6.3	148.4	46
4.8	5.0	2.4	2.5	1,233.8	725.3	1,240.3	515.0	2.396	2.505	4.4	149.5	45
5.2	5.5	2.6	2.7	1,232.0	723.6	1,233.8	510.2	2.415	2.486	2.9	150.7	31
5.7	6.0	2.7	2.9	1,236.0	723.2	1,237.5	514.3	2.403	2.458	2.2	149.9	19
6.1	6.5	3.0	3.2	1,241.4	721.7	1,242.3	520.6	2.385	2.436	2.1	148.8	14

Mg/m3 = 0.01618 lb/ft3
N = 4.448 lbf

TABLE 55 - HVEEM METHOD MIX DESIGN DATA FOR CALIFORNIA (HIGHWAY 97) RECYCLED MIX CONTAINING AR 1000 RECYCLING AGENT (AGGREGATE BLEND CONSTANT)

Total Binder % by Wgt. of		RA Wgt., %		Mass, g			Bulk Vol., cm^3	Bulk S.G.	Theo. Max. S.G.	Air Voids %	Density, lb/ft^3	Stabilometer Value
Mix	Agg.	of Mix	of Agg.	In Air	In Water	Sat. Sur. Dry						
4.3	4.5	1.6	1.7	1,236.8	722.4	1,251.0	528.6	2.340	2.515	7.0	146.0	53
4.8	5.0	2.1	2.2	1,234.4	718.9	1,243.3	524.4	2.354	2.496	5.7	146.9	46
5.2	5.5	2.6	2.7	1,232.5	718.0	1,236.2	518.2	2.378	2.481	4.2	148.4	42
5.7	6.0	3.0	3.2	1,231.0	719.2	1,233.0	513.8	2.396	2.462	2.7	149.5	31
6.1	6.5	3.5	3.7	1,229.0	720.5	1,230.4	509.9	2.410	2.447	1.5	150.4	13

Mg/m^3 = 0.01618 lb/ft^3
N = 4.448 lbf

CKE 4.0
Percent Oil Retained. 3.6
Surface Area 33.15
K_f. 1.2
K_c. 1.6
K_m. 1.3
Approximate Asphalt Content by CKE Method . . 5.5

TABLE 56 - MARSHALL METHOD MIX DESIGN FOR CALIFORNIA (HIGHWAY 97)
RECYCLED MIX CONTAINING AR 1000 RECYCLING AGENT (AGGREGATE BLEND CONSTANT)

Total Binder % by Wgt. of Mix		RA by Wgt. of Mix, %	Mass, g In Air	Mass, g In Water	Mass, g Sat. Sur. Dry	Bulk Vol., cm^3	Bulk S.G.	Theo. Max. S.G.	Air Voids %	Density, lb/ft^3	Stability, lbf Meas.	Stability, lbf Adjust.	Flow 0.01 in.
4.3	A	1.6	1,238.2	717.0	1,247.2	530.2	2.335	-	-	145.7	6,069	5,826	13
	B	-	1,236.6	720.6	1,245.0	524.4	2.358	-	-	147.1	5,940	5,702	13
	C	-	1,238.0	720.9	1,248.0	527.1	2.349	-	-	146.6	5,360	5,146	11
	Avg.	-	-	-	-	-	2.347	2.506	6.3	146.5	-	5,558	12
4.0	A	2.1	1,234.0	713.1	1,236.4	523.3	2.358	-	-	147.1	5,160	4,954	12
	B	-	1,235.9	717.2	1,240.5	523.3	2.362	-	-	147.4	5,390	5,174	12
	C	-	1,236.6	719.4	1,243.3	523.9	2.360	-	-	147.3	5,180	4,973	10
	Avg.	-	-	-	-	-	2.360	2.487	5.1	147.3	-	5,034	11
5.2	A	2.6	1,232.6	716.5	1,235.0	518.5	2.377	-	-	148.3	4,790	-	13
	B	-	1,234.6	720.2	1,237.1	516.9	2.388	-	-	149.0	4,270	-	12
	C	-	1,234.0	722.4	1,235.2	512.8	2.406	-	-	150.1	4,440	-	12
	Avg.	-	-	-	-	-	2.390	2.472	3.3	149.1	4,500	-	12
5.7	A	3.0	1,229.2	718.4	1,230.8	512.4	2.399	-	-	149.7	3,980	-	13
	B	-	1,231.3	717.0	1,232.1	515.1	2.390	-	-	149.1	4,610	-	13
	C	-	1,232.2	720.0	1,232.7	512.7	2.403	-	-	149.9	4,340	-	14
	Avg.	-	-	-	-	-	2.397	2.453	2.3	149.6	4,310	-	13
6.1	A	3.5	1,233.0	720.2	1,233.3	513.1	2.403	-	-	149.9	3,960	-	13
	B	-	1,229.0	719.5	1,229.4	509.9	2.410	-	-	150.4	4,340	-	16
	C	-	1,229.5	720.1	1,229.8	509.7	2.412	-	-	150.5	4,060	-	15
	Avg.	-	-	-	-	-	2.408	2.438	1.2	150.3	4,120	-	15

Mg/m^3 = 0.01618 lb/ft^3
N = 4.448 lbf

TABLE 57 - MARSHALL METHOD MIX DESIGN DATA FOR CALIFORNIA (HIGHWAY 97) RECYCLED MIX CONTAINING AR 1000 RECYCLING AGENT (ASPHALT BLEND CONSTANT)

Total Binder % by Wgt. of Mix	RA by Wgt. of Mix, %	Mass, g In Air	Mass, g In Water	Mass, g Sat. Sur. Dry	Bulk Vol., cm^3	Bulk S.G.	Theo. Max. S.G.	Air Voids %	Density, lb/ft^3	Stability, lbf Meas.	Stability, lbf Adjust.	Flow 0.01 in.
4.3 A	2.1	1,233.8	721.1	1,241.7	520.6	2.370	-	-	147.9	5,022	-	14
B	-	1,236.4	722.3	1,242.0	519.7	2.379	-	-	148.4	4,932	-	10
C	-	1,235.0	723.4	1,242.7	519.3	2.378	-	-	148.4	4,492	-	10
Avg.	-	-	-	-	-	2.376	2.540	6.5	148.3	4,815	-	11
4.8 A	2.4	1,232.7	717.7	1,236.1	518.4	2.378	-	-	148.4	4,895	-	15
B	-	1,233.6	721.5	1,237.4	515.9	2.391	-	-	149.2	4,713	-	11
C	-	1,233.6	719.4	1,237.5	518.1	2.381	-	-	148.6	4,344	-	11
Avg.	-	-	-	-	-	2.383	2.505	4.9	148.7	4,651	-	12
5.2 A	2.6	1,234.0	720.2	1,236.6	516.4	2.390	-	-	149.1	4,492	-	11
B	-	1,233.7	722.5	1,234.4	511.9	2.410	-	-	150.4	4,817	-	11
C	-	1,231.1	719.4	1,231.6	512.2	2.404	-	-	150.0	4,805	-	12
Avg.	-	-	-	-	-	2.401	2.486	3.4	149.8	4,705	-	11
5.7 A	2.7	1,231.9	719.0	1,232.5	513.5	2.399	-	-	149.7	5,018	-	13
B	-	1,233.6	719.7	1,234.5	514.8	2.396	-	-	149.5	4,620	-	15
C	-	1,232.6	720.1	1,233.3	513.2	2.402	-	-	149.9	5,153	-	15
Avg.	-	-	-	-	-	2.399	2.458	2.4	149.7	4,930	-	14
6.1 A	3.0	1,236.2	718.9	1,236.5	517.6	2.388	-	-	149.0	4,371	-	17
B	-	1,236.9	720.4	1,237.4	517.0	2.392	-	-	149.3	4,038	-	18
C	-	1,235.2	721.0	1,235.5	514.5	2.401	-	-	149.8	4,867	-	17
Avg.	-	-	-	-	-	2.394	2.436	1.7	149.4	4,425	-	17

$Mg/m^3 = 0.01618\ lb/ft^3$
N = 4.448 lbf

TABLE 58 - MARSHALL METHOD MIX DESIGN DATA FOR UTAH (U.S. 89) RECYCLED MIX (AGGREGATE BLEND CONSTANT)

Total Binder % by Wgt. of Mix		RA by Wgt. of Mix, %	Mass, g In Air	Mass, g In Water	Mass, g Sat. Sur. Dry	Bulk Vol., cm^3	Bulk S.G.	Theo. Max. S.G.	Air Voids %	Density, lb/ft^3	Stability, lbf Meas.	Stability, lbf Adjust.	Flow 0.01 in.
4.6	A	1.6	1,192.5	680.7	1,200.0	519.3	2.296	-	-	143.3	4,104	-	15
	B	-	1,195.5	680.8	1,201.0	520.2	2.298	-	-	143.4	4,255	-	11
	C	-	1,197.3	681.8	1,202.4	520.6	2.300	-	-	143.5	4,806	-	13
	Avg.	-	-	-	-	-	2.298	2.462	6.7	143.4	4,388	-	13
5.1	A	2.1	1,195.0	686.0	1,197.6	511.6	2.336	-	-	145.8	4,152	-	13
	B	-	1,193.2	686.5	1,196.7	510.2	2.339	-	-	146.0	4,299	-	13
	C	-	1,195.9	688.4	1,197.8	509.4	2.348	-	-	146.5	4,246	-	13
	Avg.	-	-	-	-	-	2.341	2.443	4.2	146.1	4,232	-	13
5.6	A	2.6	1,188.3	686.6	1,188.9	502.3	2.366	-	-	147.6	2,971	3,090	14
	B	-	1,191.0	688.5	1,191.5	503.0	2.368	-	-	147.8	3,442	3,560	13
	C	-	1,190.1	668.9	1,190.7	501.8	2.372	-	-	148.0	3,560	3,702	13
	Avg.	-	-	-	-	-	2.369	2.425	2.3	147.8	-	3,457	13
6.1	A	3.1	1,190.3	688.7	1,191.2	502.5	2.369	-	-	147.8	3,008	3,128	16
	B	-	1,191.4	689.1	1,191.7	502.6	2.370	-	-	147.9	3,053	3,175	13
	C	-	1,190.4	687.7	1,190.6	502.9	2.367	-	-	147.7	3,358	3,492	17
	Avg.	-	-	-	-	-	2.369	2.407	1.6	147.8	-	3,265	15
6.6	A	3.6	1,184.0	685.0	1,184.3	499.3	2.371	-	-	148.0	2,231	2,320	18
	B	-	1,190.5	687.0	1,190.7	503.7	2.364	-	-	147.5	2,394	2,490	21
	C	-	1,189.0	684.5	1,189.3	504.8	2.355	-	-	147.0	2,565	2,668	19
	Avg.	-	-	-	-	-	2.363	2.390	1.1	147.5	-	2,493	19

$Mg/m^3 = 0.01618\ lb/ft^3$
N = 4.448 lbf

TABLE 59 - MARSHALL METHOD MIX DESIGN DATA FOR UTAH (U.S. 89)
RECYCLED MIX (ASPHALT BLEND CONSTANT)

Total Binder % by Wgt. of Mix	RA by Wgt. of Mix, %	Mass, g In Air			Bulk Vol., cm^3	Bulk S.G.	Theo. Max. S.G.	Air Voids %	Density, lb/ft^3	Stability, lbf		Flow 0.01 in.
		In Air	In Water	Sat. Sur. Dry						Meas.	Adjust.	
4.6 A	2.1	1,194.4	684.6	1,199.9	515.3	2.318	-	-	144.6	4,213	-	12
B	-	1,196.0	681.9	1,201.5	519.6	2.302	-	-	143.6	4,221	-	12
C	-	1,194.1	681.2	1,199.4	518.2	2.304	-	-	143.8	4,645	-	12
Avg.	-	-	-	-	-	2.308	2.481	7.0	144.0	4,360	-	12
5.1 A	2.3	1,195.5	687.0	1,196.6	509.6	2.346	-	-	146.4	3,913	-	15
B	-	1,194.6	684.5	1,196.3	511.8	2.334	-	-	145.6	3,718	-	12
C	-	1,194.8	683.7	1,200.0	516.3	2.314	-	-	144.4	3,940	-	11
Avg.	-	-	-	-	-	2.331	2.448	4.8	145.5	3,857	-	13
5.6 A	2.6	1,194.4	686.4	1,196.1	509.7	2.343	-	-	146.2	3,383	3,383	11
B	-	1,192.7	688.1	1,193.3	505.2	2.361	-	-	147.3	3,348	3,482	11
C	-	1,193.0	686.6	1,193.3	506.7	2.354	-	-	146.9	3,493	3,633	14
Avg.	-	-	-	-	-	2.353	2.425	3.0	146.8	-	3,499	12
6.1 A	2.8	1,190.3	688.5	1,190.3	501.8	2.372	-	-	148.0	2,920	3,037	17
B	-	1,188.1	683.7	1,188.5	504.8	2.354	-	-	146.9	3,074	3,197	14
C	-	1,192.3	687.4	1,192.3	504.9	2.361	-	-	147.3	2,927	3,044	15
Avg.	-	-	-	-	-	2.362	2.418	2.3	147.4	-	3,093	15
6.6 A	3.0	1,191.0	685.8	1,191.0	505.2	2.357	-	-	147.1	2,813	2,926	19
B	-	1,190.7	684.9	1,190.8	505.9	2.354	-	-	146.9	2,575	2,678	19
C	-	1,188.8	686.1	1,188.9	502.8	2.364	-	-	147.5	2,432	2,529	19
Avg.	-	-	-	-	-	2.358	2.381	1.0	147.1	-	2,711	19

$Mg/m^3 = 0.01618\ lb/ft^3$
N = 4.448 lbf

Table 60 - DENSITY, PERCENT AIR VOIDS AND STABILITY FOR CORES FROM RECYCLED PAVEMENTS

		Density, lb/ft^3	Air Voids %	Marshall Stability lbf	Marshall Flow 0.01 in.	Hveem Stability Value	Theo Max. S.G.
			North Carolina (I-95)				
	No.	4	4	4	4		
	Mean	150.4	3.2	1529	14.0		
	Std. Dev.	1.03	0.8	263	0.8		
	No.	4	4			4	
	Mean	150.5	3.4			24.7	
	Std. Dev.	1.42	0.81			1.5	
	No.	14	14				
	Mean	150.0	3.8				
	Std. Dev.	1.6	1.6				
	No.	4	4				4
	Mean	149.3	5.0				2.508
	Std. Dev.	2.3	2.4				
			New Mexico (I-40)				
	No.	21	21				2
	Mean	144.9	5.9				2.469
	Std. Dev.	2.6	1.6				
	No.	12	12	12	12		
	Mean	144.0	6.4	1272	13.5		
	Std. Dev.	2.1	1.3	356	1.9		
	No.	5	5			5	
	Mean	146.2	5.0			27.6	
	Std. Dev.	2.2	1.4			3.9	
			Utah (U.S. 89)				
All	No.	14	14				2
	Mean	145.8	3.1				2.413
	Std. Dev.	2.0	1.3				
	No.	11					
Top	Mean	147.0					
	Std. Dev.	1.5					
	No.	11					
	Mean	144.6					
Bottom	Std. Dev.	3.1					
	No.	7	7			7	
Both	Mean	145.2		1		23.2	
	Std. Dev.	2.5				3.8	
	No.	10	10	10	10		
Both	Mean	145.6		1737	19.1		
	Std. Dev.	3.0		472	3.1		
			Virginia (U.S. 220)				
	No.	14	14				2
	Mean	153.3	4.507				2.574
	Std. Dev.	4.0	2.5315				
	No.	5	5	5	5		
	Mean	151.3	5.7	1420	30.8		
	Std. Dev.	5.1	3.2	622	2.1		
	No.	5	5			5	
	Mean	153.7	4.2			19.8	
	Std. Dev.	2.7	1.7			2.5	

Mg/m^3 = 0.01618 lb/ft^3
N = 4.448 lbf

Table 61 - ASPHALT EXTRACTION TESTS AND TESTS ON RECOVERED ASPHALT AND AGGREGATE FROM RECYCLED PAVEMENT CORE SAMPLES
(New Mexico I-40, No. Carolina I-95, Utah U.S. 89, Virgina U.S. 220)

	New Mexico I-40	North Carolina I-95	Utah U.S. 89	Virginia U.S. 220
Percent by Weight Finer than: Sieve Size				
1 in.		100.0	100.0	100.0
3/4 in.	100.0	96.0	98.9	99.4
1/2 in.	93.9	75.6	89.1	87.0
3/8 in.	84.9	64.3	76.5	71.9
No. 4	61.8	47.4	53.2	
No. 8	45.8	37.9	42.4	34.8
No. 16	36.5	32.0	35.0	26.6
No. 30	30.1	24.1	29.0	19.9
No. 50	23.2	15.5	22.2	15.1
No. 100	14.6	8.9	14.3	11.7
No. 200	9.2	5.2	8.6	9.1
Asphalt: Percent by Weight of Total Mix	4.67	4.75	6.0	5.1
Recovered Asphalt:				
Pen 77° F, 100g, 5 sec	56	53	132	41
Vis 140°F, poises	2,104	6,128	545	6,476
Vis 275°F, cSt	405	673	185	647

Table 62 - DYNAMIC MODULUS | E* | FOR RECYCLED PAVEMENT CORE SAMPLES
(New Mexico I-40, No. Carolina I-95, Utah U.S. 89, Virgina U.S. 220)

Project	Temp. °F(°C)		Loading Frequency 1 Hz	4 Hz	16 Hz
			| E* | 10^5 psi	| E* | 10^5 psi	| E* | 10^5 psi
New Mexico (I-40)	41(5)	Mean	10.19	13.39	16.93
		Std. Dev.	0.52	0.28	0.60
	77(25)	Mean	2.29	3.25	5.22
		Std. Dev.	0.014	0.007	0.14
	104(40)	Mean	0.45	0.70	1.21
		Std. Dev.	0.00	0.014	0.021
No. Carolina (I-95)	41(5)	Mean	9.94	13.93	22.0
		Std. Dev.	0.46	0.87	1.29
	77(25)	Mean	2.16	3.66	5.79
		Std. Dev.	0.007	0.06	0.02
	104(40)	Mean	0.49	0.82	1.39
		Std. Dev.	0.007	0.06	0.02
Utah (U.S. 89)	41(5)	Mean	11.3	14.1	19.1
		Std. Dev.	0.37	1.0	3.2
	77(25)	Mean	1.52	2.69	4.78
		Std. Dev.	.23	.29	.60
	104(40)	Mean	0.28	0.40	0.75
		Std. Dev.	.04	.08	.15
Virginia (U.S. 220)	41(5)	Mean	10.61	14.85	17.79
		Std. Dev.	0.693	0.163	0.240
	77(25)	Mean	2.57	3.71	5.85
		Std. Dev.	0.035	0.134	0.233
	104(40)	Mean	0.48	0.91	1.51
		Std. Dev.	0.007	0.049	0.099

1 psi = 6,894 Pa

APPENDIX A

PLANS FOR SAMPLING ASPHALT PAVING MIXTURES BEFORE RECYCLING

I. PLAN FOR SAMPLING ASPHALT CONCRETE PAVEMENT IN PLACE

1.0 Sampling

1.1 Investigate construction and maintenance records and determine as nearly as possible the composition of the pavement along the roadway to be recycled. Separate the pavement into construction units that have similar composition.

1.2 If the construction unit is two lanes wide, divide each construction unit into six to eight sections of equal length. Randomly select one sampling location in each lane of each section. Suitable tables of random numbers can be found in Appendix B or Reference (29).

1.3 If the construction unit is only one lane wide, divide the length into 12 to 16 subsections of equal length and select one random sampling location in each section.

1.4 Obtain one sample of pavement at each sampling location of sufficient size, at least 15 lb (6.8 kg), for extraction and recovery testing. There will be a total of 12 to 16 samples or more to be tested individually for each construction unit.

2.0 Testing

2.1 Extract and recover asphalt from each sample. Perform the following tests on each sample:

1) Aggregate grading

2) Asphalt content

3) Penetration at 77°F (25°C)

4) Viscosity at 140°F (60°C) and at 275° (135°C)

II. PLAN FOR SAMPLING MILLED OR PROCESSED RECLAIMED ASPHALT CONCRETE FROM TRUCKS

1.0 Sampling

1.1 Investigate construction and maintenance records and determine as nearly as possible the composition of the pavement along the roadway to be recycled. Separate the pavement into construction units that have similar composition.

1.2 Divide the production into 12 to 16 (one or two day) time periods. Randomly select two trucks from each time period for sampling. If a production day is less than half a work day, include with next half or full day. Suitable tables of random numbers can be found in Appendix B or Reference (29).

1.3 Obtain one sample of reclaimed asphalt concrete pavement from each truck of sufficient size, at least 15 lbs. (6.8 kg), for an extraction and recovery test and for possible use in mix design. There should be a total of 12 to 16 samples or more to be tested individually for each construction unit.

2.0 Testing

2.1 Extract and recover asphalt from each sample. Perform the following tests on each sample:

1) Aggregate grading

2) Asphalt content

3) Penetration at 77°F (25°C)

4) Viscosity at 140°F (60°C) and at 275°F (135°C)

III. PLAN FOR SAMPLING STOCKPILES OF RECLAIMED ASPHALT CONCRETE USING POWER EQUIPMENT

1.0 Sampling

1.1 Investigate records of the owner of an existing stockpile to obtain information about the source and composition of the material in the stockpile.

1.2 If the stockpile consists of unprocessed pavement slabs, or has been sitting for a long time, it may be necessary to process the material before sampling.

1.3 If the material appears to be uniform in composition and from one source, proceed to step 1.6.

1.4 If the material is from different sources, if sources cannot be identified, or if the material appears to be of different composition:

1.4.1 Thoroughly mix or reprocess the stockpile material into one uniform lot, or

1.4.2 Separate the stockpile into uniform-appearing lots and treat as separate stockpiles.

1.5 Since appearance alone cannot guarantee uniformity, the stockpile should be sampled in such a way as to enable non-uniformity to be detected.

1.6 Using a rectangular grid-pattern divide the stockpile into blocks of approximately 2,000 tons (1 800 metric tons) each. The blocks and grid pattern need not be square or rectangular shapes, but blocks should cover approximately the same area or quantity of material. Figure A.1 may be used as a guide. A minimum of 12 to 16 blocks should be selected.

1.7 Number the blocks in a regular manner.

1.8 Select the X - Y coordinates for the sampling point in each block using a random number procedure. This may be done by selecting two random numbers from 0.1 to 1.0 and multiplying them times the length of the X and Y sides of the blocks to locate the coordinates in feet. Use the same relative origin in each block. Suitable tables of random numbers can be found in Appendix B or Reference (29).

1.9 If peaks or valleys occur in the stockpile to such an extent that the normal sampling plan is not effective, then either rework the stockpile or modify the sampling plan. In some cases, the stockpile may be subdivided into smaller lots. In others, substitute random samples from a higher level for samples that would be located where there is a valley.

1.10 Using a front-end loader obtain approximately 1 ton (907 kg) of material from each randomly selected location in the section at the upper third level and one similar sample from the lower third level of the stockpile. Record the location of each sample.

1.11 Using the method of quartering or a large sample splitter, reduce each one ton sample to a sample of sufficient size, at least 15 lbs. (6.8 kg) for extraction and recovery testing and for possible use in mix design.

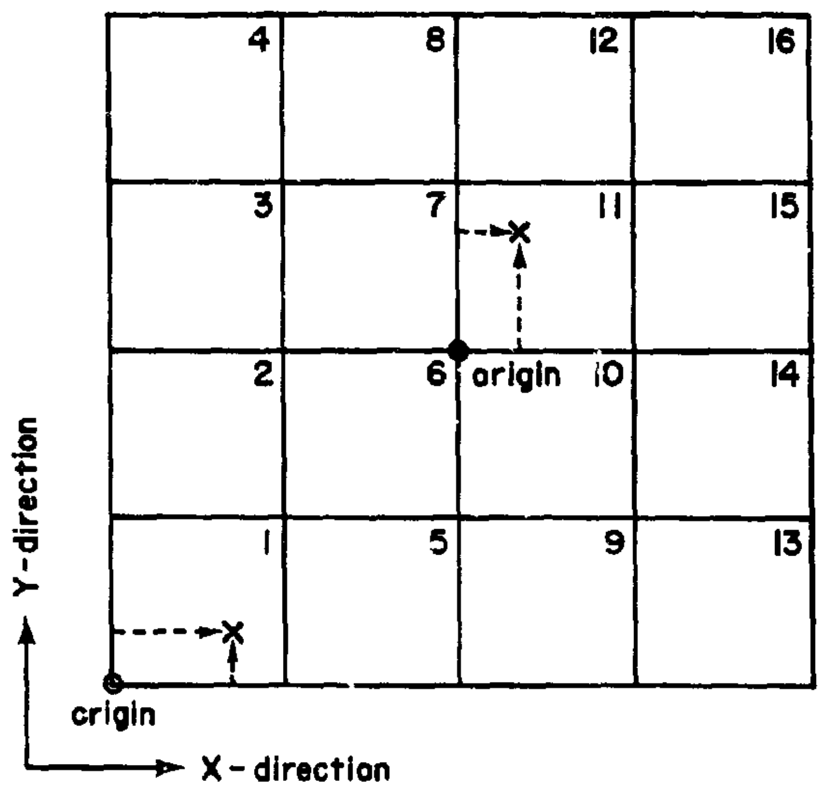

Figure A.1 - 16-Block Grid Pattern

2.0 Testing

2.1 Extract and recover asphalt from each sample. Perform the following tests:

1) Aggregate gradation

2) Asphalt content

3) Penetration at 77°F (25°C)

4) Viscosity at 140°F (60°C) and at 275°F (135°C)

IV. PLAN FOR SAMPLING STOCKPILES OF RECLAIMED ASPHALT CONCRETE WHEN POWER EQUIPMENT IS NOT AVAILABLE

This plan is based on the following assumptions:

1) Stockpiles will not exceed two layers in height, and

2) Power equipment, such as a front end loader, is not available for sampling.

1.0 Sampling

1.1 Investigate records of the owner of an existing stockpile to obtain information about the source and composition of the material in the stockpile.

1.2 If the stockpile consists of unprocessed pavement slabs, or has been sitting for a long time, it may be necessary to process the material before sampling.

1.3 If the material appears to be uniform in composition and from one source, proceed to step 1.6.

1.4 If the material is from different sources, if sources cannot be identified, or if the material appears to be of different composition, separate the stockpile into uniform-appearing lots.

1.5 Since appearance alone cannot guarantee uniformity, the stockpile should be sampled in such a way as to enable non-uniformity to be detected.

1.6 Using a rectangular grid-pattern arbitrarily divide the stockpile into blocks of approximately 2,000 tons (1,800 metric tons) each. The blocks and grid pattern need not be square or rectangular shapes, but blocks should cover approximately the same area or quantity of material. Figure A.1 may be used as a guide. A minimum of 12 to 16 blocks should be selected.

1.7 Number the blocks in a regular manner.

1.8 Select the X - Y coordinates for the sampling point in each block using a random number procedure. This may be done by selecting two random numbers from 0.1 to 1.0 and multiplying them times the length of the X and Y sides of the blocks to locate the coordinates in feet. Use the same relative origin in each block. Suitable tables of random numbers can be found in Appendix B or Reference (29).

1.9 By hand, remove one to three feet of material from the top of the pile at each sample location and carefully remove a 15 to 25 lb. (6.8 to 11.3 kg) sample. Record block and location within the block.

1.10 If the stockpile is two layers in height it may be impossible to sample the interior of the bottom layer of the stockpile. Therefore, the bottom layer should be sampled from the side, using only the outer blocks. Use a new set of coordinates and locate the samples along the Y-axis (X coordinate = 0), at about midheight. Cut a vertical face about two feet into the stockpile face and remove a 15 to 25 lb. (6.8 to 11.3 kg) sample. Record block, layer number and location within the block.

2.0 <u>Testing</u>

2.1 Extract and recover asphalt from each sample. Perform the following tests on each sample:

1) Aggregate grading

2) Asphalt content

3) Penetration at 77°F (25°C)

4) Viscosity at 140°F (60°C) and at 275°F (135°C)

APPENDIX B

SELECTING SAMPLING LOCATIONS

1.0 Sampling from Roadway

Table B.1 contains random numbers to be used with the above sampling procedures. (For alternate procedure see Reference 30.) To use Table B.1 for selecting locations for sampling or testing, the following steps are necessary:

1.1 Designate sections or blocks as specified in the sampling procedure being used.

1.2 Determine the number of sampling locations within a section as specified in the sampling procedure being used.

1.3 Select a column of random numbers in Table B.1 by placing 28 pieces of cardboard 25 mm (1 in.) square, numbered 1 through 28, into a container (such as a bowl), shaking them to get them thoroughly mixed and drawing one out.

1.4 Go to the column of random numbers identified with the number drawn from the container. In subcolumn A locate all numbers equal to and less than the number of sampling locations per section desired.

1.5 Multiply the total length of the section by the decimal values in subcolumn B, found opposite the numbers located in subcolumn A. Add the result to the station number at the beginning of the section to obtain the station of the sampling location.

1.6 Multiply the total width of the lane (or lanes) in the section by the decimal values in subcolumn C, found opposite the numbers located in subcolumn A. These are the offset distances from the pavement centerline at which samples are to be taken.

1.7 Repeat the procedure for each section.

2.0 Sampling from Stockpile

2.1 Designate sections or blocks as specified in the sampling procedure being used. Locate X-Y coordinates as shown in Figure A.1.

2.2 Select a column of random numbers in Table B.1 by placing 28 pieces of cardboard 25 mm (1 in.) square, numbered 1 through 28, into a container (such as a bowl), shaking them to get them thoroughly mixed and drawing one out.

2.3 Go to the column of random numbers identified with the number drawn from the container. In subcolumn A locate all numbers equal to or less than the number of sampling locations in each block or section. The corresponding numbers in subcolumns B and C may be used to locate the X-Y coordinates for one block a section.

2.4 Multiply the total length of the block or section in the X direction by the decimal values in subcolumn B, found opposite the number located in subcolumn A to find the length of coordinate X. Multiply the width of the block or section in the Y direction by the corresponding decimal value from subcolumn C to find the length of coordinate Y.

2.5 Repeat the procedure for each block or section.

TABLE B.1 - RANDOM NUMBERS FOR GENERAL SAMPLING PROCEDURE

APPENDIX C

ANALYSIS OF TEST RESULTS OBTAINED USING SAMPLING PLANS

Introduction

Several statistical sampling plans are described in Appendix A. These plans were designed to obtain random samples of asphalt concrete from existing pavements, from milled material sampled from trucks, or from milled or other material processed and stored in stockpiles. The plans were developed using simple statistical concepts. Each sample obtained using these plans is tested. The asphalt and aggregate are extracted and tested for:

1) aggregate gradation

2) asphalt content

3) penetration at 77°F (25°C)

4) viscosity at 140°F (60°C) and 275°F (135°C)

The test samples provide data that can be used to estimate the variability to be expected from pavements to be recycled and to estimate how this variability might affect the quality of the final recycled asphalt mixture.

The analysis techniques selected for use are based on simple analysis of variance (ANOVA) procedures to test for significant differences between sections, blocks or lanes, or other variables that may be established by the sampling plan. In addition, guidelines are given for using sample standard deviations to estimate the ability of a particular source of material to meet job-mix formula or other limits and to test for other significant differences between sample means.

Analysis of Variance

Two applications of analysis of variance have been selected for use in analyzing the results of extraction and recovery tests on asphalt concrete reclaimed from the pavement before recycling. These procedures are shown in Table C.1 and Table C.3.

The analysis of variance is used to estimate whether or not there are statistically significant differences between the test variables of interest (grading, asphalt content, etc.) that can be attributed to their location in the pavement or stockpile. This is done by comparing variances or mean squares (MS) that can be attributed to location to variances or mean squares that can be attributed to random or chance variations (error).

In Table C.1 and Table C.3, this comparison is made by a technique that involves calculating a term called "sum of squares," designated SS, a term called "mean square," designated MS, and a term called the "F-ratio". Sum of squares (SS) may be defined as the sum of the squares of deviations of individual data points about the mean value. The variance or mean square (MS) is the sum of squares divided by the degrees of freedom (df). Degrees of freedom is often defined as the number of comparisons that can be made between data points. The standard deviation is the square root of the variance.

In the analysis of variance, the total or overall sums of squares is divided into portions that can be attributed to the different treatments included in the experiment, plus a portion that represents the random "error" involved in the process. Thus, in Table C.3 the total sum of squares is composed of three subtotals: the amount attributed to differences between sections (SS_s), the amount attributed to lane or layer effects (SS_l) and the remainder (SS_e). ($SS_t = SS_s + SS_l + SS_e$). In Table C.1 "error" is represented by the within section sum of squares (SS_w).

Each sum of squares is divided by its respective degrees of freedom to determine an appropriate mean square (MS = SS/df). The next step is to divide mean squares that represent treatment effects (section or lanes) by the mean square for error (MS_s/MS_e) in Table C.3, or by the mean square that represents within section variability (MS_s/MS_w) in Table C.1.

The ratio of these two mean squares is called the F-ratio. Calculated values of F are compared to critical values of F that can be expected from pure chance. Calculated F-ratios larger than critical F-ratios indicate that the differences probably are greater than would be expected by chance, and the differences due to location are declared statistically significant.

Critical F-ratios are found in most general statistics books (30). Critical F-ratios depend on the degrees of freedom (df) associated with the numerator and denominator used in calculating F and the probability level ($1-\alpha$) associated with the decision.

Table C.1 and Table C.3 show how F-ratios are calculated for two types of sampling plans, and examples of each plan are given. Table C.1 outlines an analysis of variance tables for situations where the test variable may be classified into one category with more than one test value in each category. This procedure is applicable to roadway samples from one lane and to milled materials sampled from trucks, as described in this study. If there is more than one construction unit involved, the analysis would apply only to each separate construction unit.

TABLE C.1 -- Analysis of Variance (ANOVA) for Roadway Samples from One Lane and Milled Materials Sampled from Trucks

Source	df	SS	MS	F	F Critical (α = 0.05)
Sections (i = 1 ... k)	$k - 1$	SS_s	SS_s/df	MS_s/MS_w	
Within Sections (j = 1 ... ℓ)	$k(\ell-1)$	SS_w	SS_w/df		
Total (n)	$n - 1$	SS_t	SS_t		

$$CT = \frac{1}{n} (\Sigma_i \Sigma_j y_{ij})^2$$

$$SS_s = \Sigma_i \frac{1}{\ell} (\Sigma_j y_{ij})^2 - CT$$

$$SS_t = \Sigma_i \Sigma_j (y_{ij})^2 - CT$$

$$SS_w = SS_t - SS_s$$

Example 1

Table C.2 contains an example of an analysis of variance (ANOVA) table for data from Table 6, results of viscosity tests at 140°F on extracted asphalt from the North Carolina project. The data used are given below. Actual data have been coded by dividing by 1000.

Section No. (i)	Test Values (y_{ij})		Section Sums (Σ_i)	Section Means
1	24.4	34.4	58.8	29.9
2	10.2	38.8	49.0	24.5
3	34.8	74.6	109.4	54.7
4	205.6	9.0	214.6	107.3
5	41.0	9.3	50.3	25.2
SUMS	316.0	166.1	482.1	
MEAN	63.2	33.2		

Computations for the ANOVA table, computed as indicated in Table C.1, are as follows:

$CT = 1/10\ (482.1)^2 = 23242.041$

$SS_s = 1/2\ (58.8^2 + 49.0^2 \ldots +50.3^2)\text{-}CT = 33205.025 - 23242.041 = 9962.984$

$SS_t = (24.4^2 + 34.4^2 + 10.2^2 \ldots + 9.3^2)\text{-}CT = 54284.25\text{-}CT = 31042.209$

$SS_w = 31042.209 - 9962.984 = 21079.225$

MS_s (sections) = 9962.984/4 = 2490.746

MS_w (within sections) = 21079.225/5 = 4215.845

F ratio (sections) = 2490.746/4215.845 = 0.59

The F ratio for sections was tested using critical F ratios for different probability levels (1 - α), and for the indicated degrees of freedom. In this case, $F_{4,5}$ (1 - α = 0.95) = 5.19. Since the calculated F = 0.59 is less than the critical $F_{4,5}$ (1 - α = 0.95) = 5.19, the differences in section means are declared not significant.

TABLE C.2 -- Analysis of Variance Table for Results of Viscosity Tests at 140°F (60°C) on Samples of Extracted Asphalt

ANALYSIS OF VARIANCE (ANOVA)

SOURCE	DF	SS	MS	F
Sections	4	9,962.984	2,490.746	0.59
Within Sections	5	21,079.225	4,215.845	
Total	9	31,042.209	3,449.134	

k = 5 ℓ = 2 n = 10

Table C.3 outlines an analysis of variance table for situations where the test variable may be classified into more than one category with one test value in each category. This procedure is applicable to roadway samples from two lanes or material sampled from stockpiles with two layers, as described in this study. If there is more than one construction unit involved, the analysis would apply only to each separate construction unit.

TABLE C.3 -- Analysis of Variance (ANOVA) for Roadway Samples from Two Lanes and Stockpile Samples with Two Layers

Source	df	SS	MS	F	F critical (α = 0.05)
Section or Block ($i=1\ldots k$)	$k-1$	SS_s	MS_s	MS_s/MS_e	
Lane or Layer ($j=1\ldots \ell$)	$\ell-1$	SS_ℓ	MS_ℓ	MS_ℓ/MS_e	
Error	$n-k-\ell+1$	SS_e	MS_e		
Total	$n-1$	SS_t			

$$CT = 1/n\ (\Sigma\ y_{ij})^2$$

$$SS_s = 1/\ell\ \Sigma_j\ (\Sigma y_i)^2 - CT$$

$$SS_\ell = 1/k\ \Sigma_i\ (\Sigma y_j)^2 - CT$$

$$SS_t = \Sigma_{ij}\ (y_{ij})^2 - CT$$

$$SS_e = SS_t - SS_s - SS_l$$

$$MS = SS/df$$

Example 2

Table C.4 contains an example of an analysis of variance (ANOVA) table for data from Table 16, percent asphalt obtained from extraction and recovery tests on the Virginia project. The data used, from Table 16, are given below:

SECTION NO.	LANE 1	LANE 2	SECTION SUMS	SECTION MEANS
1	5.1	4.8	9.9	4.95
2	5.5	5.5	11.0	5.50
3	5.3	5.3	10.6	5.30
4	5.3	5.2	10.5	5.25
5	5.4	5.4	10.8	5.40
6	5.5	5.2	10.7	5.35
SUM	32.1	31.4	63.5	
MEAN	5.35	5.23		

Computations for the ANOVA table, computed as indicated in Table C.3, are as follows:

$CT = 1/12\ (63.5)^2 = 336.021$

$SS_s = 1/2\ (9.9^2 + 11.0^2 \ldots + 10.7^2) - CT = 336.375 - 336.021 = 0.354$

$SS_\ell = 1/6\ (32.1^2 + 31.4^2) - CT = 336.062 - 336.021 = 0.041$

$SS_t = (5.1^2 + 4.8^2 + 5.5^2 \ldots + 5.2^2) - CT = 336.470 - 336.021 = 0.449$

MS_s (sections) = 0.354/5 = 0.0708

MS_ℓ (lanes) = 0.041/1 = 0.041

MS_e (error) = 0.054/5 = 0.0108

F ratio (sections) = 0.0708/0.0108 = 6.56

F ratio (lanes) = 0.041/0.0108 = 3.80

TABLE C.4 Analysis of Variance Table for Percent Asphalt Obtained From Extraction and Recovery Tests, From Table 16.

ANALYSIS OF VARIANCE (ANOVA)

SOURCE	DF	SS	MS	F
Sections	5	0.354	0.0708	6.56
Lanes	1	0.041	0.041	3.80
Error	5	0.054	0.0108	
TOTAL	11	0.449		

$k = 6 \quad \ell = 2 \quad n = 12$

The F ratios for sections and for lanes were tested using critical F ratios for different probability levels, and for the indicated degrees of freedom. In this case the F ratio (sections) = 6.56. From a table of F ratios (Reference 6), it is seen that a critical F ratio for $F_{5,5}$ $(1 - \alpha = 0.95)$ is approximately equal to 5.05; and we can conclude that there is a statistically significant difference between sections, with a high degree of confidence.

Similarly the calculated F ratio (lanes) = 3.80 can be compared to a critical $F_{1,5}(1 - \alpha = 0.95) = 6.61$. Since 3.80 is less than 6.61, we conclude that there is no statistically significant difference between lanes.

Unlike the case in example 1, section means in example 2 have been declared statistically different, and consideration could be given to dividing the project into several separate construction units. (Reference 1 contains a discussion of a procedure, referred to as the Newman-Keuls test, for determining which sections can be grouped together. In the Newman-Keuls procedure the sections are arranged in a rank order and all possible pairs are compared using a test for least significant ranges.) From a practical point of view, it might not be an advantage to do so, however. The next article discusses one method for looking at this aspect of the analysis.

Comparing to Job-Mix Limits

It is not always practicable, nor desirable, to separate a project into smaller construction units, even if the results of ANOVA indicate that there are statistically significant differences between sections. In example 2, section means were indicated to be significantly different. However, inspection of the individual data points indicates that there might not be any practical advantage in breaking the project into sections. This can be illustrated by comparing the asphalt content data to recommended job-mix limits.

The following procedure can be used to make these comparisons.

1. Using example 2 to illustrate the techniques, from Table C.4 calculate the overall standard deviation $= \sqrt{SS_t \;/\; N-1} = \sqrt{0.040818}$ $= 0.20$.

2. Assume that the standard deviation determined in step 1 is the population standard deviation σ. (A value of σ obtained from other sources can be used, also.)

3. Calculate $1.96\ \sigma$ limits. In this case $1.96\ (0.20) = \pm 0.392$. (Use ± 0.4)

4. Calculate the job mean asphalt content $(\bar{x})$, plus or minus the 1.96σ limits:

   $\bar{x} = 63.5/12 = 5.29$ (Use 5.3)

   $\bar{x} \pm 1.96\alpha = 5.3 \pm 0.4$ (Range $= 4.9 - 5.7$)

5. Compare the values calculated in step 4 to acceptable job-mix limits.

In this example, the estimated range in asphalt contents is 4.9 - 5.7. The example 2 data show that all but one data point (section 1, lane 2) fall within the range, and it could be assumed that there would be no great practical risk involved in assuming that the job can be made to conform to ASTM limits (±0.5) through normal quality control methods.

More sophisticated procedures for estimating expected variability can be used, but considering that the test data refer to material that will be combined with virgin materials and subject to quality control, the extra effort is not likely to provide better results insofar as the final recycled mixture is concerned.

Comparing Two Sets of Test Data

It sometimes can be helpful to determine if there is a statistically significant difference between two sets of samples. For example, consider the following data taken from Table 19:

Roadway Samples			Milled Material		
No. Tests N_1	Mean $\bar{x}_1$	Std. Dev. S_1	No. Tests N_2	Mean $\bar{x}_2$	Std. Dev. S_2
Percent Passing No. 8 Sieve					
12	41	2.1	6	52	1.1

The T-test is useful in determining if there has been a significant change in percent passing the No. 8 sieve. The following steps illustrated the procedure.

1. Calculate a pooled standard deviation:

$$S_p = \frac{(N_1 - 1)S_1^2 + (N_2 - 1)S_2^2}{N_1 + N_2 - 2}$$

$$S_p = \frac{(12 - 1)\ (2.1)^2 + (6 - 1)(1.1)^2}{12 + 6 - 2} = 2.654$$

2. Calculate the T statistic

$$T = \frac{|\bar{x}_1 - \bar{x}_2|}{S_p \; (1/N_1) + (1/N_2)}$$

$$T = \frac{|41 - 52|}{2.654 \;\; 1/12 + 1/6} = 8.29$$

3. Assume that T has a distribution for T with $N_1 + N_2 - 2 = 16$ degrees of freedom, and that the probability level $(1 - \alpha) = 0.95$.

4. From a table of percentiles for the T distribution (Reference 6) find $T_{.95}$ (df = 16) = 1.746 for a single-tail test.

5. Compare 8.29, calculated for the test data, with 1.746. If the calculated value is larger than the value obtained from the table then we can conclude that the difference between the two test sample means is significantly larger than zero. In this case we conclude that 52% passing the No. 8 sieve after milling is significantly greater than the value of 41% obtained from roadway samples.

APPENDIX D

METHOD OF TEST FOR EFFECT OF WATER, FREEZING AND THAWING ON INDIRECT TENSILE STRENGTH OF COMPACTED RECYCLED ASPHALT MIXTURES*

1.0 Scope

1.1 This method covers measurement of the change of indirect tensile strength resulting from the effects of vacuum saturation, water conditioning, and freeze-thaw conditioning of compacted recycled asphalt mixtures. Numerical indices of retained indirect tensile strength are obtained by comparing the indirect tensile strength of water conditioned and of water and freeze-thaw conditioned laboratory specimens with the similar properties of dry specimens.

The method of short-term stripping (TRS-Subset II) is included for information. Since none of the mixes indicated stripping using this test, further research is needed to evaluate the method.

2.0 Apparatus

2.1 Water bath - two water baths of sufficient size for total immersion of the test specimens, one bath capable of maintaining a temperature of 140 ± 3.6°F (60 ± 2°C) and the other a temperature of 77 ± 1.8°F (25 ± 1°C).

2.2 Freezer - A freezer controlled to maintain a temperature of -0.4 ± 3.6°F (-18 ± 2°C).

2.3 Vacuum Pump and accessories - A vacuum pump with capacity to obtain a partial vacuum, 4-in. (102 mm) Hg absolute pressure, in the vacuum chamber for the water saturation of the test specimens. Accessory equipment includes borosilicate glass or equivalent vacuum chambers of sufficient strength to withstand essentially full vacuum at least 6 in. (15 cm) in diameter and 8 in. (20 cm) high with smooth edges, a donut-shaped gasket made of rubber-type sponge, a stiff metal round plate greater than 6 in. (15 cm) in diameter and 8 in. (20 cm) high with suitable vacuum hose receptacle and hole bored through the plate thickness, vacuum hose attached to receptacle fitting and vacuum pump, and a 6-in. (15 cm) diameter screen-type or highly porous specimen spacer seat approximately .25 in. (6 mm) high.

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* This method is based on the predictive moisture damage test method used in NCHRP Project 4-8(3).

2.4 Compression testing machine - A compression testing machine meeting the requirements of ASTM Method D 1559 and producing a uniform vertical movement of 2 in. (50.8 mm)/min.

2.5 Loading strip - Two steel loading strips 0.5 in. (13 mm) wide and 3 in. (76 mm) long with concave surfaces having a radius of curvature equal to the nominal radius of the test specimen to apply load to the specimens.

2.6 Miscellaneous Apparatus - A supply of plastic film for wrapping and heavy-duty leak-proof plastic bags to wrap and enclose the saturated specimens for preventing moisture loss during handling and freezing, several metal jars of at least 4 in. (10.2 cm) diameter and at least 6 in. (15 cm) height for bringing dry specimens in the water bath. A controlled air temperature cabinet may be used in lieu of the metal jars for bringing dry specimens to test temperature.

3.0 <u>Test Specimens</u>

3.1 Prepare nine 4-in. (102 mm) diameter by 2.5-in (63.5 mm) high cylindrical test specimens of the same mixture according to the procedures described in Mix Design Method for Reclaimed Asphalt Concrete Using Marshall Apparatus or Mix Design Method for Reclaimed Asphalt Concrete Using Hveem Apparatus (see Appendix E). Prior to compaction place the loose mixtures in the closed metal tins in a 140°F (60°C) oven for 16 hours.

Determine by preliminary tests the number of compaction hammer blows, or number of tamps and tamping foot pressures required to compact test specimens with an average air void content within the range of 5.0 to 9.0 percent determined by ASTM D3203. Discard individual specimens with air voids differing from the average by more than 1 percentage point.

3.2 Prepare two duplicate batches of mixture used for the test specimens, condition them for 16 hours at 140°F (60°C) as in 3.1, and determine theoretical maximum specific gravity of the mixture in accordance with ASTM Method D 2041 for use in determining percent air voids in the compacted specimens.

4.0 <u>Grouping, Vacuum Saturation and Determination of Bulk Specific Gravity and Voids Properties of Test Specimens</u>

4.1 Label the specimens with waterproof identification and determine their bulk specific gravity in accordance with ASTM D 2726 and their percent air voids in accordance with ASTM D 3203. Calculate the volume of specimens with data obtained during the bulk specific gravity test using the following formula:

$$V_b = B - C$$

where

V_b = bulk volume of specimen, cm^3

B = weight of saturated surface dry specimen in air, g

C = weight of specimen in water

4.2 Separate the specimens into three subsets, each having approximately the same average bulk specific gravity. Randomly select a subset, I, of three specimens, place them in metallic jars and then place the jars in a water bath at a temperature of 77 ± 1.8°F (25 ± 1°C) maintaining the top lip of the jars above the water level of the bath. Place an insulating stuffing in the top of the jars, making contact with the top specimen's surface and with the jar walls. The specimens may be placed in a controlled air temperature cabinet at a temperature of 77 ± 1.8°F (25 ± 1°C) in lieu of the metallic jars.

4.3 Vacuum saturate subset II and subset III specimens. Place a porous spacer seat on the bottom of a vacuum chamber and then place two or more of the specimens, depending on chamber height, in the jar using another porous spacer seat between the specimens. Fill the vacuum chamber with water at 77°F (25°C) to about 1 in. 2.5 cm) above the upper specimen's surface. Place a dampened donut gasket and a stiff metallic plate on top of the chamber. Attach a vacuum hose from the plate receptacle to the vacuum pump. Subject the contents of the chamber to a partial vacuum, 4-in. (102 mm) Hg absolute pressure, for 30 minutes. (A partial vacuum, 4-in. (102 mm) Hg absolute pressure, is approximately equivalent to 25.9 in. (658 mm) Hg reading on a vacuum gauge at sea level.) Remove the vacuum and leave the specimens submerged in the chambers at atmospheric pressure for 30 minutes.

4.4 Remove each of the specimens from the vacuum chambers, quickly surface dry the specimens by towel blotting and weigh immediately in air and then weigh submerged in water at 77°F (25°C). Immediately after weighing each submerged specimen, return the specimens to the water-filled vacuum chambers and submerge each specimen under the water at atmospheric pressure.

4.5 Calculate the water permeable voids, bulk specific gravity, air voids, and air voids filled with water, of each of the vacuum saturated test specimens as follows:

$$\text{Water Permeable voids, \%} = \frac{100\ (B - A)}{B - C}$$

and

$$\text{Bulk Specific Gravity} = \frac{A}{B - C}$$

where

A = weight of dry specimen in air, g,

B = weight of surface-dry (blotted) vacuum saturated specimen in air, g,

C = weight of vacuum saturated specimen submerged in water, g

$$\text{Air Voids, \%} = 100 \quad 1 - \frac{\text{bulk specific gravity}}{\text{theoretical maximum specific gravity}}$$

$$\text{Air Voids Filled with Water, \%} = 100\ \frac{\text{water permeable voids, \%}}{\text{air voids, \%}}$$

The original dry weight of the specimen prior to conditioning is used to calculate the bulk specific gravity. The theoretical maximum specific gravity determined in 3.2 is used to calculate percent air voids. The specimen bulk volume, which is equal to the quantity B - C in the formulas for Percent Water Permeable Voids and Bulk Specific Gravity, can be compared to the original specimen bulk volume determined in 4.1.

4.6 Place subset II specimens into a water bath at a temperature of 77 ± 1.8°F (25 ± 1°C) for 3 h. Proceed with the indirect tensile tests on subset II specimens and subset I specimens previously brought to the test temperature of 77 ± 1.8°F (25 ± 1°C) as described in 6. Condition the subset III specimens using procedures described in 5.

5.0 <u>Accelerated Conditioning Procedure</u>

5.1 Maintain specimen surface dampness and internal saturation, and wrap tightly each of the three specimens of subset III with two layers of plastic film using masking tape to hold the wrapping if necessary. Place each wrapped specimen into a leak-proof plastic bag, and seal the bag with a tie or tape.

5.2 Immerse each of the three individually wrapped and bagged specimens of subset III into the freezer for 15 h at -.4 ± 3.6°F (-18 ± 2°C).

5.3 Remove the three wrapped and bagged specimens of subset III from the freezer and immerse them immediately into a water bath at 140 ± 3.6°F (60 ± 2°C) for 24 h. After 1/2 h carefully remove the bag and wrapping from the specimens and re-immerse the specimens in the water bath for the rest of the 24 h period.

5.4 Remove the specimens from the water bath and immerse them in a water bath at a temperature of 77 ± 1.8°F (25 ± 1°C) for 1 1/2 h. Determine water permeable voids, air voids, air voids filled with water of each specimen as described in 4.5. Place the specimens in water bath for 1 1/2 h and proceed with the indirect tensile strength tests on specimens as described in 6.

6.0 Indirect Tensile Strength Test

6.1 Test each specimen subset rapidly following the completion of their respective test-temperature water-bath soak times as prescribed in 4.2 for subset I, 4.6 for subset II, and 5 for subset III.

6.2 Remove a subset specimen from the controlled temperature bath or chamber and surface dry if specimen is from subsets II and III by blotting with a towel. Measure and record the specimen height (thickness) and identification. Place the specimen into the compression testing machine and position the loading strips to be parallel and centered on the diametral vertical plane. Apply the diametral loading at a vertical deformation rate of 2 in. per minute. Record the maximum compressive load. Immediately release the load and remove specimen. The elapsed time from removal of the specimens from the bath or chamber to the maximum load determination should not exceed 1 minute.

6.3 Calculate the specimen's indirect tensile strength as follows:

$$St = \frac{2P}{\pi tD}$$

where

S_t = indirect tensile strength, psi (kPa),

P = maximum compressive load on specimen, lb. (N),

t = thickness of specimen, in. (cm),

D = diameter of specimen, in. (cm).

6.4 Test the two remaining specimens in the subset, and calculate the average indirect tensile strength for the subset of three specimens.

6.5 Examine the fractured faces of the specimen immediately after testing ignoring the surface of aggregate particles fractured during the indirect tensile test. Observe the absence or loss of asphalt coating on any aggregate particles. Rate and record the amount of stripping or loss of asphalt coatings as not discernible, very slight, slight, moderate or severe.

7.0 Calculation

7.1 Calculate the numerical indices to the nearest hundredth of the effects of vacuum saturation and accelerated conditioning as the ratios of the indirect tensile strength or subsets II and III to the indirect tensile strength of subset I as follows:

$$TSR_1 = \frac{S_t(II)}{S_t(I)} \quad \text{and} \quad TSR_2 = \frac{S_t(III)}{S_t(I)}$$

where

TSR_1 = indirect tensile strength ratio of vacuum saturation conditioning,

TSR_2 = indirect tensile strength ratio of accelerated conditioning,

$S_t(I)$ = average indirect tensile strength of specimen subset I, psi (k Pa),

$S_t(II)$ = average indirect tensile strength of specimen subset II, psi (K Pa), and

$S_t(III)$ = average indirect tensile strength of specimen subset III, psi (k Pa).

8.0 Report

8.1 Report the following:

8.1.1 Report the tensile strength ratio, TSR_1 for vacuum saturated conditioned specimens

8.1.2 Report the tensile strength ratio, TSR_2 for the accelerated conditioned specimens

8.1.3 Report the average diametral tensile strength for each subset of specimens

8.1.4 Report the average percent, air voids determined in 4.1 (prior to vacuum saturation) for each subset of specimens

8.1.5 Report the average percent of air voids filled water for subset II and subset III specimens

8.1.6 Report the visual rating of amount of stripping for subset II and subset III specimens.

APPENDIX E

MIX DESIGN METHOD FOR RECLAIMED ASPHALT CONCRETE USING MARSHALL OR HVEEM APPARATUS

1.0 SCOPE

1.1 This method covers procedures for the design of reclaimed asphalt paving mixtures using Marshall and Hveem apparatus. It is applicable to mixtures containing reclaimed asphalt concrete, new aggregates and new paving grade asphalt cements and recycling agents or both. The method may be used for mixtures containing aggregates with maximum sizes of 1 inch (25 mm) and dense mixture designations of 1 in. (25.0 mm), 3/4 in. (19.0 mm), 1/2 in. (12.5 mm) and 3/8 in. (9.5 mm) meeting ASTM Specification D 3515 or similar requirements.

> For further information on proportioning, reclaiming procedures and construction, reference is made to The Asphalt Institute Manual Series MS-20, *Asphalt Hot-Mix Recycling*.

2.0 SUMMARY OF METHOD

2.1 Preliminary to the mix design it is required that representative samples of the reclaimed asphalt concrete, new aggregate, new asphalt or recycling agent to be used have been obtained, and the proposed materials meet requirements of the project specifications. Steps in the mix design include:

1) Determine the amount and the viscosity of the asphalt in the reclaimed asphalt concrete, the gradation of the aggregate in the reclaimed asphalt concrete, and the gradation of the new aggregate.

2) Based on established or proposed proportions of reclaimed asphalt concrete and new aggregate to be used, calculate a combined aggregate grading meeting the specification requirements using the gradations of the aggregate in the reclaimed asphalt concrete and new aggregate.

3) Determine the approximate asphalt demand of the combined aggregate.

4) Calculate the amount of new asphalt or recycling agent required to satisfy the asphalt demand, the ratios of new asphalt or recycling agent to total asphalt content and ratio of new aggregate to total aggregate.

5) Using a viscosity blending chart and the ratio of new asphalt or recycling agent to total asphalt select a new asphalt or recycling agent.

6) Calculate amounts of each ingredient in the mix for a series of test specimens containing the estimated amount of new asphalt or recycling agent, and at increments of new asphalt or recycling agent above and below the estimated amount.

7) Prepare and test specimens using Marshall or Hveem apparatus.

8) Determine the optimum new asphalt or recycling agent content.

9) Finally determine if the test properties of the mix at the optimum new asphalt or recycling agent content are within allowable limits of mix design criteria.

3.0 APPARATUS

3.1 Marshall Test Apparatus

The apparatus specified in ASTM Test Method D 1559 is required when the Marshall method is selected for performing the mix design.

3.2 Hveem Test Apparatus

The apparatus specified in ASTM Test Methods D 1560 and D 1561 are required when the Hveem method is selected for the mix design.

3.3 Containers

Metal containers with lids, approximately 4 in. (64.5 mm) in diameter and 5 1/2 in. (139.7 mm) high for maintaining the temperature of mixture batches at the compaction temperature.

4.0 ANALYSIS OF RECLAIMED ASPHALT CONCRETE

4.1 Prepare the processed (milled or crushed) reclaimed asphalt concrete sample for the mix design by thoroughly mixing representative portions of randomly selected samples of processed reclaimed asphalt concrete. (See Appendices A, B and C.) Mix designs, other than preliminary, should be performed using the field processed reclaimed asphalt concrete that is used for construction.

4.2 Determine the asphalt content of the reclaimed asphalt concrete to be used for the mix design by AASHTO Method T 164 Method A or ASTM Method D 2172 Method A. Perform sieve analyses on the recovered aggregate according to ASTM Methods C 117 (AASHTO T 11) and C 136 (AASHTO T 27). Recover asphalt from the reclaimed asphalt concrete according to ASTM Method D 1856 (AASHTO T 170).

4.3 Determine the viscosity of recovered asphalt at 140°F (60°C) by ASTM method D 2171 (AASHTO T 202).

5.0 NEW MINERAL AGGREGATE

5.1 Perform sieve analyses on the new mineral aggregate to be used for the mix design according to ASTM Methods C 117 (AASHTO T 11) and C 136 (AASHTO T 27).

6.0 COMBINED AGGREGATE GRADATIONS

6.1 Using proposed or the established proportions of the reclaimed asphalt concrete and new aggregate that are to be used in the recycled mix, calculate r, new aggregate expressed as a percent of total aggregate in the recycled mix with the formula:

$$r = \frac{P_{ns}}{P_{sm} - \frac{(P_{sm} \times P_{sb})}{100} + P_{ns}} \times 100$$

where:

r = new aggregate expressed as percent of total aggregate in the recycled mix

P_{ns} = new aggregate in recycled mix, percent

P_{sb} = asphalt in the reclaimed asphalt concrete, percent by weight of mix, determined by extraction

P_{sm} = reclaimed asphalt concrete in the recycled mix, percent

6.2 Calculate a combined aggregate gradation from the gradation of the aggregate in reclaimed asphalt concrete and gradation of the new aggregate which meets the aggregate gradation specification requirements.

7.0 APPROXIMATE ASPHALT DEMAND

7.1 Determine the approximate asphalt demand of the combined aggregate by the formula as follows:

$$P = 0.035\,a + 0.045\,b + KC + F$$

where:

P = approximate asphalt demand of combined aggregate percent by weight of total mixture

K = 0.18 for 6-10 percent passing No. 200 sieve (75 μm)
= 0.20 for 5 percent or less passing No. 200 sieve (75 μm)

a = percent mineral aggregate retained on No. 8 Sieve (2.36 mm)

b = percent of mineral aggregate passing No. 8 Sieve (2.36 mm) and retained on No. 200 (75 μm) sieve

c = percent of mineral aggregate passing No. 200 (75 μm) sieve

F = 0-2.0 percent. Based on absorption of light or heavy aggregate.

This formula is based on an average specific gravity of 2.60 to 2.70. In the absence of other data, a value of 0.7 is suggested.

Note: As an alternate the approximate asphalt demand, P, may be determined by the Centrifuge Kerosine Equivalent test included in the Asphalt Institute Hveem Method of Mix Design (26) or by State of California Department of Transportation Test 303, Method of Test for Centrifuge Kerosine Equivalent and Approximate Bitumen Ratio (ABR) (32).

8.0 AMOUNT OF NEW ASPHALT OR RECYCLING AGENT IN MIX

8.1 If the asphalt content is expressed as percent by weight of total mix, calculate the quantity of new asphalt or recycling agent required in the recycled mix with the formula:

$$P_{nb} = \frac{(100^2 - P_{sb}\, r)\ P_b}{100\ (100 - P_{sb})} - \frac{(100 - r)\ P_{sb}}{100 - P_{sb}}$$

where:

r = new aggregate expressed as a percent of total aggregate in recycled mix

P_{nb} = new asphalt or recycling agent in recycled mix, percent

P_b = asphalt content of recycled mix, percent (approximate asphalt demand, P, determined in 7.1)

P_{sb} = asphalt content of reclaimed asphalt concrete, percent

Note: If asphalt content is expressed as percent by weight of aggregate, the formula is:

$$P_{nb} = P_b - \frac{(100 - r)\, P_{sb}}{100}$$

9.0 GRADE OF NEW ASPHALT OR RECYCLING AGENT

9.1 The grade of new asphalt or recycling agent is determined using a log-log viscosity vs. percent new asphalt or recycling agent blending chart as shown in Example Figures E.1 and E.2. A target viscosity for the blend of recovered asphalt and the new asphalt or recycling agent is selected. The target viscosity is usually the viscosity of the mid-range of the grade of asphalt normally used depending on type of construction, climatic conditions, amount and nature of traffic. If the asphalt content is expressed by weight of total mix, calculate the amount of new asphalt or recycling agent as a percentage of asphalt content in the recycled mix with the formula:

$$R = \frac{P_{nb} \times 100}{P_b}$$

where:

R = new asphalt or recycling agent expressed as a percentage of total asphalt content

P_{nb} = new asphalt or recycling agent in recycled mix, percent (new asphalt content or recycling agent as determined in 8.2)

P_b = asphalt content of recycled mix, percent (the approximate asphalt demand, P, determined in 7.1, is used initially)

Note:	The same formula is used when asphalt content is expressed as percent by total weight of mix and asphalt content is expressed as percent by weight of aggregate.

9.2 Draw a vertical line as illustrated in Figure E.1 representing the percentage of new asphalt or recycling agent calculated in 9.1, and determine its intersection with the horizontal line representing the target viscosity, Point A. Plot the viscosity of the aged asphalt in the reclaimed asphalt concrete on the left hand vertical scale, Point B. Then draw a straight line from Point B, through Point A and extend it to intersect the right hand scale, Point C. Point C is the viscosity at 140°F (60°C) of the new asphalt or recycling agent required to blend with the asphalt in the reclaimed asphalt concrete to obtain the target viscosity in the blend. Select the grade of new asphalt or recycling agent that has a viscosity range that includes or is closest to the viscosity at Point C. Selection of the grade of new asphalt cement is illustrated in Example 1.

Example 1

The reclaimed asphalt concrete contains 5.2 percent asphalt by weight of total mix. The viscosity of the asphalt recovered from the reclaimed asphalt concrete is 46,149 poises at 140°F (60°C). The grade of asphalt cement normally used is AC-20, and the target viscosity at a temperature of 140°F (60°C) for the blend of recovered asphalt and new asphalt or recycling agent is 2000 poises. The gradations of the aggregate recovered from the reclaimed asphalt concrete, and gradations of the new coarse aggregate and new fine aggregate are:

Sieve Size	Percent Passing Reclaimed Asphalt Concrete	New Coarse Aggregate	New Fine Aggregate
1 in.		100	
3/4 in.	100	99.7	
1/2 in.	99.1	64.2	100
3/8 in.	94.5	36.4	99.8
No. 4	71.9	9.2	91.5
No. 8	51.5	4.3	79.2
No. 16	37.2	3.6	59.4
No. 30	26.9	3.1	33.5
No. 50	20.3	2.6	13.2
No. 100	16.1	2.0	5.4
No. 200	13.0	1.3	3.1

A. Combined Aggregate Gradation

Forty percent of reclaimed asphalt concrete and 60 percent new aggregate is selected for the recycled mix. The new aggregate as percent of the total aggregate in the recycled mix is calculated as follows:

$$r = \frac{P_{ns}}{P_{sm} - \dfrac{P_{sm} \times P_{sb}}{100} + P_{ns}} \times 100$$

$$r = \frac{60}{40 - \dfrac{40 \times 5.2}{100} + 60} \times 100$$

$r = 61.3$ percent

A combined aggregate grading is then calculated using 61.3 percent new aggregate (49 percent coarse and 12.3 percent fine) and 38.7 percent aggregate from the reclaimed asphalt concrete. The combined aggregate grading is shown in Figure E.2.

B. Approximate Asphalt Demand

$$P = 0.035\,a + 0.045\,b + KC + F$$

$$P = 0.035 \times 68.3 + 0.045 \times 25.7 + 0.18 \times 6.0 + 1.0$$

$P = 5.6$ percent

C. Amount of New Asphalt or Recycling Agent in Mix

$$P_{nb} = \frac{(100^2 - P_{sb}\,r)\,P_b}{100\,(100 - P_{sb})} - \frac{(100 - r)\,P_{sb}}{100 - P_{sb}}$$

$$P_{nb} = \frac{(100^2 - 5.2 \times 61.3)\,5.6}{100\,(100 - 5.2)} - \frac{(100 - 61.3)\,5.2}{100 - 5.2}$$

$P_{nb} = 3.6$ percent

D. Grade of New Asphalt or Recycling Agent

1) new asphalt or recycling agent, percent of total asphalt content

$$R = \frac{P_{nb}}{P_b} \times 100$$

$$R = \frac{3.6}{5.6} \times 100$$

$R = 64.3$ percent

2) On Figure E.1, point A is located using values of 2,000 poises for the target viscosity and 63.4 percent new asphalt, expressed as percent of the blend of the new asphalt or recycling agent and recovered asphalt. Point B is located using the value of 46,149 poises for the viscosity of the asphalt recovered from the reclaimed asphalt concrete. The projected line from point B through point A to point C indicates that the viscosity at 140°F (60°C) of the new asphalt or recycling agent should be approximately 450 poises, which is within the viscosity range specified for an AC-5 viscosity grade asphalt cement.

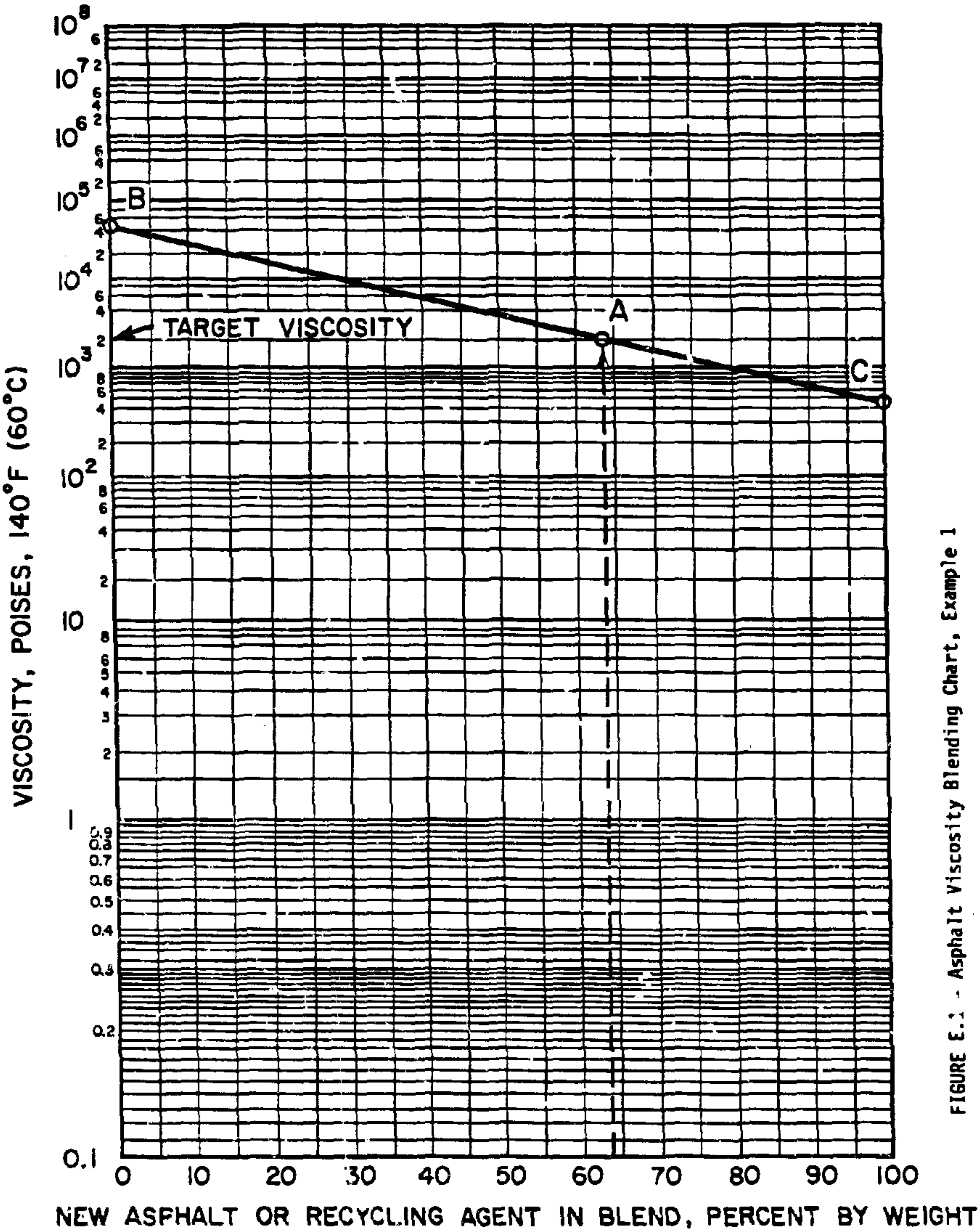


FIGURE E.1 - Asphalt Viscosity Blending Chart, Example 1

FIGURE E.2 - Combined Aggregate Gradation

Sieve Size	38.7% Reclaimed Asphalt Concrete Aggregate Percent Passing		49% Coarse Aggregate Percent Passing		12.3% Fine Aggregate Percent Passing	Combined Aggregate Percent Passing	Specification Requirements Percent Passing
1 in. (25.0 mm)	[100 x .387 = 38.7]	+	[100 x .49 = 49.0]	+	[100 x .123 = 12.3] =	100	100
3/4 in. (19.0 mm)	[100 x .387 = 38.7]	+	[99.7 x .49 = 48.9]	+	[100 x .123 = 12.3] =	99.9	90-100
1/2 in. (12.5 mm)	[99.1 x .387 = 38.4]	+	[64.2 x .49 = 31.5]	+	[100 x .123 = 12.3] =	82.2	
3/8 in. (9.5 mm)	[94.5 x .387 = 36.6]	+	[36.4 x .49 = 17.8]	+	[99.8 x .123 = 12.3] =	66.7	56-80
No. 4 (4.75 mm)	[71.9 x .387 = 27.8]	+	[9.2 x .49 = 4.5]	+	[91.5 x .123 = 11.3] =	43.6	35-65
No. 8 (2.36 mm)	[51.5 x .387 = 19.9]	+	[4.3 x .49 = 2.1]	+	[79.2 x .123 = 9.7] =	31.7	25-49
No. 16 (1.18 mm)	[37.2 x .387 = 14.4]	+	[3.6 x .49 = 1.8]	+	[59.4 x .123 = 7.3] =	23.5	
No. 30 (600 μm)	[26.9 x .387 = 10.4]	+	[3.1 x .49 = 1.5]	+	[33.4 x .123 = 4.1] =	16.0	
No. 50 (300 μm)	[20.3 x .387 = 7.9]	+	[2.6 x .49 = 1.3]	+	[13.2 x .123 = 1.6] =	10.8	5-19
No.100 (150 μm)	[16.1 x .387 = 6.2]	+	[2.0 x .49 = 1.0]	+	[5.4 x .123 = 0.7] =	7.9	
No.200 (75 μm)	[13.0 x .387 = 5.0]	+	[1.3 x .49 = 5.0]	+	[3.1 x .123 = 0.4] =	6.0	2-8

9.3 If point C falls below the viscosity range of the lowest standard grade of asphalt cement, alternatives are to establish a new blend of reclaimed asphalt concrete and new aggregate that contains less reclaimed asphalt concrete, or to use a recycling agent with lower viscosity than standard grades of asphalt cement. Another alternative in recycling is to use a low viscosity recycling agent along with new asphalt cement. The use of a low viscosity recycling agent along with new asphalt cement is illustrated in example 2.

EXAMPLE 2

The reclaimed asphalt concrete contains 6.2 percent asphalt by weight of mix. The viscosity of the asphalt recovered from the reclaimed asphalt concrete is 7,000 poises at 140°F (60°C). An AC-5 new asphalt with a viscosity of 590 poises at 140°F (60°C) is selected for use along with a low viscosity recycling agent having a viscosity of 1 poise at 140°F. The grade of asphalt cement normally used is AC-20, and the target viscosity recycling agent is 2,000 poises. The gradations of the aggregate recovered from the reclaimed asphalt concrete, and gradations of the new aggregates are:

Sieve Size	Percent Passing: Reclaimed Asphalt Concrete	Percent Passing: New Coarse Aggregate	Percent Passing: New Fine Aggregate
3/4 in.	100	100	
1/2 in.	91.4	74.0	
3/8 in.	85.0	47.5	100
No. 4	68.1	11.6	13.6
No. 8	56.7	7.0	10.0
No. 16	48.5	5.6	7.6
No. 30	40.5	4.8	5.8
No. 50	30.4	4.2	4.3
No. 100	18.3	3.6	3.0
No. 200	9.8	2.6	2.0

A. <u>Combined Aggregate Gradation</u>

Fifty percent of reclaimed asphalt concrete and 50 percent new aggregate is selected for the mix. The new aggregate as precent of of the total aggregate in the recycled mix is calculated as follows:

$$r = \frac{Pns}{Psm - \frac{Psm \times Psb}{100} + Pns} \times 100$$

$$r = \frac{50}{50 - \frac{50 \times 62}{100} + 50} \times 100$$

$$r = 51.6 \text{ percent}$$

A combined aggregate grading is then calculated using 51.6 percent new aggregate (35.8 percent coarse and 15.8 percent fine) and 48.4 percent aggregate from the reclaimed asphalt concrete. The combined aggregate is shown in Figure E.3.

FIGURE E.3 - Combined Aggregate

	48.4% Reclaimed Asphalt Concrete Aggregate		35.8% Coarse Aggregate		15.8% Fine Aggregate	Combined Aggregate	Specification Requirements
Sieve Size	Percent Passing		Percent Passing		Percent Passing	Percent Passing	Percent Passing
3/4 in. (19.0 mm)	[100 x .484 = 48.4]	+	[100 x .358= 35.8]	+	[100 x .158 = 15.8] =	100	100
1/2 in. (12.5 mm)	[91.4 x .484= 44.2]	+	[74.0 x .358= 26.5]	+	[100 x .158 = 15.8] =	86.5	70-100
3/8 in. (9.5 mm)	[85.0 x .484= 41.1]	+	[47.5 x .358= 17.0]	+	[100 x .158 = 15.8] =	73.9	
No. 4 (4.75 mm)	[68.1 x .484= 33.0]	+	[11.6 x .358= 4.2]	+	[86.1 x .158= 13.6] =	50.8	48-76
No. 8 (2.36 mm)	[56.7 x .484= 27.4]	+	[7.0 x .358= 2.5]	+	[63.3 x .158= 9.7] =	39.9	36-59
No. 16 (1.18 mm)	[48.5 x .484= 23.5]	+	[5.6 x .358= 2.0]	+	[48.1 x .158= 7.6] =	33.1	27-45
No. 30 (600 µm)	[40.5 x .484= 19.6]	+	[4.8 x .358= 1.7]	+	[36.7 x .158= 5.8] =	27.1	
No. 50 (300 µm)	[30.4 x .484= 14.7]	+	[4.2 x .358= 1.5]	+	[27.2 x .158= 4.3] =	20.5	16-29
No.100 (150 µm)	[18.3 x .484= 8.9]	+	[3.6 x .358= 1.3]	+	[19.0 x .158= 3.0] =	13.2	
No.200 (75 µm)	[9.8 x .484= 4.7]	+	[2.6 x .358= 0.9]	+	[12.7 x .158= 2.0] =	7.6	5-11

B. <u>Approximate Asphalt Demand</u>

$$P = 0.35a + 0.045b + KC + F$$

$$= (0.35 \times 60.1) + (0.45 \times 32.3) + (0.18 \times 7.6) + 0.7$$

$$= 2.104 + 1.545 + 1.368 + 0.7$$

$$P = 5.6 \text{ percent}$$

C. <u>Amount of New Asphalt or Recycling Agent in Mix</u>

$$Pnb = \frac{(100^2 - P_{sb}\ r)Pb}{100(100 - Psb)} - \frac{(100 - r)Psb}{100 - Psb}$$

$$P_{nb} = \frac{(100^2 - 6.2 \times 51.6)\ 5.6}{100\ (100 - 6.2)} - \frac{(100 - 51.6)\ 6.2}{(100 - 6.2)}$$

$$P_{nb} = 2.6 \text{ percent}$$

D. <u>Grade of New Asphalt or Recycling Agent</u>

1) new asphalt or recycling agent, percent of total asphalt content

$$R = \frac{Pnb}{Pb} \times 100$$

$$R = \frac{2.6}{5.6} \times 100$$

$$R = 46.4 \text{ percent}$$

2) On Figure E.4, point A is located using values of 2,000 poises for the target viscosity and 46.4 percent new asphalt, expressed as percent of the blend of the new asphalt or recycling agent and recovered asphalt. Point B is located using the value of 7,000 poises for the viscosity of the asphalt recovered from the reclaimed asphalt concrete. The projected line from point B through point A to point C indicates that the required viscosity at 140°F (60°C) of the new asphalt or recycling agent should be 450 poises. To determine how much of the one poise viscosity recycling agent is necessary to blend with the 590 poise viscosity new asphalt to obtain a 450 poise viscosity blend of the two, point D is located using the value of 590 poises for the viscosity of the new asphalt and point E is located using the value of one poise for the viscosity of low viscosity recycling agent. A straight line is drawn between points D and E. Point F, located where the line intersects the desired target viscosity of 450 poises, indicates approximately 2.5 percent of the one poise viscosity recycling agent is required to blend with the 590 poise new asphalt to obtain a blend of the two having the desired viscosity of 450 poises at 140°F (60°C).

2) On Figure E.4, point A is located using values of 2,000 poises for the target viscosity and 46.4 percent new asphalt, expressed as percent of the blend of the new asphalt or recycling agent and recovered asphalt. Point B is located using the value of 7,000 poises for the viscosity of the asphalt recovered from the reclaimed asphalt concrete. The projected line from point B through point A to point C indicates that the required viscosity at 140°F (60°C) of the new asphalt or recycling agent should be 450 poises. To determine how much of the one poise viscosity recycling agent is necessary to blend with the 590 poise viscosity new asphalt to obtain a 450 poise viscosity blend of the two, point D is located using the value of 590 poises for the viscosity of the new asphalt and point E is located using the value of one poise for the viscosity of low viscosity recycling agent. A straight line is drawn between points D and E. Point F, located where the line intersects the desired target viscosity of 450 poises, indicates approximately 2.5 percent of the one poise viscosity recycling agent is required to blend with the 590 poise new asphalt to obtain a blend of the two having the desired viscosity of 450 poises at 140°F (60°C).

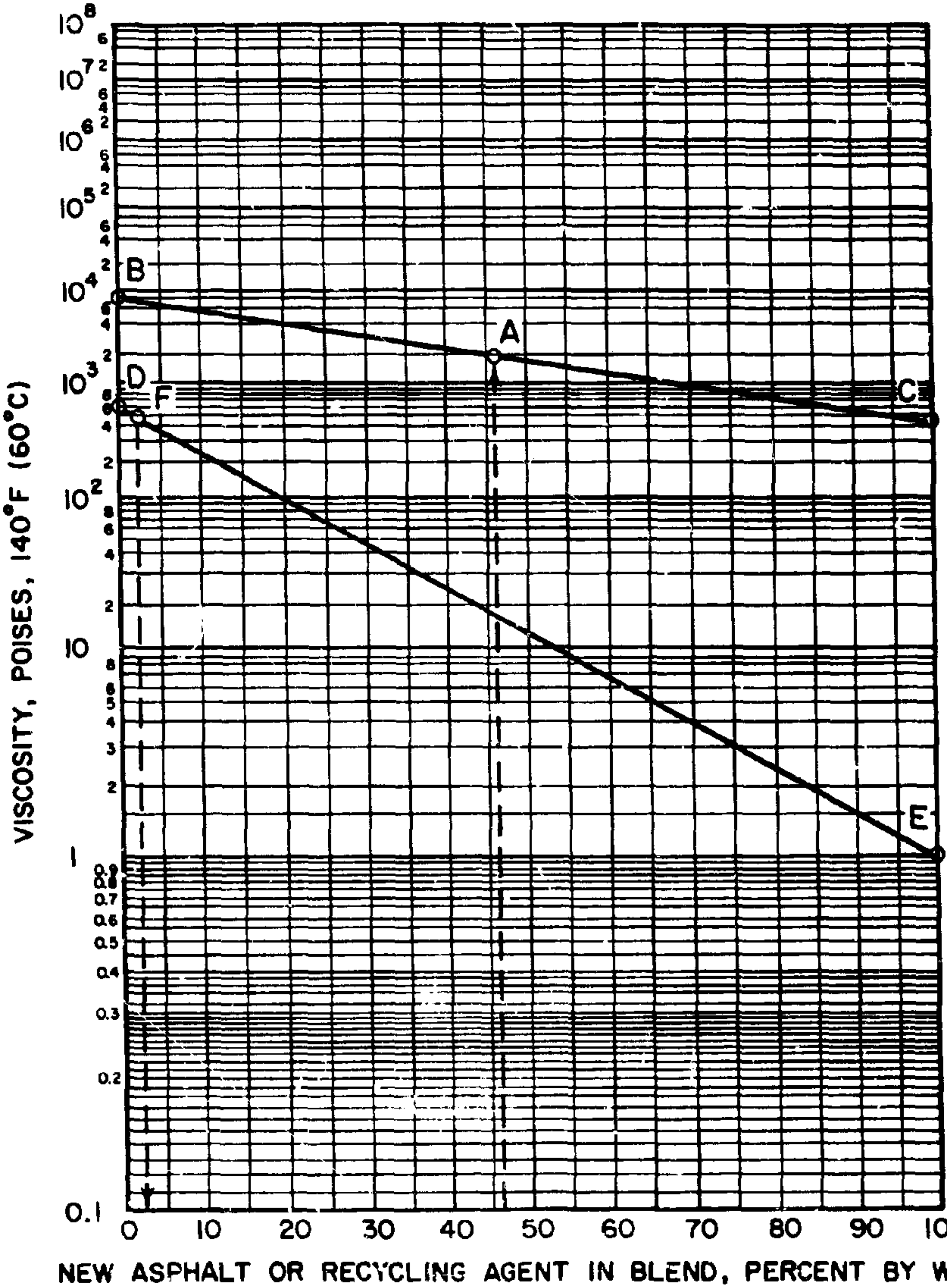


FIGURE E.4 - Asphalt Viscosity Blending Chart, Example 2

10.0 AMOUNT OF RECLAIMED ASPHALT CONCRETE IN RECYCLED MIX

10.1 If the asphalt content is expressed as percent by weight of total mix, calculate the quantity of reclaimed asphalt concrete in the recycled mix with the formula:

$$P_{sm} = \frac{100\,(100 - r)}{100 - P_{sb}} - \frac{(100 - r)\,P_b}{100 - P_{sb}}$$

where:

P_{sm} = reclaimed asphalt concrete in the recycled mix, percent

r = new aggregate expressed as percent of total aggregate in recycled mix (Equation 6.1)

P_{sb} = asphalt content of reclaimed asphalt concrete, percent

P_b = asphalt content of recycled mix, percent (the approximate asphalt demand, P, determined in 7.1 is used initially)

> Note: If the asphalt content is expressed as percent by weight of aggregate, the formula is:
>
> $$P_{sm} = \frac{(100 + P_{sb})(100 - r)}{100}$$

11.0 AMOUNT OF NEW AGGREGATE IN RECYCLED MIX

11.1 If the asphalt content is expressed as percent by weight of total mix, calculate the quantity of new aggregate in the recycled mix with the formula:

$$P_{ns} = r - \frac{r\,P_b}{100}$$

where:

P_{ns} = new aggregate in recycled mix percent

r = new aggregate expressed as percent of total aggregate in recycled mix (Equation 6.1)

P_b = asphalt content of recycled mix, percent (the approximate asphalt demand, P, determined in 7.1 is used initially)

Note:	If the asphalt content is expressed by weight of aggregate P_{ns} = r.

12.0 CALCULATION OF MIX COMPONENTS FOR INCREMENTS OF NEW ASPHALT OR RECYCLING AGENT ABOVE AND BELOW THE APPROXIMATE ASPHALT DEMAND

12.1 Calculate amounts of mix components for recycled mixes containing 0.5 percent increments of total asphalt content, P_b, above and below the approximate asphalt demand, P, determined in 7.1 using the formulas in 8.2, 10.1 and 11.1. Schedule tests with asphalt contents at the approximate asphalt demand, with three asphalt contents below and one asphalt content above the approximate asphalt demand when Marshall test apparatus is used. When Hveem test apparatus is used, schedule tests with asphalt contents at the approximate asphalt demand, with two asphalt contents below, and one asphalt content above the approximate asphalt demand.

> It is not likely that the viscosity of the binder at optimum conditions will be out of specifications but it may be. In any case, it is still a "theoretical" viscosity in the actual recycled mix and, at this point in the state of the art, this viscosity may not be of much practical significance.

13.0 TEST SPECIMENS

13.1 Mix and compact recycled mix test specimens by ASTM Method D 1559 when Marshall test apparatus is used and by ASTM Method D 1561 when Hveem test apparatus is used with the following changes or special provisions:

1) If necessary reduce processed reclaimed asphalt concrete in size to pass the 1 in. (25.0 mm) sieve and separate it by dry sieving into the following size fractions:

1 to 3/4 in. (25.0 to 19.0 mm)

3/4 to 3/8 in. (19.0 to 9.5 mm)

3/8 to No. 4 (9.5 to 4.75 mm)

Passing No. 4 (4.75 mm)

2) Heat the new aggregate 50°F (28°C) above the standard ASTM Method D 1559 or ASTM Method D 1561 mixing temperatures.

3) Heat the reclaimed asphalt concrete to the standard ASTM Method D 1559 or ASTM Method D 1561 compaction temperatures.

4) Dry mix the new aggregate and reclaimed asphalt concrete 30 seconds.

5) Add the new asphalt and/or recycling agent previously heated to the mixing temperature to new-aggregate and reclaimed asphalt concrete and mix 60 seconds.

6) Transfer completed batches of mix to covered tins and place them in an oven maintained at the compaction temperature for a minimum of one hour and not exceeding two hours prior to compaction of the specimens.

7) Prepare duplicate batches of mix at each asphalt content for determining the theoretical maximum specific gravity of bituminous paving mixtures by ASTM Method D 2041.

> Note: The mixing and compaction temperatures are based on the viscosity of the blend established in 9.1 of the recycling agent and aged asphalt recovered from the reclaimed asphalt concrete. Determine viscosity of the blend at temperatures of 140°F (60°C) and 275°F (135°C) to establish mixing and compaction temperatures if the Marshall test apparatus is used or to verify the specification grade for the blend if Hveem test apparatus are used.

14.0 TEST PROCEDURES

14.1 Determine the bulk specific gravity of the compacted specimens according to ASTM Method D 2726.

14.2 Determine the maximum load and flow value of the specimens according to ASTM Method D 1559 if Marshall test apparatus are used, or the stabilometer value of the specimens according to ASTM Method D 1560 if Hveem test apparatus are used.

14.3 Calculate the percent air voids in compacted specimens according to ASTM Method D 3203.

15.0 TEST DATA

15.1 If Marshall test apparatus are used, prepare graphical plots of maximum load (stability) versus recycling agent or new asphalt content, flow value versus recycling agent or new asphalt content, density of specimens versus recycling agent or new asphalt content and percent air voids versus recycling agent or new asphalt content.

15.2 If Hveem test apparatus are used prepare graphical plots of stabilometer values (Hveem stability) versus recycling agent or new asphalt content, density of specimens versus recycling agent or new asphalt content, and percent air voids versus recycling agent or new asphalt content.

16.0 OPTIMUM RECYCLING AGENT OR NEW ASPHALT CONTENT

16.1 If Marshall test apparatus are used, determine the optimum asphalt content by Asphalt Institute Marshall Method of Mix Design (26) procedures for asphalt concrete giving consideration to three of the test property curves prepared in 15.1. Determine recycling agent or new asphalt contents from the test property curves yielding the following:

a) maximum load (stability)

b) maximum density

c) four percent air voids

Select the optimum asphalt content as the average of the values for the recycling agent or new asphalt content determined as above. If peaks are not obtained for maximum load or density curves, select the optimum asphalt content as the recycling agent or new asphalt content yielding four percent air voids.

16.2 If Hveem test apparatus are used, the optimum asphalt content for the mix design should be the highest percentage the mix will accommodate without reducing stability or void content below minimum values. The optimum asphalt content is determined from stabilometer values, percent air voids and observations of surface flushing of specimens after compaction. The following steps are used to select the optimum asphalt content:

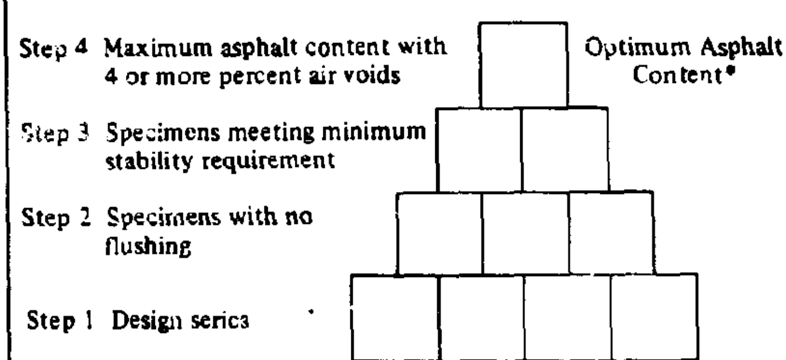
(a) Using the stepped diagram shown below, insert in Step (1) of the pyramid, the asphalt contents used for preparing the series of mix design specimens. Insert asphalt contents in order of increasing amounts from left to right with the maximum asphalt content used in the square on the right.

(b) Select from Step (1) the three highest asphalt contents that do not exhibit moderate or heavy surface flushing and record on Step (2). (Surface flushing and/or bleeding is considered "Slight" if the surface has a slight sheen. It is considered "Moderate," if sufficient free asphalt is apparent to cause paper to stick to the surface but no distortion is noted. Surface flushing is considered "Heavy" if there is sufficient free asphalt to cause surface puddling or specimen distortion after compaction).

(c) Select from Step (2) the two highest asphalt contents that provide the specified minimum stabilometer value and enter them in Step (3).

(d) Select from Step (3) the highest asphalt content that has at least 4.0% air voids and enter in Step (4).

(e) The asphalt content in Step (4) is the optimum asphalt content. However, if the maximum asphalt content used in the design set (Step 1) is the asphalt content entered on Step (4), additional specimens must be prepared with increased asphalt content in 0.5 percent increments and a new optimum asphalt content determination made.



*Optimum asphalt content is not valid if the maximum asphalt content used in the design series (Step 1) is the asphalt content arrived at in Step 4. In this event additional specimens must be prepared with increased asphalt content in 0.5 percent increments and a new analysis made.

17.0 DESIGN CRITERIA

17.1 Compare recycled mix test data at the optimum recycling agent or new asphalt content to the appropriate tentative Marshall design criteria in Table E.1 or tentative Hveem design criteria in Table E.2 to determine if the mix is satisfactory.

Table E.1 -- TENTATIVE MARSHALL DESIGN CRITERIA FOR RECYCLED HOT-MIX ASPHALT CONCRETE

Criteria	Light Traffic[1] Surface & Base Min.	Light Traffic[1] Surface & Base Max.	Medium Traffic[1] Surface & Base Min.	Medium Traffic[1] Surface & Base Max.	Heavy Traffic[1] Surface & Base Min.	Heavy Traffic[1] Surface & Base Max.
Compaction, number of blows each end of specimen	35		50		75	
Stability, lb. (N)	500 (2,224)	--	750 (3,336)	--	1,500 (6,672)	
Flow, 0.25 mm (0.01 in.)	8	20	8	18	8	16
Percent Air Voids	3	5	3	5	3	5

[1] Traffic Classifications:

Light: Traffic conditions resulting a Design EAL < 10^4.
Medium: Traffic conditions resulting a Design EAL between 10^4 and 10^6.
Heavy: Traffic conditions resulting in a Design EAL > 10^6.

Table E.2 -- TENTATIVE HVEEM DESIGN CRITERIA FOR RECYCLED HOT-MIX ASPHALT CONCRETE

Criteria	Light Traffic[1] Surface & Base Min.	Light Traffic[1] Surface & Base Max.	Medium Traffic[1] Surface & Base Min.	Medium Traffic[1] Surface & Base Max.	Heavy Traffic[1] Surface & Base Min.	Heavy Traffic[1] Surface & Base Max.
Stabilometer value	30	--	35	--	37	--

[1] Traffic Classifications:

Light: Traffic conditions resulting a Design EAL < 10^4.
Medium: Traffic conditions resulting a Design EAL between 10^4 and 10^6.
Heavy: Traffic conditions resulting in a Design EAL > 10^6.

• Note: The Marshall and Hveem design criteria for recycled mixes are adapted from The Asphalt Institute Marshall and Hveem design criteria for conventional asphalt concrete mixes (25). The tentative design criteria are based on extensive laboratory studies and limited field performance information. Their use is suggested until additional data correlating field performance and the laboratory mix design test properties becomes available.

18.0 MOISTURE DAMAGE AND STRIPPING BEHAVIOR

18.1 If the reclaimed asphalt concrete is obtained from pavements that have experienced moisture damage or stripping, or if new aggregates are used which are known or thought to be susceptible to moisture damage or stripping, evaluate the recycled mix at the optimum recycling agent content by The Method of Test for Effect of Water, Freezing and Thawing on Indirect Tensile Strength of Compacted Recycled Mix. (See Appendix D.)

18.2 If tensile strength ratios are below 0.8 as suggested in NCHRP Report 246 (23), use of anti-stripping agents should be considered and evaluated by The Method of Test for Effect of Water, Freezing and Thawing on Indirect Tensile Strength of Compacted Recycled Mix.

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FEDERALLY COORDINATED PROGRAM (FCP) OF HIGHWAY RESEARCH, DEVELOPMENT, AND TECHNOLOGY

The Offices of Research, Development, and Technology (RD&T) of the Federal Highway Administration (FHWA) are responsible for a broad research, development, and technology transfer program. This program is accomplished using numerous methods of funding and management. The efforts include work done in-house by RD&T staff, contracts using administrative funds, and a Federal-aid program conducted by or through State highway or transportation agencies, which include the Highway Planning and Research (HP&R) program, the National Cooperative Highway Research Program (NCHRP) managed by the Transportation Research Board, and the one-half of one percent training program conducted by the National Highway Institute.

The FCP is a carefully selected group of projects, separated into broad categories, formulated to use research, development, and technology transfer resources to obtain solutions to urgent national highway problems.

The diagonal double stripe on the cover of this report represents a highway. It is color-coded to identify the FCP category to which the report's subject pertains. A red stripe indicates category 1, dark blue for category 2, light blue for category 3, brown for category 4, gray for category 5, and green for category 9.

FCP Category Descriptions

1. Highway Design and Operation for Safety
Safety RD&T addresses problems associated with the responsibilities of the FHWA under the Highway Safety Act. It includes investigation of appropriate design standards, roadside hardware, traffic control devices, and collection or analysis of physical and scientific data for the formulation of improved safety regulations to better protect all motorists, bicycles, and pedestrians.

2. Traffic Control and Management
Traffic RD&T is concerned with increasing the operational efficiency of existing highways by advancing technology and balancing the demand-capacity relationship through traffic management techniques such as bus and carpool preferential treatment, coordinated signal timing, motorist information, and rerouting of traffic.

3. Highway Operations
This category addresses preserving the Nation's highways, natural resources, and community attributes. It includes activities in physical maintenance, traffic services for maintenance zoning, management of human resources and equipment, and identification of highway elements that affect the quality of the human environment. The goals of projects within this category are to maximize operational efficiency and safety to the traveling public while conserving resources and reducing adverse highway and traffic impacts through protections and enhancement of environmental features.

4. Pavement Design, Construction, and Management
Pavement RD&T is concerned with pavement design and rehabilititation methods and procedures, construction technology, recycled highway materials, improved pavement binders, and improved pavement management. The goals will emphasize improvements to highway performance over the network's life cycle, thus extending maintenance-free operation and maximizing benefits. Specific areas of effort will include material characterizations, pavement damage predictions, methods to minimize local pavement defects, quality control specifications, long-term pavement monitoring, and life cycle cost analyses.

5. Structural Design and Hydraulics
Structural RD&T is concerned with furthering the latest technological advances in structural and hydraulic designs, fabrication processes, and construction techniques to provide safe, efficient highway structures at reasonable costs. This category deals with bridge superstructures, earth structures, foundations, culverts, river mechanics, and hydraulics. In addition, it includes material aspects of structures (metal and concrete) along with their protection from corrosive or degrading environments.

9. RD&T Management and Coordination
Activities in this category include fundamental work for new concepts and system characterization before the investigation reaches a point where it is incorporated within other categories of the FCP. Concepts on the feasibility of new technology for highway safety are included in this category. RD&T reports not within other FCP projects will be published as Category 9 projects.