TECHNICAL REPORT STANDARD TITLE PAGE

| 1. Report No. | 2. Government Accession No. | 3. Recipient's Catalog No. |
|---|---|---|
| FHWA/TX-86/22+252-2 | | |

| 4. Title and Subtitle | 5. Report Date |
|---|---|
| GUIDELINES FOR DESIGN AND CONSTRUCTION OF RECYCLED ASPHALT MIXTURES | September 1985 |
| | 6. Performing Organization Code |
| 7. Author(s) | 8. Performing Organization Report No. |
| Thomas W. Kennedy, Maghsoud Tahmoressi, and James N. Anagnos | Research Report 252-2 |
| 9. Performing Organization Name and Address | 10. Work Unit No. |
| Center for Transportation Research<br>The University of Texas at Austin<br>Austin, Texas 78712-1075 | 11. Contract or Grant No.<br>Research Study 3-9-79-252 |
| | 13. Type of Report and Period Covered<br>Interim |
| 12. Sponsoring Agency Name and Address | |
| Texas State Department of Highways and Public Transportation; Transportation Planning Division<br>P. O. Box 5051<br>Austin, Texas 78763 | 14. Sponsoring Agency Code |

15. Supplementary Notes

Study conducted in cooperation with the U. S. Department of Transportation, Federal Highway Administration

Research Study Title: "Design and Characterization of Recycled Pavement Mixtures"

16. Abstract

This report provides information related to the feasibility of recycling salvaged asphalt mixtures, describes a design procedure that can be used to design asphalt mixtures containing salvaged asphalt material, and provides recommendations to insure satisfactory performance of pavements constructed with salvaged material. After the causes of distress or characteristics of salvaged material have been determined, detailed recommendations are made for determining (1) if additives, softening and antistripping agents, are needed, (2) if virgin aggregate and asphalt should be added, and (3) if so, how much. Examples demonstrate the use of the mixture design technique.

| 17. Key Words | 18. Distribution Statement |
|---|---|
| recycling, mixture design procedures, asphalt mixtures, salvaged materials, engineering properties, recycling agents, antistripping additives | No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161. |

| 19. Security Classif. (of this report) | 20. Security Classif. (of this page) | 21. No. of Pages | 22. Price |
|---|---|---|---|
| Unclassified | Unclassified | 56 | |

Form DOT F 1700.7 (8-69)

# GUIDELINES FOR DESIGN AND CONSTRUCTION OF RECYCLED ASPHALT MIXTURES

by

Thomas W. Kennedy
Maghsoud Tahmoressi
James N. Anagnos

Research Report Number 252-2

Design and Characterization of Recycled Pavement Mixtures

Research Project 3-9-79-252

conducted for

Texas
State Department of Highways and Public Transportation

in cooperation with the
U.S. Department of Transportation
Federal Highway Administration

by the

CENTER FOR TRANSPORTATION RESEARCH
BUREAU OF ENGINEERING RESEARCH
THE UNIVERSITY OF TEXAS AT AUSTIN

September 1985

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

## PREFACE

This is the second in a series of reports dealing with the design and characterization of recycled pavement materials. This report provides updated information and recommendations concerning the feasibility of recycling and the design of asphalt mixtures containing salvaged materials. The report includes a mixture design procedure, as well as a description of the preliminary activities involved in recycling asphalt mixtures, and includes guidelines related to mixture design to insure satisfactory pavement performance.

This report was completed with the assistance of many people. Special appreciation is due to Messrs. Pat Hardeman and Eugene Betts for the extensive field and laboratory testings that provided the background for this report. Appreciation is expressed to Billy R. Neeley, Paul Krugler, Donald O'Connor, and C. Weldon Chaffin, and District personnel of the Texas State Department of Highways and Public Transportation for their assistance, both in the field and in securing specimens and material samples. Appreciation is extended to Center for Transportation Research staff for their assistance in the preparation of manuscript materials. The support of the Federal Highway Administration, Department of Transportation, is acknowledged.

Thomas W. Kennedy
Maghsoud Tahmoressi
James N. Anagnos

September 1985

## LIST OF REPORTS

Report No. 252-1, "Mixture Design Procedure for Recycled Asphalt Pavements," by Thomas W. Kennedy, Freddy L. Roberts, and James N. Anagnos, provides an evaluation and mixture design procedure that includes the use of salvaged materials from a road that is to be recycled. May 1982.

Report No. 252-2, "Guidelines for Design and Construction of Recycled Asphalt Mixtures," by Thomas W. Kennedy, Maghsoud Tahmoressi, and James N. Anagnos, provides detailed design and quality assurance procedures for recycled asphalt mixtures. September 1985.

## ABSTRACT

This report provides information related to the feasibility of recycling salvaged asphalt mixtures, describes a design procedure that can be used to design asphalt mixture containing salvaged asphalt material, and provides recommendations to insure satisfactory performance of pavements constructed with salvaged material. After the causes of distress or characteristics of salvaged material have been determined, detailed recommendations are made for determining (1) if additives, softening and antistripping agents, are needed (2) if virgin aggregate and asphalt should be added, and (3) if so, how much. Examples demonstrate the use of the mixture design technique.



KEY WORDS: Recycling, mixture design procedures, asphalt mixtures, salvaged materials, engineering properties, recycling agents, antistripping additives.

## SUMMARY

This report includes guidelines and information that can be used by the engineer to determine if the use of salvaged material is a viable alternative for the construction or rehabilitation of highways. Once recycling of salvaged asphalt materials is determined to be a cost effective option for a particular pavement, three phases in mixture design must occur: general design considerations, preliminary design, and final design. Design considerations include evaluating causes of failure and determining whether the problems are mixture related or structure related and determining the characteristics of the salvaged material proposed to be recycled. In addition, a sampling plan must be developed and materials secured for the actual mixture design. Preliminary design includes evaluating the effects of various recycling agents or new asphalt on the properties of the salvaged asphalt cement. Recycling agents or new asphalts, if required, should restore the aged asphalt cement to its original viscosity. Preliminary design involves determining the combinations of components, such as recycling agents, new aggregates, and antistripping additives, that are to be considered. Final design involves preparing specimens at various combinations to provide an indication of the effects of these components on test results. The test recommended for use in these evaluations are stability, unconfined compression, indirect tensile strength, and resilient modulus of elasticity. The last step in the final design includes comparing test results for the recycled mixture combinations with standard values for conventional asphalt mixtures or a range of properties from conventional flexible pavement mixtures that have provided satisfactory field performance. Quality assurance recommendations are also outlined in this report.

## IMPLEMENTATION STATEMENT

Based on the experience gained with recycled mixtures studied in this project and national experience, it is recommended that the Texas State Department of Highways and Public Transportation allow the use of salvaged materials in asphalt mixtures and implement policies which will increase the cost effectiveness of recycling. This report contains guidelines related to needed departmental policies, decisions regarding recycling, and design considerations and procedures.

Utilization of the recommendations and guidelines contained in this report will allow the Texas State Department of Highways and Public Transportation to routinely recycle salvaged asphalt mixtures and will help to assure quality pavements which will exhibit performance equal to that of conventional mixtures and pavements. In addition, it is anticipated that a significant savings in cost can be realized.

TABLE OF CONTENTS

# CHAPTER 1. INTRODUCTION

The purpose of this report is to provide guidelines and recommendations related to the hot mix recycling of asphalt mixtures, including feasibility of hot mix recycling, design procedures, and recommendation for quality assurance.

At the time this study was initiated, there was no readily available and accepted procedures for the design and construction of pavements and mixtures containing recycled asphalt mixtures, although a great deal of information had been accumulated from research studies and field experience.

Subsequently, based on a previous study, Research Project 3-9-72-183 "Tensile Characterization of Highway Pavement Materials" (Refs 1,2, and 3) and this study, a design procedure was developed and used on a number of projects. It was anticipated that modifications would be required as additional information and experience were obtained.

This report provides modifications of the previous design procedures (Ref 4) and guidelines based on field experience. Chapter 2 summarizes considerations related to the feasibility of hot mixed recycling of asphalt mixtures including economic considerations, departmental policies, and engineering feasibility of recycling. Chapter 3 describes the recommended design procedures and considers the general design considerations related to reusing the salvaged material on the same project or other future projects. Chapter 4 summarizes quality assurance recommendations. Chapter 5 contains recommendations.

# CHAPTER 2. FEASIBILITY OF HOT MIXED RECYCLING OF ASPHALT MIXTURE

The use of hot mixed recycled mixtures has been shown to be a viable option to the construction of highways and streets; however, only a limited number of projects in Texas have involved the use of recycled asphalt mixtures. The principal reasons seem to be a lack of economic or practical motivation and the feeling that the relative quality of mixtures and pavements containing recycled asphalt mixtures will not be satisfactory.

## ECONOMIC CONSIDERATIONS

At this time it is not possible to accurately estimate the savings to the state, which could result from recycling for either a specific project or for projects throughout the state. The actual savings will depend on the cost of asphalts and aggregates in various regions of the state, the need for removal of the existing pavement exclusive of recycling considerations, the recycling experience of the district and contractors, and departmental policies regarding recycling as an alternative.

### Cost of Asphalt and Aggregates

The cost of asphalt and aggregates will significantly influence the savings which can be achieved by recycling asphalt mixtures. Areas which have minimal supplies of locally available, high quality aggregates and high cost asphalts will achieve greater savings by recycling salvaged mixtures. Closely associated is the question of whether the existing materials must be removed regardless of whether the salvaged material is to be recycled. If recycling of the salvaged material is not allowed, then the state can expect to pay for the disposal by either the state or the contractor.

### Experience of Districts and Contractors

Districts which have consistently allowed and encouraged recycling would be expected to achieve greater savings since the contractors operating in these districts will have experience with recycling and will reflect this experience in bids for proposed construction projects and will be less likely because of anticipated problems related to recycling to bid conventional construction with new materials rather than construction involving recycled mixtures.

DEPARTMENTAL POLICIES

A statewide policy allowing the use of recycled asphalt mixtures in all projects and allowing the contractor to own salvaged materials can significantly increase the savings to the state.

Recycling often is interpreted to mean that salvaged material must be reused in the roadway from which it was removed. Closely associated is the concept that the state should own the salvaged material and that it must be used in the same roadway or ownership retained by the state. Rather, the state should allow the contractor to own the salvaged material and allow the material to be used in the rehabilitation project from which it was obtained or in other state or local projects. Such a policy would increase the value of removed pavement, and would be reflected in the bid process for removal, hauling, and eventual reuse or disposal for projects which involve removal of existing material and in the bid price of subsequent projects in which the recycled material can be used. In addition, the state is not faced with storing the salvaged material, requiring that salvaged material be recycled, and striving for the use of large quantities of recycled material in a specific project.

The salvaged material will be a valuable resource to the contractor and can be used in smaller percentages in existing or future projects. The use of smaller quantities of salvaged material will minimize the variations in the properties of the recycled mixture due to inherent variations in the salvaged material and will result in a more consistent higher quality mixture. The department should also accept recycled asphalt mixtures on an equal basis with conventional asphalt mixtures providing that the recycled mixtures conform to all requirements and specification demanded of mixtures containing all new material. If the quality of recycled mixtures is doubted, then the use of recycled mixtures can be restricted to base material or to use in shoulders, detours, and secondary roads, etc. It is also possible, but unlikely, that the contractor might propose the use of salvaged material obtained from parking lots, local streets, or other projects which may not have been constructed to state specifications. The use of material could be prohibited or the contractor could be required to show evidence that the material was satisfactory.

Such a policy of course may be questioned in isolated rural locations which do not have other proposed projects in which the salvaged material can be readily used. In these cases, the bidding will obviously reflect the contractors' plans and available options, and bid prices may be higher. Nevertheless, the option to reuse the material, transport it to a new location, or dispose of it rests with the contractor. The state, however, is not required to store or dispose of the material.

## FEASIBILITY OF RECYCLING

The final decision criterion should be to minimize the pavement life cycle costs. These costs include not only the first cost of construction as reflected in the bids, but also the related first costs to the state, the maintenance costs during the service life of the pavement, and the cost of future rehabilitation.

The feasibility considerations of recycling must involve an evaluation of the salvaged material for a proposed roadway. Thus, depending on the quality of the salvaged material, it may not be feasible to allow the mixture to be reused in certain highways or to be used only in small quantities.

If the contractor is allowed to retain salvaged material and use it in future projects, it is mandatory that any mixture which includes salvaged material be tested to insure that the mixture satisfies current specifications and standards and that the mixture does not vary due to the inherent variations which may occur in the salvaged material from a variety of sources.

If the recycled mixture is to be reused on the project from which it was obtained, it is necessary to identify and correct the cause of the distress prior to recycling.

# CHAPTER 3. DESIGN CONSIDERATIONS

Design considerations differ slightly depending on whether the salvaged material is to be reused on the same project or stockpiled and used on future projects. Thus the discussion has been subdivided into reuse in the same project and reuse in other projects.

Factors considered are

1. determining the nature and causes of distress,
2. determining the gradation and moisture susceptibility of the salvaged aggregate,
3. determining the residual asphalt content of the salvaged mixture,
4. determining the penetration/viscosity of the salvaged asphalt, and
5. specifying the aggregate gradation after pulverization and the addition of new aggregate.

Since evaluation of many of these factors is fairly straight forward and laboratory procedures well established, each factor is not discussed in detail. In addition, the necessary steps and procedures vary depending on whether the salvaged material is to be reused on the same project or stockpiled for use in other projects.

## REUSE IN SAME PROJECT

### Causes of Distress

If the salvaged material is to be reused on the same project, it is essential that the cause of the distress which led to the need for recycling be identified and corrected in order to obtain a satisfactory recycled asphalt mixture and satisfactory pavement performance. Texas experience suggests that one or more of the following three causes are involved in most failures leading to recycling.

1. aging (brittleness) of the asphalt cement,
2. stripping of the asphalt from the aggregate, and
3. structural inadequacy.

A detailed condition survey should be conducted to determine the severity and extent of the distress present on the job for which recycling is being considered. The standard condition survey forms of the Texas State Department of Highways and Public Transportation (SDHPT) can be used.

A separate condition survey should be conducted for each section of road that is determined to be different, based on

1. surface thickness or mixture design,
2. evidence of discontinuous heavy maintenance carried out along the section,
3. seal or friction coat difference, and
4. half-section skin patching, etc.

For each section identified using the suggestions listed above, the types of distress and the severity should be evaluated to determine the primary cause of the distress.

These failures may be associated with the characteristics of the salvaged mixture to be recycled or with the pavement structure. Pavement failure analysis is discussed in Ref 5.

Mixture Problems. Aging or brittleness, stripping, and stability problems are usually mixture associated and can be categorized as either brittle or nonbrittle.

Brittle failures occur when axle loads, thermally induced stresses, and shrinkage of underlying layers combine with aged asphalt cements to produce cracking, e.g., alligator, transverse, block (map), and longitudinal. Typically, when such an asphalt mixture is to be recycled, it is necessary to restore the salvaged asphalt cement to its original viscosity or to an acceptable viscosity. This normally involves the addition of soft asphalts and/or a recycling agent.

Nonbrittle failures are usually associated with mixtures that are either stripping or exhibiting poor stability. Distresses typical of these conditions are rutting, shoving, corrugations, and bleeding. Rutting can also occur due to deformation or lateral movement of underlying layers of the pavement structure. The cause of rutting in each case is different and the treatment to alleviate the problem must be selected and applied either prior to or during the recycling operation if the recycled pavement is expected to perform adequately. The use of a recycling agent, if not needed, can produce an unstable mixture that is prone to shoving and rutting.

In some cases, poor stability may be due to low viscosity (soft) asphalt cements or excessive asphalt. In these cases, it may be necessary to add harder asphalts or additional aggregate. In addition, stability often can be improved by the addition of new aggregate to improve gradation and introduce more angular aggregate particles. Better gradation may also result in higher densities.

In the case of a stripping mixture, an appropriate treatment must be applied to the salvaged mixture to solve the stripping problem or the mixture must be discarded or used for other purposes such as low volume roadways, patching, or shoulders. If the stripping problem is eliminated, the salvaged mixture can be evaluated and a mixture design developed.

A high level of density should be achieved during construction since low void contents will prevent moisture penetration and subsequent moisture damage and will minimize rutting and fatigue cracking.

Special attention should be given to the final gradation including new aggregate if added. Grading curves similar to those shown in Figures 1 and 2 (Ref 6) have shown excellent performance. Figure 3 indicates the types of problems associated with gradations which deviate from the recommended gradation curves. The grading curve should not have humps in the region of the No. 30 to No. 60 sieves nor should there be significant deviations either coarser or finer in the regions above the No. 10 sieve. Variations in these regions are especially important with regard to certain types of distress.

Goode and Lufsey (Ref 6) have shown that humps in the region of the No. 30 to No. 60 sieves above the lines shown in Figure 1 through 3 produce tender mixes. In addition, these finer mixes can have significantly lower stabilities. If the mixture is both too coarse and made with stripping prone aggregate, the greater porosity of the mix may actually enhance the opportunity for water damage.

While it is recommended that the final gradation approximate the idealized 0.45* gradation relationship, which plots as a straight line as shown in Figure 2, it must be noted that this gradation tends to produce

---

* The equation for Federal Highway Administration maximum density curve is:

$P = 100\ (d/D)^{0.45}$ where P = total percent passing given size
d = size of sieve opening
D = largest size (sieve opening) in gradation

The fuller equation for maximum density is: $P = 100\ (d/D)^{0.5}$

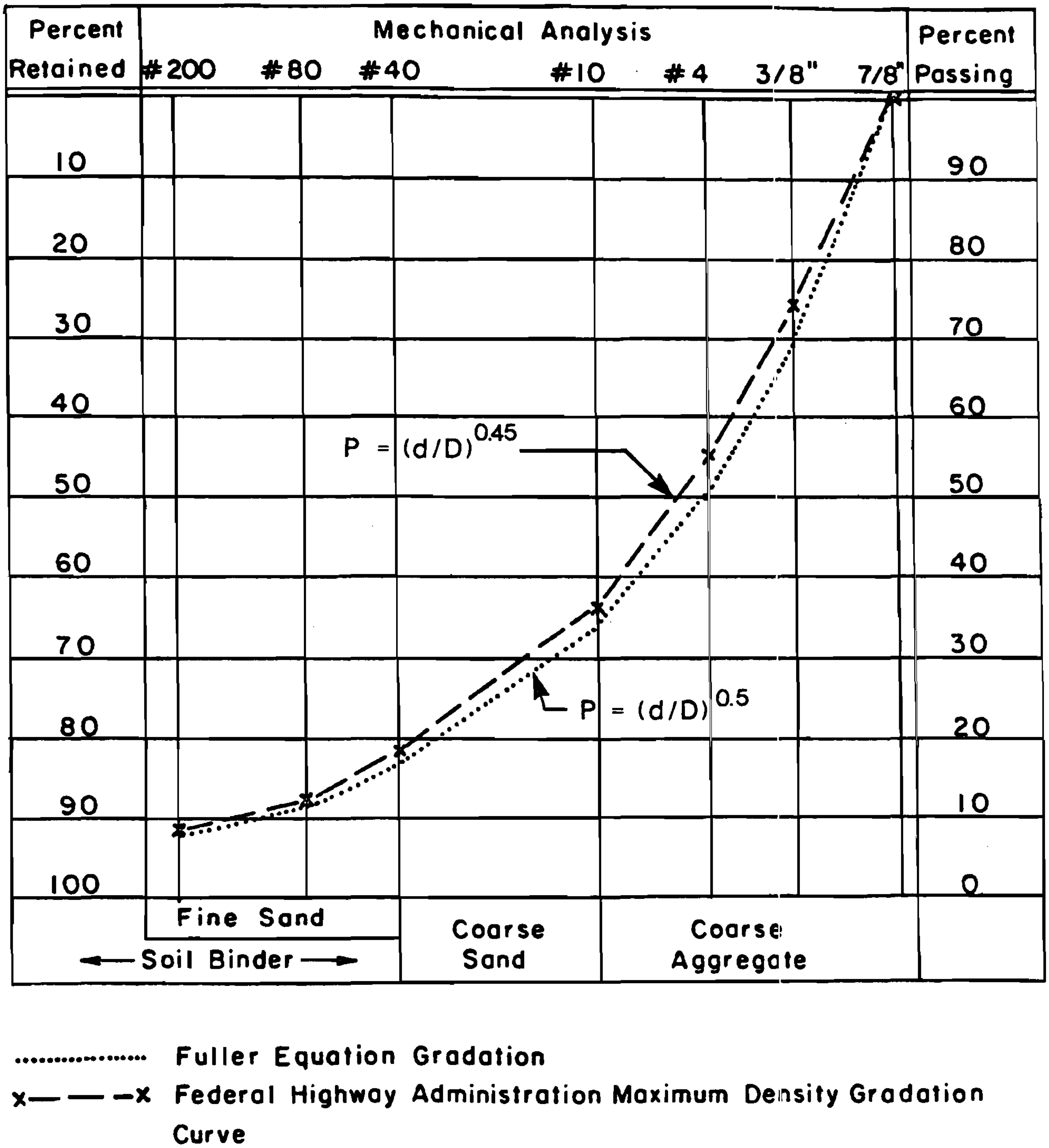



Fig 1. Grading curves for dense graded asphalt concrete mixtures (Ref 6).

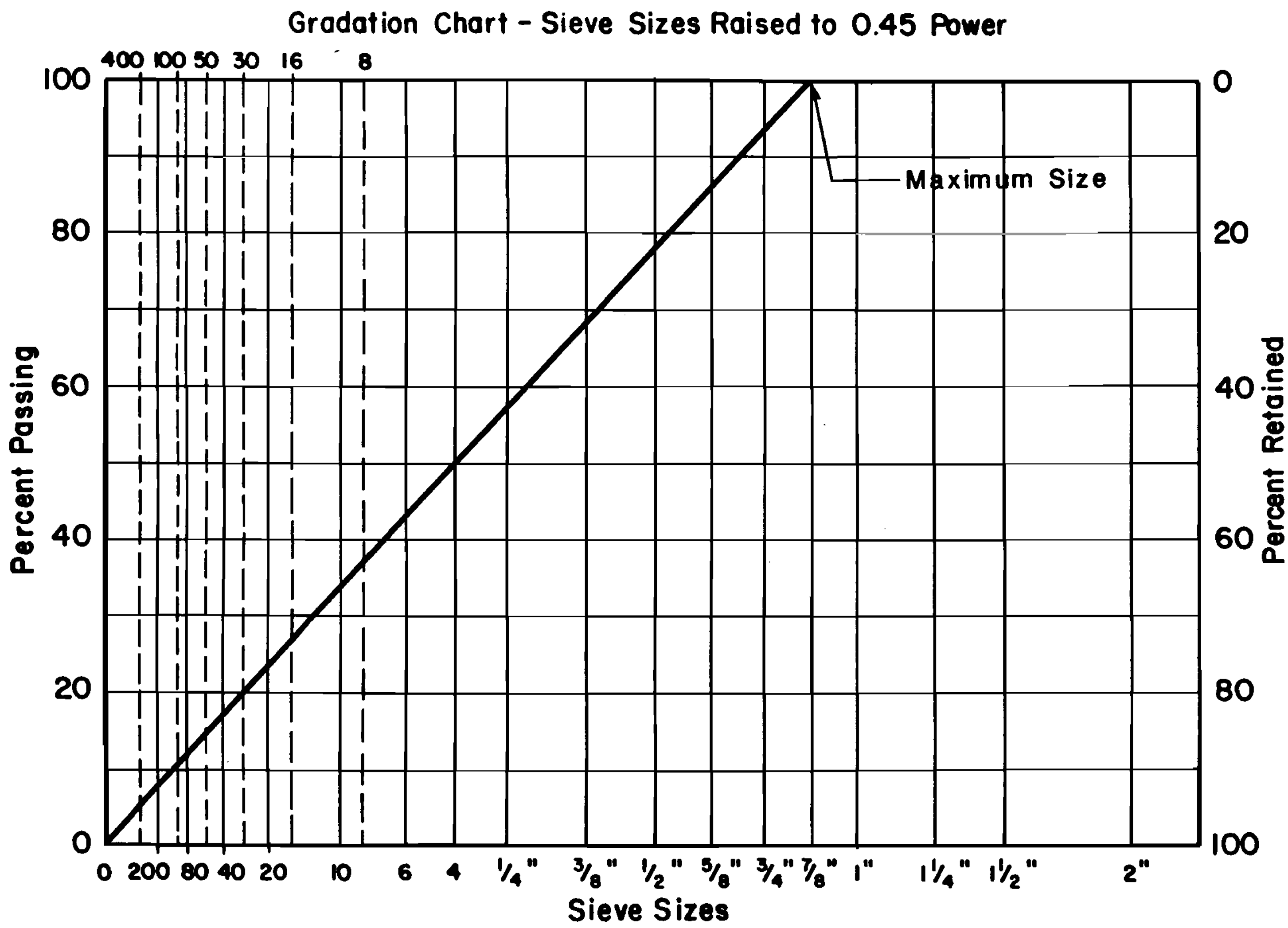



Fig 2. The Federal Highway Administration maximum density gradation line with seive sizes raised to 0.45 power.

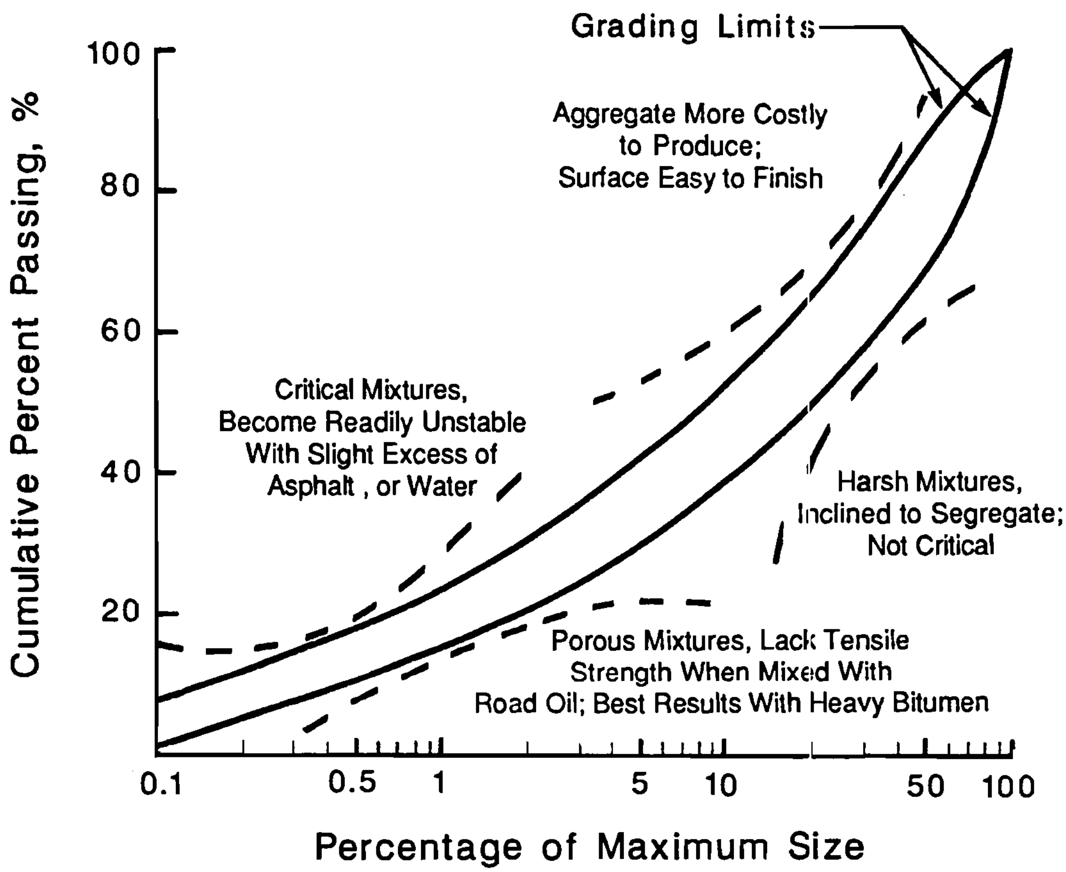



Fig 3. Problems associated with gradations which deviate from the recommended gradation curves.

maximum density and could result in extremely low voids in the mineral aggregates resulting in low stabilities and flushing or bleeding. Thus, voids in the mineral aggregate should be calculated and the final gradation altered to insure that a minimum level is achieved. The Asphalt Institute recommendations for minimum voids in the mineral aggregates are contained in Table 1.

Structural Problems. Structural inadequacies may occur as the result of underdesign, increased traffic volumes and axle load, decreased support values due to the action of water, and brittleness of asphalt due to aging, all of which can produce increased stresses and strains. If these increased stresses and strains exceed limiting values, premature fatigue or longitudinal cracking in the surface layer or permanent deformations can occur. This cracking can be localized or quite extensive.

An evaluation of the strength conditions of the existing pavement structure can be made by performing and analyzing a Dynaflect survey or other nondestructive testing. Such an analysis will help define the extent of soft spots and establish the limits on sections where the underlying support characteristics or layer thicknesses are different or inadequate. Application of these techniques and formulas for estimating moduli for underlying layers have been presented by Lytton and Machalak (Ref 7).

## Sampling Plan

Each identified subsection should be treated as a separate design and a representative sample should be secured from each. Sampling sites within each subsection should be selected randomly. The engineer should choose at least six sampling sites for each subsection and secure an adequate sample, a minimum of 200 pounds, of material for subsequent laboratory analysis (Ref 8).

The effect of discontinuities or variations of material properties along the length of the pavement or across the width may lead to difficulties in securing representative materials. The effect of large discontinuous areas of patching, the addition of hot mixed overlays or seal coats to surface courses which were originally cold mixed, and variations in materials combinations in the cross-section may make selection of representative samples for a single mixture design for the entire pavement difficult, if not

TABLE 1. Minimum Percent Voids in Mineral Aggregate (Ref 20)

| Nominal Maximum Particle Size* | Sieve** | Minimum Voids in Mineral Aggregate % |
|---|---|---|
| .049 | No. 16 | 23.5 |
| .093 | No. 8 | 21 |
| .187 | No. 4 | 18 |
| .375 | 3/8 in. | 16 |
| .500 | 1/2 in. | 15 |
| .750 | 3/4 in. | 14 |
| 1.0 | 1 in. | 13 |
| 1.5 | 1 1/2 in. | 12 |
| 2.0 | 2 in. | 11.5 |
| 2.5 | 2 1/2 in. | 11 |

* For processed aggregate, the nominal maximum particle size is the largest sieve size listed in the applicable specification upon which any material is permitted to be retained.

** Standard specification for wire cloth sieves for testing purposes, ASTM designation E11 (AASHTO designation M92).

impossible. In such cases, further subdivision of the subsection may be necessary or the recycling alternative may have to be abandoned if only short subsections are identified or the salvaged material may have to be blended to insure uniformity.

Of special concern in developing the sampling plan are the causes of failure and variations in asphalt content or gradations of the material to be salvaged. Since brittle and nonbrittle failures require different treatment of the salvaged asphalt cement, the first break in the sampling plan probably should be based on type of failure. The second primary areas of concern is that of variations in asphalt cement content and aggregate gradations down the road. Since seal coats, patching and other surface treatments do not necessarily involve the entire roadway, these operations will affect the selection of relatively homogeneous sections for mixture design considerations. If the materials are to be removed from the site, crushed, sized, and reblended, these problems are minimized but should be considered in developing the sampling plan. If the recycling is to be accomplished in place, careful laboratory studies should be conducted to determine the magnitude of systematic variations in asphalt content and gradations across the roadway and to evaluate the effect of those variations on stability, void contents, density, and strength. If these variations are significant enough to produce instabilities, high void contents or other problems in portions of the recycled mixture, then the engineer should carefully consider whether the recycling option should be abandoned or whether to proceed but modify the construction sequence to eliminate or minimize these problems. A final decision on these factors could be delayed until more complete information is available on which to evaluate the effect of these variations on mixture properties.

## REUSE IN OTHER PROJECTS

Many of the problems related to reuse of salvaged material in other projects are similar to those encountered in reusing the salvaged materials in the same project. Nevertheless, special considerations are summarized below.

## Characteristics and Variations of Stockpiled Salvaged Material

This is similar to determining the cause of distress. Salvaged material from a number of projects may be stockpiled by the contractor. Thus there is a possibility that significant variations in aggregate type, gradation asphalt viscosity, and residual asphalt content may be present in a stockpile of salvaged material. Thus, it is important to determine the extent of variations as well as the characteristics of the salvaged material. If variations are substantial, then the salvaged material may have to be blended. Another approach would be for the contractor to separately stockpile salvaged material which have similar characteristics and to develop mixture designs for each salvaged material.

Material Problems. As with recycled mixture proposed for reuse on the same project, it is necessary to determine the basic characteristics of the salvaged material and to correct deficiencies which may exist. Such problems include aged brittle asphalt, soft low viscosity asphalts, too much asphalt, moisture susceptible mixtures, and unsatisfactory aggregate gradations. Correction of these deficiencies is necessary prior to recycling and recommended correction procedures are similar to those previously discussed.

Structural Problems. The structural cross section of any pavement which is to be constructed or rehabilitated with mixtures containing salvaged materials must be adequate or failure can be expected. This, of course, is true of conventional pavements as well as pavements containing salvaged materials.

## Sampling Plan

The stockpile should be sampled in a manner to determine its characteristics and the extent of variations. If large variations exist, it may not be possible to utilize the material unless it is blended to produce a more uniform material. If a relatively uniform salvaged material is available, adequate samples for testing and evaluation should be obtained.

# CHAPTER 4. MIXTURE DESIGN

The design of mixtures containing salvaged asphalt mixtures has been subdivided into

1. preliminary design
2. final design

## PRELIMINARY DESIGN

The primary objective of the preliminary design is to select the type and amount of additive which should be used to either recondition the asphalt or eliminate asphalt aggregate problems in the salvaged mixture. If a brittle mixture is involved, this portion of the design involves the selection of a recycling agent which will soften the existing asphalt and return it to its original or a specified viscosity. A variety of materials are available, such as commercially available recycling agents, soft asphalts, or some combinations of these materials. If failure is due to a soft asphalt, it may be necessary to add a harder asphalt in order to produce a binder with a specified or desirable viscosity. If a nonbrittle failure has occurred, the techniques or type and amount of additive which will minimize the distress must be selected. Materials such as hydrated lime and some chemical antistripping additives are capable of reducing stripping and moisture damage in asphalt mixtures; however, it is imperative that proposed antistripping additives be tested to ascertain their effectiveness.

### Recycling Agents

Asphalt binders in salvaged asphalt mixtures often are brittle and have physical and chemical properties which make the salvaged asphalt undesirable for reuse without modification.

Viscosity of the aged and brittle asphalt can be lowered by addition of adequate amounts of a recycling agent. For brittle mixtures, the recycling agent, including soft asphalts, must have a lower viscosity than the aged asphalt and should be added as soon as possible to the salvaged material. Recycling agents are also called softening agents, reclaiming agents, modifiers, rejuvenating agents, fluxing oils, extender oils, aromatic oils, etc. Many major oil companies market products of this type. The general definition of modifier is "a material when added to asphalt cement will alter the physical-chemical properties of the resulting binder" (Ref 9). The 13th Pacific Coast User-Producer Conference on Asphalt Specifications Committee adopted the term "Recycling Agent" and defined it as "a hydrocarbon product with physical characteristics selected to restore aged asphalt to the requirements of current asphalt specifications (Ref 10).

Specifications for Recycling Agents. A number of specifications for recycling agents have been proposed and are summarized below and in Tables 2, 3, and 4. A specification typical of that currently used by the Texas Department of Highways and Public Transportation is shown in Table 5. This specification is written as a special provision for each individual project after the characteristics of the asphalt in the material to be recycled have been determined. The purpose is to insure that any recycling agent used, when combined in some maximum amount with old asphalt, will produce a material meeting the requirements for new asphalt cement.

Table 2 lists the specifications proposed by Witco (Ref 11). These specifications are for the cyclogen series of recycling agents produced by Witco Chemical Corporation. Compatibility and composition ratio specifications are based on chemical composition which will ensure that the new binder will have an optimum proportion of each chemical component. Specifications proposed by Chevron U.S.A. are contained in Table 3 (Ref 12). The three grades of recycling agents, designated as H-1, H-2.5, and H-5, satisfy the requirements for a broad range of salvaged asphalt viscosities. The number designation is approximately the median viscosity of the agent in poises divided by 100. Specifications (Table 4) developed by the Pacific Coast User-Producer Conference on Asphalt Specification Committee (Ref 10) consider the compatibility requirements of the old asphalt and the recycling agent by specifying a maximum allowable saturates concentration.

Soft asphalts can also be used to rejuvenate the aged asphalt; however, care must be taken in selecting the type of asphalt. Soft asphalt contains all the components of a recycling agent; however, the ratio of these components is uncontrolled and could result in poor durability of the combined asphalt binder (Ref 13). The specification, used in Texas on a

TABLE 2. Witco Proposed Specifications for Reclaiming Agents (Ref 11)

| Property | Function & Purpose | Test Method | Agent L* | Agent M* | Agent H* |
|---|---|---|---|---|---|
| Viscosity @ 140°F, cST | Asphalt viscosity adjustment in recycled mix | ASTM D 2170-74 | 80-500 | 1000-4000 | 5000-10000 |
| Flash Point, COC, °F | Handling precaution | ASTM D 92-72 | 350 min. | 350 min. | 350 min. |
| Volatility, IBP, °F<br>2%, °F<br>5%, °F | Avoidance of air pollution and hardening by evaporation | ASTM D 1160-61, 10 mm | 300 min.<br>375 min.<br>410 min. | 300 min.<br>375 min.<br>410 min. | 300 min.<br>375 min.<br>410 min. |
| Compatibility, N/P | Avoidance of syneresis | ASTM D 2006-70 | 0.5 min. | 0.5 min. | 0.5 min. |
| Chemical Composition, $(N+A_1)/(P+A_2)$ | Durability of asphalt in recycled mix | ASTM D 2006-70 | 0.2-1.2 | 0.2-1.2 | 0.2-1.2 |
| Specific Gravity | Calculations | ASTM D 70-72 | Report | Report | Report |

* Suitable pumping temperatues are the following: L = 140°F, M = 190°F, and H = 200°F.

TABLE 3. Chevron Proposed Specifications for High Flash Recycling Agents (Ref 12)

| Tests | AASHTO Test Method | Grade H-1 Min. | Grade H-1 Max. | Grade H-2.5 Min. | Grade H-2.5 Max. | Grade H-5 Min. | Grade H-5 Max. |
|---|---|---|---|---|---|---|---|
| Original Material: | | | | | | | |
| Viscosity, 60°C (140°F), Poise | T-202 | 50 | 200 | 200 | 300 | 400 | 600 |
| Viscosity, 135°C (275°F), cs | T-201 | 50 | - | 80 | - | 110 | - |
| Flash Point, COC, °F | T-48 | 450 | - | 450 | - | 450 | - |
| RTFC Residue: | T-240* | | | | | | |
| Weight Loss, % | T-240 | - | 1.0 | - | 1.0 | - | 1.0 |
| Viscosity Ratio** | - | - | 3.0 | - | 3.0 | - | 3.0 |

* TFO may be used, but RTFC shall be the referee method.

** Viscosity Ratio = $\frac{\text{RTFC Viscosity at 60°C (140°F)}}{\text{Original Viscosity at 60°C (140°F)}}$

TABLE 4. Proposed Specifications for Hot Mix Recycling Agents Proposed by the Pacific Coast User-Producer Conference on Aspahlt Specification Committee (Ref 8)

| Test | ASTM Test Method | RA 5 | | RA 25 | | RA 75 | | RA 250 | | RA 500 | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | min. | max. | min. | max. | min. | max. | min. | max. | min. | max. |
| Viscosity @ 140°F, cSt | D2170 or 2171 | 200 | 800 | 1000 | 4000 | 5000 | 10000 | 15000 | 35000 | 40000 | 60000 |
| Flash Point, COC, °F | D92 | 400 | - | 425 | - | 450 | - | 450 | - | 450 | - |
| Saturates, wt. % | D2007 | - | 30 | - | 30 | - | 30 | - | 30 | - | 30 |
| Residue from RTF-C Oven Test @ 325°F | D2872[2] | | | | | | | | | | |
| Viscosity Ratio[3] | - | - | 3 | - | 3 | - | 3 | - | 3 | - | 3 |
| RTF-C Oven Weight Change ±, % | D2872[2] | - | 4 | - | 3 | - | 2 | - | 2 | - | 2 |
| Specific Gravity | D 70 or D1298 | Report | | Report | | Report | | Report | | Report | |

1. The final acceptance of recycling agents meeting this specification is subject to the compliance of the reconstituted asphalt blends with current asphalt specifications.
2. The use of ASTM D1754 has not been studied in the context of this specification; however, it may be applicable. In cases of dispute, the reference method shall be ASTM D2872.
3. Viscosity Ratio = $\frac{\text{RTF-C Viscosity at 140°F, cSt}}{\text{Original Viscosity at 140°F, cSt}}$

TABLE 5. Texas Special Provision to Item 300
Asphalts, Oils and Emulsions

---

For this project, Item 300, "Asphalts, Oils and Emulsions" of the Standard Specifications, is hereby amended with respect to the clauses cited below and no other clauses or requirements of this item are waived or changed hereby.

Article 300.2 Materials is supplemented by the following:

(12) AC-3 Asphalt Cement for Recycling Bituminous Materials. AC-3 asphalt, when used in a mix produced totally or partially from salvaged bituminous materials, in addition to complying with the requirements of this item, shall also comply with the following:

The AC-3, when uniformly blended in the laboratory with the following standard asphalt, shall have the capability of producing a material which will comply with essentially all the requirements of this item for AC-10 asphalt cement.

The standard asphalt cement for the above blend shall be obtained by Abson recovery from the salvaged bituminous pavement. It shall have a 77°F penetration of 25 to 30.

(13) Asphalt Additive. The asphalt additive shall be a petroleum oil with the following properties:

| | |
|---|---|
| Water Content......................... | Nil |
| Flash Point, C.O.C.,F.................. | 400 Mimimum |
| Viscosity at 140°F,cSt................. | 75 Minimum |
| | 250 Maximum |
| Viscosity at 275°F,cSt.................. | 10.0 Maximum |

The oil, when uniformly blended in the laboratory at a maximum of 25 percent by weight of the above standard asphalt of 25 to 30 penetration, shall result in a material which will comply with essentially all the requirments of this item for AC-10 asphalt cement.

---

project-to-project basis, considers the viscosity of the proposed recycling agent and/or asphalt cement, but does not include chemical composition or compatibility requirements of the type shown in Tables 2 and 4. The assumption is made that if the agent will produce a blend with the old asphalt meeting all the requirements for a designated grade of new asphalt cement, including the thin film oven aging test, then the mixture should perform satisfactorily. While the chemical composition and compatibility considerations are important, Texas' experience with recycled mixtures to date has, for the most part, been satisfactory.

Amount and Type of Recycling Agent. The approximate amount of recycling agent can be calculated from the asphalt demand of the recycled and new materials using the following relationships (Ref 9).

$$D_T = V_R D_R + V_N D_N \qquad \text{(Equation 1)}$$

where

$$D_R = D_{CKE} - A_R$$

and

$D_T$ = asphalt demand of recycled material plus new aggregate

$D_R$ = asphalt demand for recycled aggregate, percent

$D_{CKE}$ = CKE derived oil ratios for recycled aggregate, percent*

$A_R$ = asphalt content or recycled mixture

$D_N$ = CKE derived oil ratios for new aggregate, percent*

$V_R$ = volume of recycled aggregate in mixtures

$V_N$ = volume of new aggregate in mixtures

The maximum predicted percent modifier by weight of total binder in the recycled mixture is therefore:

$$\frac{D_T}{V_R A_R + D_T} \times 100$$

Equation 1 is a general relationship which was derived on the basis of aggregate surface area. Other simpler relationships (Ref 13) have also been established based on the surface area principals which could be used in lieu of Equation 1.

* Centrifuge Kerosene Equivalent (C.K.E.) procedure is outlined in Ref 20.

$$D_T = \frac{4R + 7S + 12F}{100} \times (1.1) \qquad \text{(Equation 2)}$$

where

R = Rock (percent retained on #8 sieve)

S = Sand (percent passing #8 sieve, retained on #200)

F = Fines (percent passing #200 sieve)

Percent asphalt demand of the combined aggregate may also be calculated using relationships developed by the Asphalt Institute (Ref 14).

$$D_T = \frac{.035a + .045b + KC + F}{R} \qquad \text{(Equation 3)}$$

where

K = 0.15 for 11-15 percent passing #200 sieve
0.18 for 6-10 percent passing #200 sieve
0.2 for 5 percent or less passing #200 sieve

a = Percent* of mineral aggregate retained on #8 sieve

b = Percent* of mineral aggregate passing #8 and retained on #200 sieve

C = Percent* of mineral aggregate passing #200 sieve

F = 0 to 2.0 percent. Based on absorption of the aggregate. The 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 to 1.0 should cover most conditions.

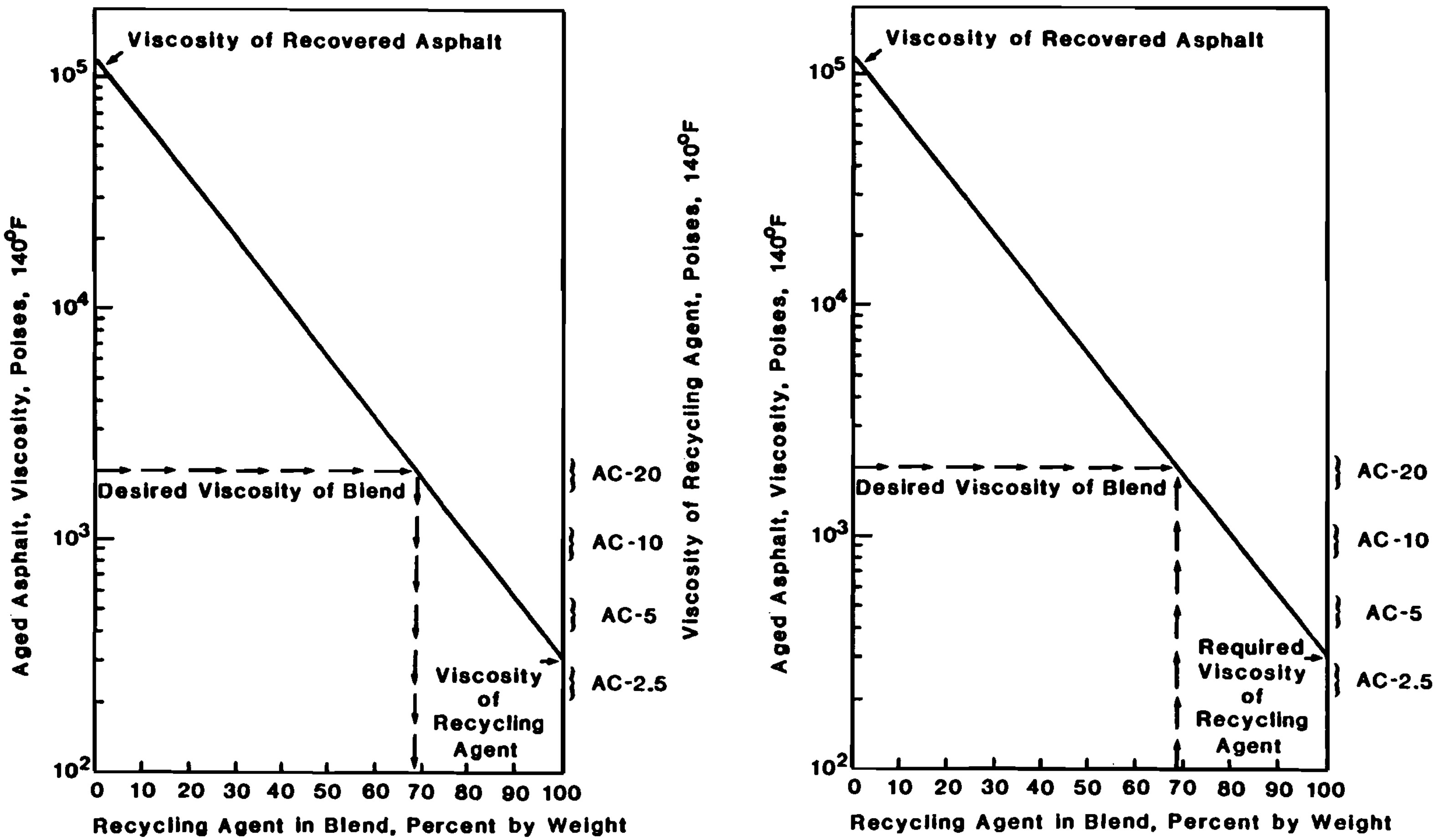
R = 1.0 for asphalt cement; 0.6 to 0.65 for asphalt emulsions

Nomographs may also be used to determine the type or amount of agent required to lower the viscosity of the aged asphalt. Figure 4a shows the use of a nomograph (Ref 15) to estimate the amount of a given recycling agent required to be blended with the salvaged asphalt to achieve a desired viscosity of the blend. The nomograph can also be used to select the type of recycling agent (viscosity) given the viscosity of the salvaged asphalt, the desired viscosity of the blend, and the amount of recycling to be used (Fig 4b).

Any of the above procedures can be used to estimate percent recycling agent but should be considered only as a starting point for mixture design

---

* Expressed as a whole number.




a. Use of Nomograph to determine required amount of recycling agent or soft agent

b. Use of a Nomograph to determine required viscosity of recycling agent or soft asphalt.

Fig 4. (Ref 15)

purposes. The final determination should be based on actual testing of proposed blends.

The recycling agent should be blended with the recovered asphalt and subject to viscosity and penetration tests to determine if the desired viscosity has been achieved. Figures 5 and 6 show the relationships between viscosity and penetration of blended asphalt and percent softening agent. As is evident from these figures, a desired consistency can be achieved with differing amounts of different softening agents. Factors to be considered are cost of each recycling agent and mixing requirements. Mixing efficiency will generally increase as the percent recycling agent is increased, since the agent will act as a fluxing agent in mixing process.

Steps involved in the final determination of the type and amount of recycling agents are summarized below:

1. Extract and recover asphalt from the salvaged mixture (Tex-211-F*).
2. Mix the recovered asphalt with the selected types and amounts of additives. Generally increments of 0.5 percent additive are adequate.
3. Measure the viscosity or penetration of the treated asphalt cement (Tex-528-C or Tex-502-C, respectively*).
4. Plot the relationship between the amount of additive and the viscosity or penetration (Figs 5 and 6).
5. Determine which additives or combinations of additives will produce the desired consistency in the salvaged asphalt cement, i.e., penetration or viscosity in the desired range.
6. Select those acceptable additives or combinations of additives that warrant preparation of laboratory mixtures for further evaluation. Factors to be considered in this selection are costs, availability, construction considerations, past reliability and experience, etc.

It should also be noted that the above procedures assume that there will be complete mixing and blending of the old asphalt and recycling agent. Based on Texas experience and the experience of others, it is doubtful that all of the old asphalt will actually become part of the binder in the recycled mixture. In addition, complete blending of the old asphalt and recycling agent may not occur.

---

* These test methods are for the Texas State Department of Highways and Public Transportation (Ref 16).

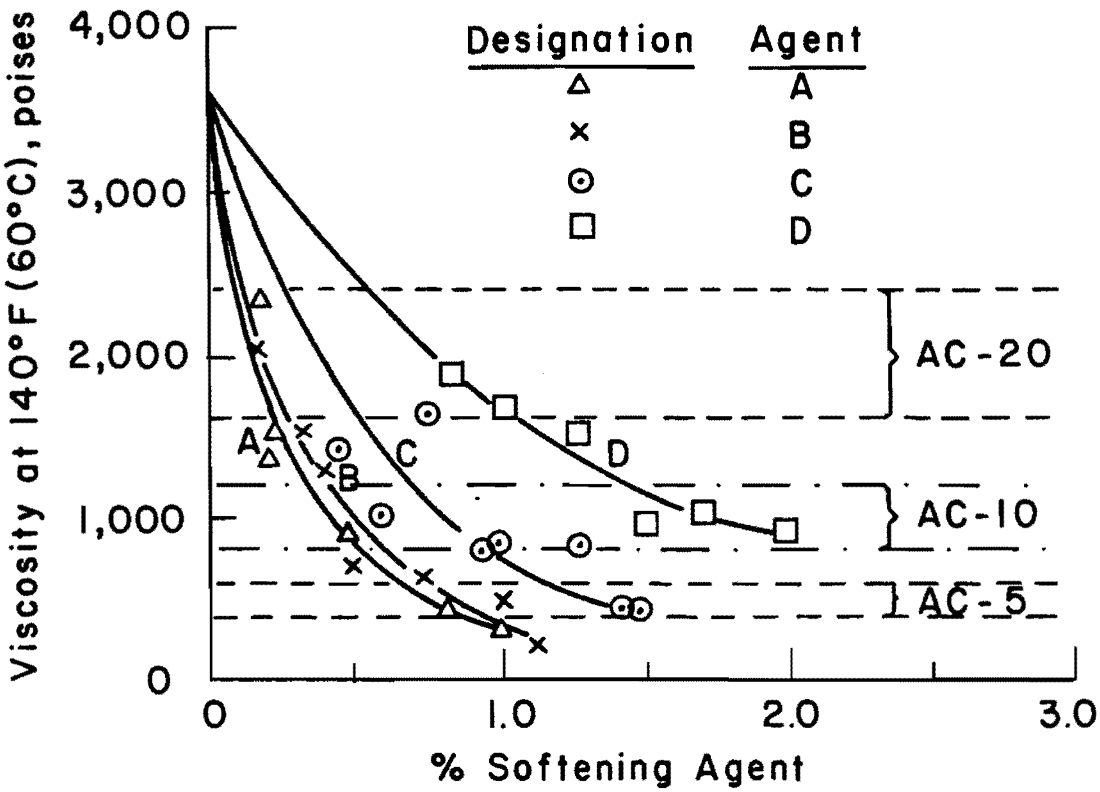



Fig 5. Typical relationships between viscosity at 140°F and percent softening agent for recovered brittle asphalt cement and four softening agents.

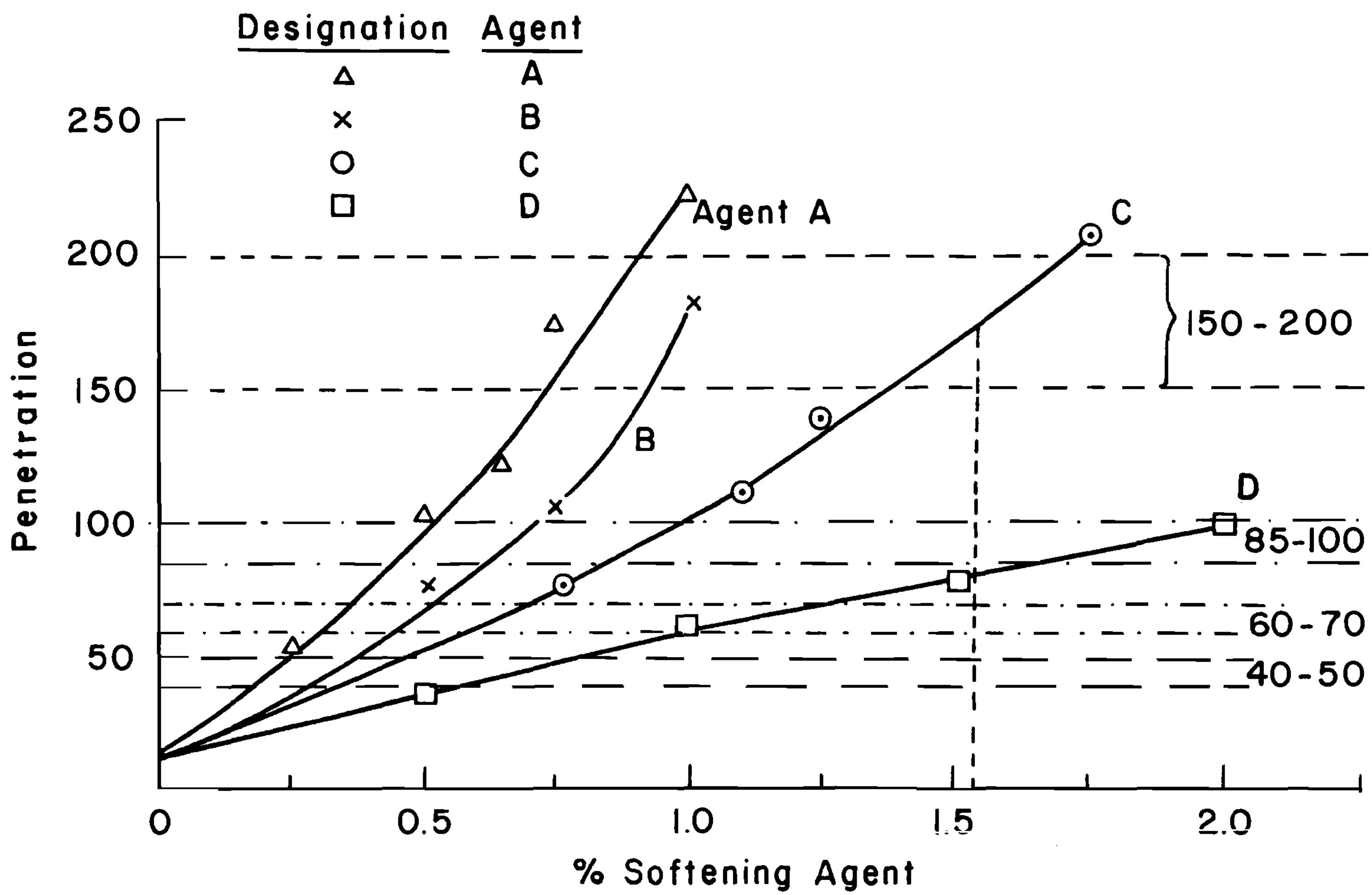



Fig 6. Typical relationships between penetration and percent softening agent for recovered brittle asphalt cement and four softening agents.

To assure compatibility of the recycling agent with the salvaged asphalt, thin film oven test can be performed on the selected blend of recycling agent and recovered asphalt. A ratio of aged viscosity to original viscosity of less than 3 indicates that the recycling agent is probably compatible with the salvaged asphalt (Ref 9).

## Antistripping Additives

If it is determined that the action of moisture on the salvaged material has resulted in premature failure, the use of an antistripping additive should be considered. Hydrated lime and commercially available chemical antistripping additives can be used. When specifying one of these additives, tests should be performed to evaluate their effectiveness when combined with the salvaged material. Since hydrated lime and chemical antistripping additives may not be effective in all mixtures, it is mandatory that any proposed antistripping additives be tested with the recycled mixture, new aggregate, and preferably the new asphalt cement to be used o ascertain their effectiveness. Possible test methods are:

1. boiling test, and
2. static and repeated-load indirect tensile tests, with and without moisture conditioning.

The departmental test methods are the boiling test (Test Method Tex-530-C) and indirect tensile test with Lottman conditioning (Test Method Tex-531-C) and are contained in Ref 16. Slightly different versions are contained in Refs 17 and 18. In addition, other tests may be developed or adopted in the future.

## New Aggregate

According to Epps and Holmgreen (Ref 8), new aggregate may have to be added to the mixture for one or more of the following reasons:

1. to satisfy gradation requirements,
2. to satisfy new surface course skid resistance requirements,
3. to meet air quality regulations associated with hot central plant recycling,
4. to meet total pavement thickness requirements,
5. to improve the properties of the mixture, such as stability, durability, flexibility, etc., and

6. to allow addition of enough modifier to restore the salvaged asphalt to meet specification requirements while maintaining required mixture properties.

Gradation requirements for recycled mixtures should be designed to produce a dense, stable mixture similar to the grading curves shown in Figures 1 and 2 or one of those in ASTM D 3515.

To provide initial and long-lasting skid resistance for the recycled bituminous surface course, it may be necessary to blend coarse, nonpolishing aggregate with the salvaged material. Moderate to high-traffic-volume facilities often require about 40 percent by volume of the plus No. 4 material be nonpolishing to provide adequate skid resistance.

To meet air quality regulations associated with most hot mix asphalt plants, 30 to 40 percent by volume new aggregate is required. However, this requirement may gradually be reduced as equipment manufacturers and contractors improve the hot recycling operation.

The salvaged material may represent only a portion of a thicker structural section required to meet predicted traffic demand. If so, and if a hot central plant is to be used, the new aggregate can be blended with the recycled pavement to meet the requirements or the engineer may elect to add layers of virgin asphalt-stabilized materials.

In addition to these reasons for adding new aggregate to the salvaged mixture, it is recommended that not more than 50 percent salvaged material be used since the mixture is more forgiving at lower percentages of recycled material and less sensitive to variations in amount and viscosity of the asphalt and gradation of the aggregates of the salvaged material.

## FINAL DESIGN

The final design involves determination of engineering properties of the recycled mixture.

The addition of recycling agents to salvaged materials will not only change the viscosity of the aged asphalt, but will also affect the engineering properties of the recycled mixture. Typical relationships between percent recycling agent and Hveem stability is shown in Figure 7 for selected agents. Relationships such as this should be established for each proposed recycling agent. Other properties, such as tensile strength and resilient and static modulus of elasticity, can be used for mixture design provided

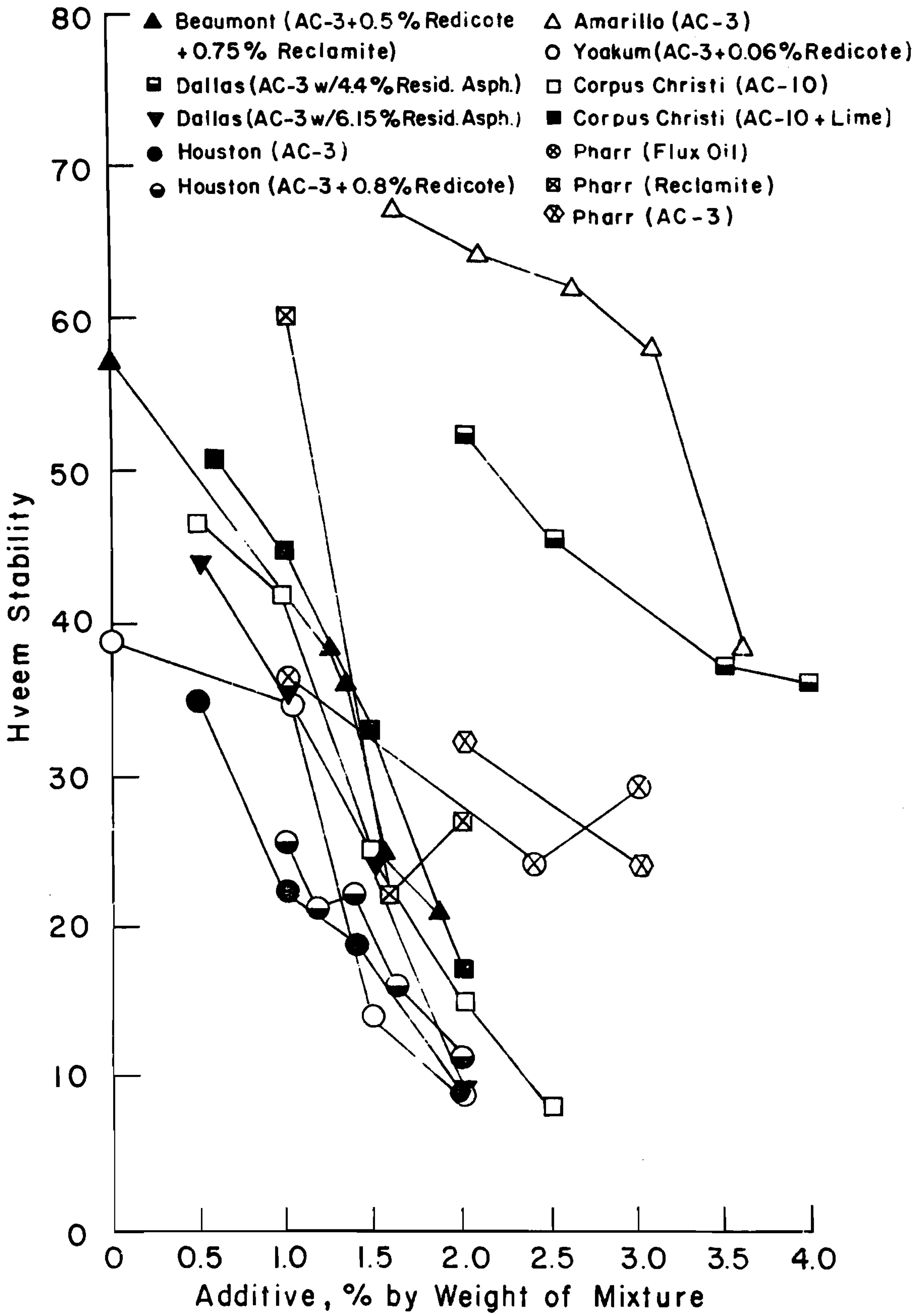



Fig 7. Effects of the amount of additive on Hveem stability of brittle and nonbrittle recycled mixtures.

that similar relationships are developed for these properties. Example relationships are shown in Figures 8 through 10. The resulting values should then be compared to standard or specified values which are representative of those required for conventional asphalt mixtures. Most specifications require minimum values of strength. For recycled asphalt mixtures, the test values on the existing pavement material normally should be specified as a range including a maximum value since the asphalt in the recycled mixture is often extremely stiff and brittle and thus quite strong.

## Required Testing

Minimum testing involves the standard test procedures currently used by the department for the design of asphalt mixtures. The design steps are as follows:

1. Prepare duplicate specimens of mixtures containing the approximate amount of selected additives based on weight of recovered asphalt, aggregate, or mixture as determined in the preliminary design and various percentages of new asphalt or other additives. The aggregate gradation, including the salvaged aggregate plus virgin aggregate, should have a gradation curve similar to that shown in Figure 1.
2. Test the prepared specimens according to the Standard Tests used by the Texas State Department if Highways and Public Transportation
   a. for blackbase--unconfined compression (Tex-126-E) and
   b. for asphalt concrete--stabilometer (Tex-208-F).
3. Compare the results from Step 2 with those required in the current specifications for conventional mixtures (Ref 16). For the Texas State Department of Highways and Public Transportation, these values for blackbases are:
   a. for the best base material, unconfined compressive strength not less than
      -- 50 psi at the slow loading rate of 0.15 in./min. and
      -- 100 psi at the fast rate of 10 in./min. and
   b. for the poorest acceptable base material, unconfined compressive strength not less than
      -- 30 psi at the slow loading rate of 0.15 in./min. and
      -- 100 psi at the fast rate of 10 in./min. and

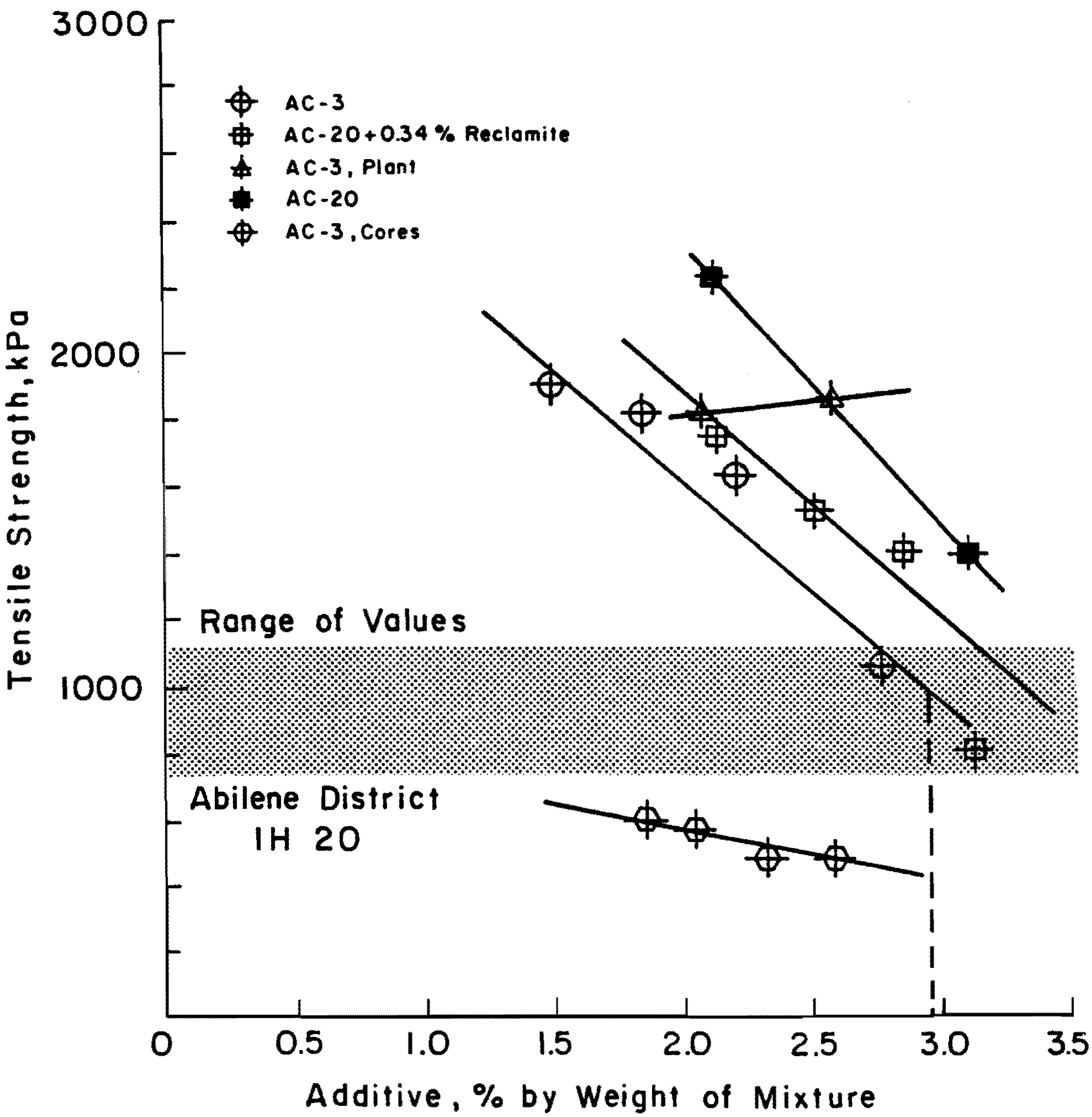



Fig 8. Determination of percent additive from a selected range of tensile strength values.

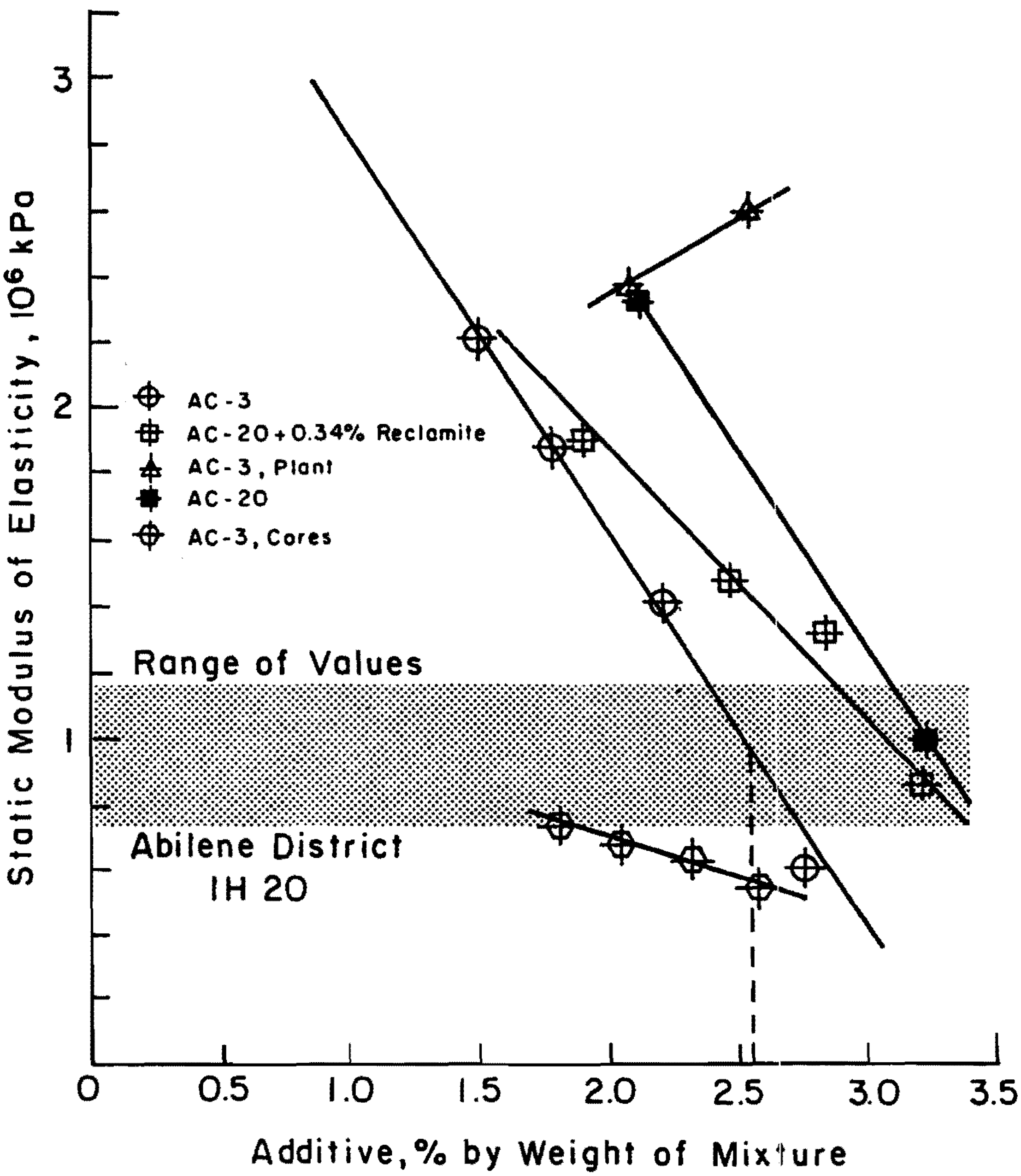



Fig 9. Determination of percent additive from a selected range of static modulus of elasticity values.

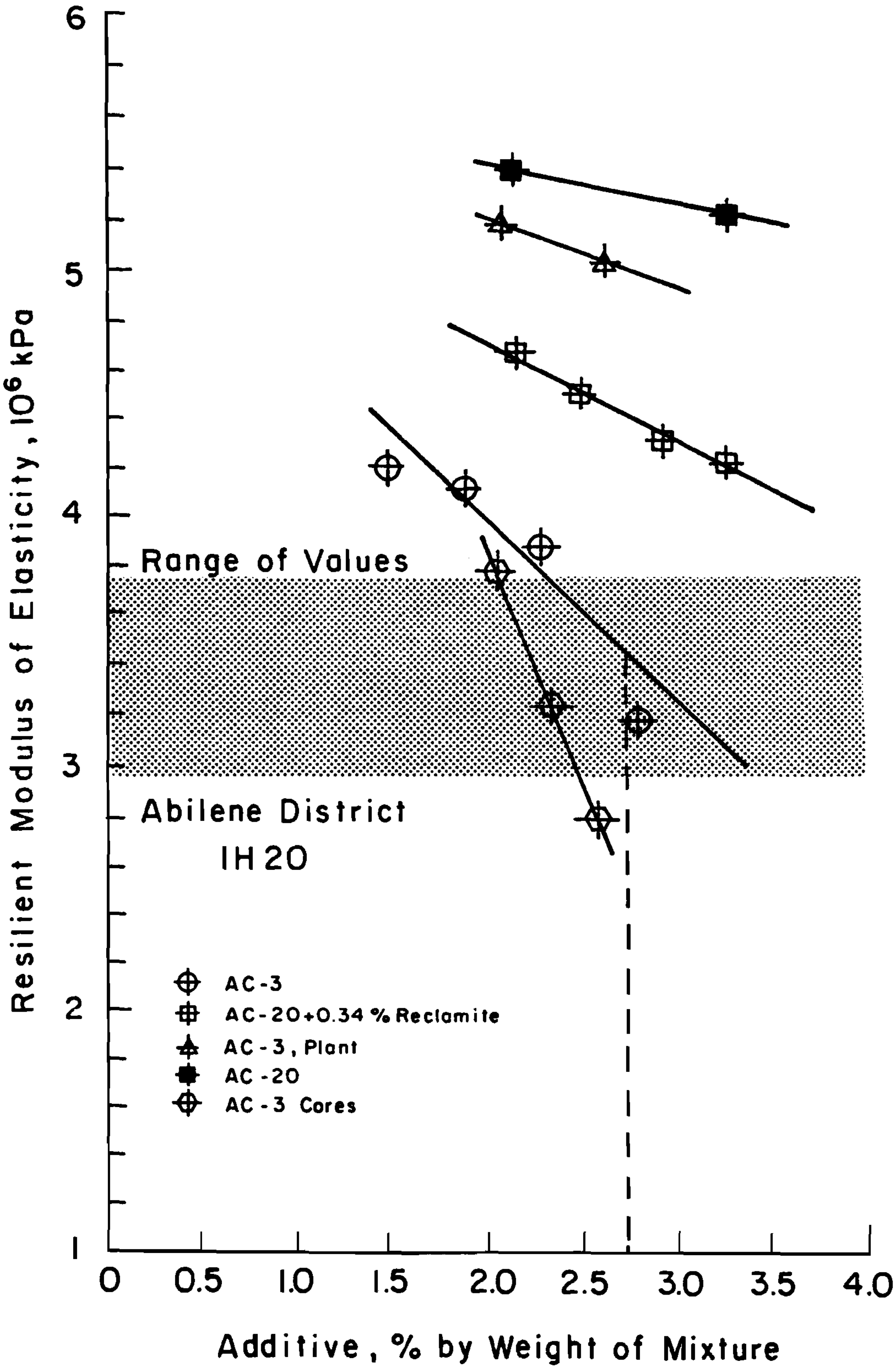



Fig 10. Determination of percent additive from a selected range of resilient modulus of elasticity values.

for asphalt concrete for all mixtures, Hveem stability not less than 35. However, recent experience with premature pavement failures from low stabilities indicates that the stability value probably should be at least 40 for facilities handling high volumes of heavy trucks.

4. Determine the resistance of the recycled mixture to adverse environmental moisture conditions as previously discussed. The boiling test (Text Method Tex-530-C) and static indirect tensile test (Test Method Tex-531-C) procedures or other tests which are developed or adopted in the future may be used.
5. Evaluate the workability of the mixture by visual inspection and make necessary adjustments in the amount of virgin aggregate and additives to be included in the recycled mixture. However, extreme care should be exercised to prevent workability requirements from adjusting gradations and binder content to the point that unstable mixes are produced.

Optional Test

It is recommended that the department begin to use the static and repeated-load indirect tensile test (Ref 18) in mixture design in order to evaluate those fundamental engineering properties directly related to fatigue, thermal cracking, and permanent deformation or rutting. Optional design testing is as follows:

1. Test the prepared specimens using the static and repeated-load indirect tensile tests. Tentative test procedures for the static test are contained in Refs 18 and 19.
2. Compare the results from Step 1 with those obtained for conventional mixtures. Properties recommended for consideration are tensile strength, static modulus of elasticity, and resilient modulus of elasticity. In addition, it may be desirable to consider fatigue life; however, fatigue tests are time consuming and expensive.

   The relationships between the above properties and the amount of additive should be developed by testing recycled mixtures prepared at various additive contents and plotting the results in the manner shown in Figures 8 through 10. The resulting values should then be compared to desired values. While a great deal of information is available for the United States and Texas, it has not been adequately analyzed and summarized with respect to performance. Thus, there is currently a limited amount of data to use to establish these desired values. Most specifications require minimum values for strength, etc. For recycled asphalt mixtures, the test values for the existing pavement material normally should be specified as a range including a maximum value since the asphalt in the salvaged mixture is often extremely stiff and brittle.

Tentative recommended values for indirect tensile tests, based on the results from previous studies (Ref 21, 22 and 23), have been used to evaluate the tensile strength, static modulus of elasticity, an resilient modulus of elasticity of both laboratory prepared and inservice asphalt mixtures (Table 6). Since these recommended values are from materials which have performed satisfactorily in the field, they represent a guide to the level of engineering properties that should provide satisfactory service for recycled mixtures, even though additional theoretical and experimental work is needed to define the range of values required.

It is recommended that desirable values of engineering properties be determined for the particular location and function of the proposed recycled material.

An example of the use of the desired range of material properties to select the percent additive is shown in Figures 8 through 10. Specimens are prepared and tested at various additive contents and the results plotted as in Figures 8 through 10. At the point where the relationship intersects the middle of the acceptable range of properties, the optimum percent additive for that property is obtained. For example, in Figures 8, 9, and 10, these percent additives are shown for each combination of asphalt or asphalt and additive. The individual optimums for the AC-3 are 2.9, 2.6, and 2.7 for tensile strength, static modulus, and resilient modulus of elasticity, respectively. Neither the AC-20 nor the AC-20 plus 0.34 percent Reclamite reduces the resilient modulus to the desirable range while maintaining the tensile strength and static modulus in the desired range.

TABLE 6. Indirect Tensile Test Design Values

| Property at 77°F | Design Value, psi |
| --- | --- |
| Tensile strength | 75 - 200 |
| Static modulus of elasticity | $0.10 - 0.50 \times 10^6$ |
| Resilient modulus of elasticity | $0.25 - 1.00 \times 10^6$ |

# CHAPTER 5. RECOMMENDATIONS AND SUMMARY

## RECOMMENDATIONS

Based on the experience gained in the design of asphalt mixtures containing salvaged materials and the construction of pavements containing recycled materials, the following recommendations were developed to insure satisfactory mixtures and pavement performance.

1. Determine the cause of distress or characteristics of the salvaged material. Any inadequacy of the salvaged material must be corrected.
2. The structural design and cross section of the pavement must be adequate for the loading and environmental conditions or failure will occur.
3. An adequate sampling plan must be developed to determine the characteristics and variations of the salvaged material.
4. The salvaged asphalt in combination with new asphalt should provide a blend with a viscosity or penetration equal to that commonly used in conventional asphalt mixtures.
5. The gradation of the salvaged aggregate plus new aggregate should be similar to the gradations shown in Figures 1 and 2. However, since these gradations could result in minimal void space in the aggregate or asphalt, the voids in the mineral aggregate should be calculated to insure a satisfactory void level. If the VMA is too low, the gradation should be modified.
6. If a moisture susceptible salvaged mixture is to be recycled, the moisture susceptibility should be corrected. If antistripping additives are employed, the resulting mixtures should be tested to insure the effectiveness of the additive.
7. The engineering properties of the recycled mixtures should satisfy the specifications and standards required of conventional asphalt mixtures.
8. The mixtures should be compacted to a density of 92 to 97 percent of the Rice theoretical maximum density.

9. No more than 50 percent salvaged material should be utilized in the recycled mixture. Generally low percentages are recommended and probably should not exceed about 25 percent.
10. The department should adopt a statewide policy allowing the use of recycled asphalt mixtures, if cost effective.
11. A statewide policy should be adopted allowing the contractor to retain all salvaged material for use in the same project or other projects. Such a policy will maximize the cost effectiveness of recycling.

## SUMMARY

Hot mixed recycled mixture is a viable option to the construction of highways and streets. The final decision to recycle should be based on life cost analysis. At this time it is felt that mixtures and pavements containing salvaged material should be equivalent to conventional asphalt mixtures and pavements. Thus, the life cycle cost will be primarily dependent on the first cost bid price.

Bid process can be significantly reduced by allowing the contractor to retain salvaged material and utilizing it on the same project or other projects providing that a satisfactory mixture can be obtained.

All recycled asphalt mixtures should satisfy the same standards and specifications required of conventional asphalt mixtures.

This report provides guidelines to insure quality insurance of recycled asphalt mixtures and contains a design procedure which should result in satisfactory recycled asphalt mixtures.

## REFERENCES


1. Perez, I., T. W. Kennedy, and A. S. Adedimila, "Evaluation of the Engineering Properties of Recycled Asphalt Mixtures," Research Report 183-10, Center for Highway Research, The University of Texas at Austin, November 1978.

2. Kennedy, T. W., and I. Perez, "Preliminary Mixture Design Procedure for Recycled Asphalt Materials," Special Technical Publication 662, American Society for Testing Materials Symposium on Recycling of Bituminous Pavements, St. Louis, Missouri, December 1977.

3. Kennedy, T. W., R. C. G. Haas, and A. S. Adedimila, "Characteristics of Recycled Asphalt Materials for Mixture Design," Proceedings: The Third Conference on Asphalt Pavements for Southern Africa, Durban, South Africa, 1979.

4. Kennedy, T. W., F. L. Roberts, and J. N. Anagnos, "Mixture Design Procedures for Recyled Asphalt Pavements," Research Report 252-1, Center for Transportation Research, The University of Texas at Austin, August 1981.

5. Finn, F. N., and J. A. Epps, "Pavement Failure Analysis with Guidelines for Rehabilitation of Flexible Pavements," Research Report 214-17, Texas Transportation Institute, Texas A&M University, College Station, Texas, August 1980.

6. Goode, J. F., and L. A. Lufsey, "A New Graphical Chart for Evaluating Aggregate Gradation," Proceedings, Association of Asphalt Paving Technologists, Vol 31, pp. 176-207, 1962.

7. Lytton, R. L., and C. H. Machalak, "Flexible Pavement Deflections Equation Using Elastic Moduli and Field Measurements," Research Report 207-7F, Texas Transportation Institute, Texas A&M University, College Station, Texas, August 1979.

8. Epps, J. A., and R. J. Holmgreen, "Design of Recycled Asphalt Concrete Mixtures," Research Report 214-2, Texas Transportation Institute, Texas A&M University, College Station, Texas, August 1980.

9. Epps, J. A., "State-of-the-Art Cold Recycling," Transportation Research Board Report 780, pp. 68-100, 1980.

10. Kari, W. J., et al., "Prototype Specification for Recycling Agents Used in Hot-Mix Recycling," Proceedings, Association of Asphalt Paving Technologists, Vol 49, pp. 177-198, 1980.

11. Escobar, S. J., and D. D. Davidson, "Role of Recycling Agents in the Restoration of Aged Asphalt Cements," Proceedings, Association of Asphalt Paving Technologists, Vol 48, pp. 375-402, 1979.

12. Kari, W. J., L. E. Santucci, and L. D. Coyne, "Hot Mix Recycling of Asphalt Pavements," Proceedings, Association of Asphalt Paving Technologists, Vol 48, pp. 192-220, 1979.

13. Canessa, W., "Rejuvenating Materials," Conference on Recycling of Asphalt Pavements, Ann Arbor, Michigan, 1980.

14. "Asphalt Cold-Mix Recycling," The Asphalt Institute, MS-21, March 1983.

15. "Asphalt Hot-Mix Recycling," The Asphalt Institute, MS-20, August 1981.

16. Manual of Testing Procedures, Texas State Department of Highways and Public Transportation, Vols 1 and 2.

17. Kennedy, T. W., F. L. Roberts, and J. N. Anagnos, "Texas Boiling Test for Evaluating Moisture Susceptibility of Asphalt Mixtures," Research Report 253-5, Center for Transportation Research, Bureau of Engineering Research, The University of Texas at Austin, January 1984.

18. Kennedy, T. W., and J. N. Anagnos, "Wet-Dry Indirect Tensile Test for Evaluating Moisture-Susceptibility of Asphalt Mixtures," Research Report 253-8, Center for Transportation Research, Bureau of Engineering Research, The University of Texas at Austin, November 1984.

19. Standard Method, "Indirect Tension Test for Resilient Modulus of Bituminous Mixtures," ASTM Designation: D4123-82, Annual Book of ASTM Standards, Part 15, April 1982.

20. "Mix Design Methods for Asphalt Concrete," The Asphalt Institute, MS-2, March 1979.

21. Adedimila, A. S., and T. W. Kennedy, "Fatigue and Resilient Characteristics of Asphalt Mixtures by Repeated-Load Indirect Tensile Test," Research Report 183-5, Center for Highway Research, The University of Texas at Austin, August 1975.

22. Navarro, D., and T. W. Kennedy, "Fatigue and Repeated-Load Elastic Characteristics of Inservice Asphalt-Treated Materials," Research Report 183-2, Center for Highway Research, The University of Texas at Austin, January 1975.

23. Rodriguez, M., and T. W. Kennedy, "The Resilient and Fatigue Characteristics of Asphalt Mixtures Processed by the Dryer-Drum Mixer," Research Report 183-8, Center for Highway Research, The University of Texas at Austin, January 1977.