(2)

AD-A242 104

ESL-TR-88-29

MODIFIERS FOR ASPHALT CONCRETE

A. ABDULSHAFI, K. E. KALOUSH

RESOURCE INTERNATIONAL, INC.
281 ENTERPRISE DRIVE
WESTERVILLE OH 43081

NOVEMBER 1990

FINAL REPORT

SEPTEMBER 1987 - APRIL 1988

APPROVED FOR PUBLIC RELEASE: DISTRIBUTION UNLIMITED

91-14416

AFESC

AIR FORCE ENGINEERING & SERVICES CENTER
ENGINEERING & SERVICES LABORATORY
TYNDALL AIR FORCE BASE, FLORIDA 32403

91 10 29 016

NOTICE

PLEASE DO NOT REQUEST COPIES OF THIS REPORT FROM HQ AFESC/RD (ENGINEERING AND SERVICES LABORATORY). ADDITIONAL COPIES MAY BE PURCHASED FROM:

NATIONAL TECHNICAL INFORMATION SERVICE
5285 PORT ROYAL ROAD
SPRINGFIELD, VIRGINIA 22161

FEDERAL GOVERNMENT AGENCIES AND THEIR CONTRACTORS REGISTERED WITH DEFENSE TECHNICAL INFORMATION CENTER SHOULD DIRECT REQUESTS FOR COPIES OF THIS REPORT TO:

DEFENSE TECHNICAL INFORMATION CENTER
CAMERON STATION
ALEXANDRIA, VIRGINIA 22314

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1a. REPORT SECURITY CLASSIFICATION: UNCLASSIFIED	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT: APPROVED FOR PUBLIC RELEASE DISTRIBUTION UNLIMITED
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S)	5. MONITORING ORGANIZATION REPORT NUMBER(S): ESL-TR-88-29
6a. NAME OF PERFORMING ORGANIZATION: RESOURCE INTERNATIONAL, INC. 6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION: HEADQUARTERS AIR FORCE ENGINEERING AND SERVICES CENTER
6c. ADDRESS (City, State, and ZIP Code): 281 ENTERPRISE DRIVE WESTERVILLE, OHIO 43081	7b. ADDRESS (City, State, and ZIP Code): HQ AFESC/RDCP TYNDALL AIR FORCE BASE FLORIDA 32403-6001
8a. NAME OF FUNDING/SPONSORING ORGANIZATION 8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER: CONTRACT #F08635-87-C-0368
8c. ADDRESS (City, State, and ZIP Code)	10. SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO	PROJECT NO	TASK NO	WORK UNIT ACCESSION NO.
65502F	3005	0024	N/A

11. TITLE (Include Security Classification)

MODIFIERS FOR ASPHALT CONCRETE

12. PERSONAL AUTHOR(S)

Abdulshafi, Abdulshafi A; Kaloush, Kamil E.

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
FINAL	FROM Sep 87 TO Apr 88	NOVEMBER 1990	

16. SUPPLEMENTARY NOTATION

AVAILABILITY OF THIS REPORT IS SPECIFIED ON REVERSE OF FRONT COVER

17. COSATI CODES

FIELD	GROUP	SUB-GROUP
13	02	
11	07	

18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)

ASPHALT, ASPHALT CONCRETE, FLEXIBLE PAVEMENT, RUTTING, ASPHALT MODIFIERS, RUBBERS, PLASTICS, CIVIL ENGINEERING

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

In this study, six different types of modifiers belonging to the polymer, elastomer and filler groups were selected and analyzed. The modifiers were used to develop a screening criteria that are able to distinguish among the modified asphalt concrete mixture performance. The screening criteria contained two major items (1) compatibility and aging, set to ensure that the modifiers are compatible with asphalt cement (AC); (2) potential candidacy of the modified AC mixture to minimize rutting and fatigue cracking distress. In addition, a cost prohibition factor to exclude modifiers with ineffective life-cycle cost was also considered.

Testing methods including Marshall criteria, compressive strength, modulus of resilience and indirect tensile strength were conducted on the modified AC mixtures. Test results could not clearly differentiate between the modified mixtures. Two additional and new testing methods were used: (1) the C*- line integral method to measure the potential for cracking, and (2) the modified compression creep-rutting method to measure the potential for rutting. Test results using these two methods were promising and better able to distinguish the performance of the modified AC mixture as related to cracking and rutting pavement problems.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT: ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION: UNCLASSIFIED
22a. NAME OF RESPONSIBLE INDIVIDUAL: MS PATRICIA SUGGS	22b. TELEPHONE (Include Area Code): (904) 283-6317 — 22c. OFFICE SYMBOL: HQ AFESC/RDCP

DD Form 1473, JUN 86 — Previous editions are obsolete — SECURITY CLASSIFICATION OF THIS PAGE

UNCLASSIFIED

(The reverse of this page is blank)

EXECUTIVE SUMMARY

This study addresses two problems. First, it addresses the evaluation of currently available modifiers for asphalt concrete that can limit distress caused by high-pressure tires and thrust vectoring on airfield pavements. Second, it discusses the development of innovative testing techniques that could be considered for screening and evaluation of potential material candidates.

Modifiers were classified by type in six groups, namely, polymer, elastomer, fiber, filler, chemical, and others. The literature and manufacturers' information indicated that modifiers belonging to the polymer, elastomer and filler groups were the most promising to solve rutting and cracking distress of asphalt concrete. Six modifiers belonging to these three groups were selected to develop a screening criteria that can distinguish among the modified asphalt concrete mixtures performance. The screening criteria contained two major items: (1) compatibility and aging, set to ensure that the modifiers are compatible with the asphalt cement (AC); (2) potential candidacy of the modified AC mixtures to minimize rutting and fatigue cracking distress.

Testing methods including Marshall criteria, compressive strength, modulus of resilience, and indirect tensile strength were conducted on the modified AC mixtures. However, the test results could not clearly differentiate between the modified mixtures. Two additional and new testing methods were used: (1) the C^* line integral method to measure the potential for cracking, and (2) the modified compression creep-rutting method to measure the potential for rutting. Test results using these two methods were promising and were able to distinguish and predict the performance of the different modified AC mixtures. Both methods have good potential application for future screening of modified asphalt concrete mixtures, since they relate directly to performance and require simple testing procedures using standard testing equipment.

(the reverse of this page is blank)

PREFACE

This report was prepared by Resource International, Inc., 281 Enterprise Drive, Westerville, Ohio 43081, under contract F08635-87-C-0368, Small Business Innovative Research AF87-067, Phase I, for the Air Force Engineering and Services Center, Engineering and Services Laboratory, Tyndall Air Force Base, Florida 32403. This report was submitted as part of the SBIR program and has been published according to SBIR directives in the format in which it was submitted.

This report summarizes work performed between September 1987 and April 1988. Mrs. Patricia C. Suggs was the AFESC/RDCP Project Engineer.

This report has been reviewed by the Public Affairs Office (PA) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nationals.

This report has been reviewed and is approved for publication.

Patricia C. Suggs
PATRICIA C. SUGGS
Project Engineer

Felix T. Uhlik III
FELIX T. UHLIK III, Lt Col, USAF
Chief, Engineering Research Division

Charles W. Manzione
CHARLES W. MANZIONE, Capt, USAF
Chief, Air Base Operating Surfaces Branch

FRANK P. GALLAGHER III, Col, USAF, BSC
Director, Engineering and Services Laboratory

(the reverse of this page is blank)

TABLE OF CONTENTS

TABLE OF CONTENTS
(Concluded)

LIST OF FIGURES

LIST OF TABLES

SECTION I

INTRODUCTION

A. OBJECTIVES

The specific objectives of this research study of modifiers for asphalt concrete are:

1. To investigate the validity and effectiveness of new technological materials in limiting distress due to high-pressure tires and thrust vectoring on airfield pavements.

2. To design a laboratory experimentation program to support comparative analyses for potential material candidates. Innovative testing techniques could be considered for screening and evaluation purposes.

B. BACKGROUND

Current and future trends toward increased tire pressure and thrust vectoring on airfield pavements are dictated by several factors. The main two factors are: (1) geometrical requirements for short takeoff and landing (STOL), and (2) change in loading conditions as associated with the state-of-the-art development of Air Force aircraft design, operation, and maneuver techniques. Several types of distress and premature failures have become evident on the airfield pavements. Excessive tire pressure and loading result in rutting, raveling, and fatigue cracking while the increased tractions result in slippage (or shear) and transverse cracking. The ultimate result is reduced service life, increased maintenance and rehabilitation (M&R) costs, and obstruction to the timely operational needs of the airfield facility.

The problem is not related to structural design as much as it is to mixture design. For instance, increasing the top asphaltic layer thickness may solve the fatigue cracking problem; however, it will also enhance the potential for development of rutting. The solution lies fundamentally in improving the behavior of the asphaltic mixture under the loading and environmental conditions cited previously. The literature indicates that asphalt cement (AC) mixtures will not provide adequate performance under conditions of increased tire pressure and surface shear loading unless additives and/or admixtures are used. Otherwise, an alternative binder should be used. The search for a new binder or even modification of the AC mixtures will pose a mixture design problem. Marshall design criteria that can assure adequate performance of AC mixtures may not be valid with the modified mix. The set of quality control and assurance limits will need to be revised. New, innovative testing methods, commensurate with the new materials and technological developments, need to be incorporated in the mixture design method as well as the quality control program during construction.

Through new technology and material innovations, a wide variety of additives, admixtures, and alternative binders have been introduced to the marketplace with potential solutions for the material-performance requirements. However, research on these new products, as well as feedback on limited field trials, have not been completed. There is a need to investigate the short-term and long-term characteristics of the modified mix, in addition to consideration of other factors, such as compatibility with the asphalt cement. Moreover, traditional testing might not be sufficient to compare the engineering behavior of the new material system; appropriate innovative testing techniques must also be introduced. Results of the laboratory investigation of the new material system may require changes in the current specification and quality control program.

Several questions must be answered by the asphalt additives study; the most important are:

1. What are the currently available asphalt modifiers used to minimize rutting and fatigue cracking of flexible pavement? Could those modifiers be grouped by functionality?

2. What are the most effective means to compare these modifiers quantitatively, considering both engineering and economic factors?

3. Given a project with selected modifier, what is the quality control testing scheme to be used during construction?

The Phase I investigation of this study is geared toward answering Question 1 and part of Question 2. The study proposed for Phase II will enable answering Question 3 and consider the cost-effectiveness of Question 2. It will also result in the development of guideline specifications as well as a total computerized system for generating an optimal set of solutions to aid the decision maker on cost-effective uses of modifiers. Figure 1 illustrates the two phases within the conceptual framework of this study.

C. SCOPE

To meet the objectives, the following scope of work is identified for this research study:

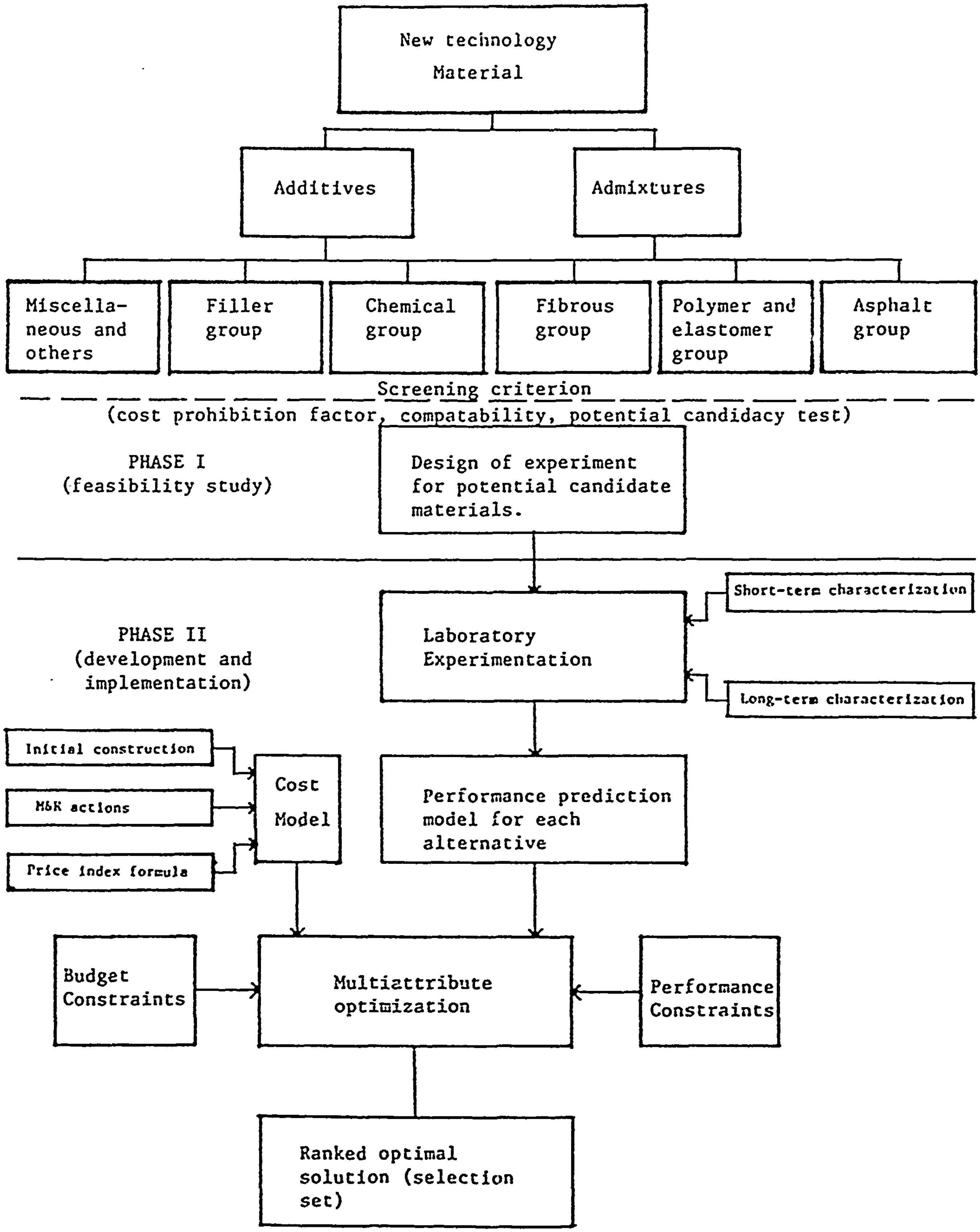

Figure 1. Conceptual Framework of Research Approach.

1. Investigate the mode of failures in asphaltic mixtures due to high-pressure tires and thrust vectoring.

2. Interrelate the above modes of failure to fundamental material system properties and establish testing program parameters.

3. Conduct a literature search on new materials' characteristics and a market survey on those materials with potential for the above specific application.

4. Conduct an initial testing program on selected products to comprehend Item 3.

5. Screen the materials for selection of potential candidates using economical measures and laboratory testing results criteria.

6. Prepare and submit a report on the findings of the above study.

This study addresses two distinct problems. First, it addresses the engineering evaluation of new, innovative materials that can limit distress severity and extent caused by high-pressure tires and thrust vectoring. Second, it discusses the development of a selection criterion, given different modifiers' solution alternatives and their effectiveness, cost, and performance.

The first problem is approached through stochastic modeling techniques, conducting a balanced experimental design and utilizing innovative testing methods (e.g., comboviscoplasticity testing, C*-line integral) as "screening windows" for the new material/mixture systems. The potential candidates are then further evaluated by conducting a comprehensive laboratory/field testing program accounting for both short-term and long-term performance characteristics. The potential candidates must meet the screening criteria of the group to which they belong. Laboratory-simulated modes of failure should include rutting, fatigue, and thermal cracking, as well as freeze-thaw durability testing. The interrelation of these modes of distresses to material properties is the key factor in the diagnosis/solution process of the problem. All the above modes of distress relate directly to the shear stress/strength characteristics of the asphaltic material system in which cohesion and internal friction of the asphalt concrete mixtures and/or the AC binder are the material system parameters to be investigated. Additives are used to modify or alter specific asphalt cement physical and/or chemical characteristics, while admixtures do the same, but for asphalt concrete mixtures.

The second problem is approached by utilizing a mathematical programming system such as optimization. In this system, a life-cycle cost model is developed to include initial construction costs (including material, production, and modifications to operation), expected maintenance and rehabilitation actions and their costs, salvage value, and service life (determined from laboratory/field test data). A multiattribute objective function will be formulated to minimize costs, subject to controlled budget and target performance standard. The idea is to be able to quickly and efficiently assess the impacts of varying scenarios of budget and performance constraints on the resulting selection process and associated costs.

SECTION II

TECHNICAL LITERATURE REVIEW

A. TYPES OF MODIFIERS AND THEIR FUNCTIONS

Currently, over 300 different modifiers are commercially available; each one is supposed to improve one or more of the fundamental properties of asphalts, yet more new modifiers are being introduced to the market. One objective of the Phase I study is to categorize these modifiers into groups with common characteristics. Laboratory testing requires identification of those modifiers that can solve rutting and cracking problems of asphaltic mixtures.

The major types of asphalt modifiers could be categorized as follows:

1. Polymer (or plastics) group
2. Rubber (or elastomers) group
3. Fibers group
4. Fillers group
5. Chemical group
6. Miscellaneous and others.

The following is a brief technical discussion of the above six groups with greater emphasis on groups (1) and (2) since these groups appear to have significant potential for solving cracking and rutting problems.

1. Polymers (or Plastic) Group

Polymer additives are generally thought of as "plastic" or vinyl-type compounds in comparison to elastomer additives that are thought of as "rubbery" type material. However, the major elemental component for both is the same; differences exist as to whether the material is derived from raw material containing rubber, whether certain substances are used (e.g., copolymers), the type of processing method used, and, finally, its contribution to the asphalt cement blend properties. Because the term "polymer" is generic, its use in the literature is confusing. Therefore, an introduction to polymers and the ways of categorizing them is presented here.

Polymers (from the Greek: poly + meros, many parts) are large molecules created by joining together many small molecules.

The simple compounds from which polymers are made are called monomers (mono = one). Polymerization processes occur by two mechanisms, namely the "addition" and "condensation" processes. "Addition" polymers are produced by covalently joining the individual molecules, producing very long chains. "Condensation" polymers are produced when two or more types of molecules are joined by a chemical reaction that releases a byproduct (such as water). Linear polymers are long chains; network polymers are three-dimensional structures. Both linear and network polymers could be produced by either the addition or the condensation process. Polymers are also categorized by behavior into thermoplastic, thermosetting, and elastomers. Thermoplastic includes linear polymers that behave in a plastic manner at elevated temperatures but, by the nature of their bonding, allow reversible behavior. Thermosetting applies to network polymers formed by a condensation process; the nature of their bonding does not allow reversible behavior because the byproduct molecules are released. Elastomers are polymers of intermediate behavior; their most important ability is to absorb enormous amounts of elastic deformation. For this research study the term, polymer, will include thermoplastics and thermosetting materials, while the term, rubber, will include only elastomers derived from vulcanized* rubber (Reference 1).

The general mechanism for blend improvement is that polymers create a lattice within the asphalt cement by combining small molecules into larger ones (Reference 2). The larger molecule lattice is more stable under high and low temperature and thus resists thermally induced cracking in the winter season and permanent deformation or "rutting" in the summer season. Several thermoplastic polymers such as styrene block copolymers, ethylene-vinyl-acetate, and polyethylene are available commercially (see Appendix A), as well as thermosetting polymers such as polychloroprene (neoprene compound), ethylene-propylene diene rubber (synthetic rubber), styrene-butadiene latex, and polyisoprene (natural rubber), which fall in the category of elastomers.

2. Rubber (Elastomer) Group

This material has been used in two primary applications: (1) rubberized asphalt, to modify the properties of asphalt cement (AC), and (2) asphalt rubber, to substantially change the characteristics of the AC (References 3,4,5,6,7,8, 9,10). The normal range of rubber in rubberized asphalt is 3 to 5 percent by weight of AC added in the form of powder, latex, or

---

*Vulcanization is the formation of sulfur bridges between different chains (sulfur + heat). These cross-links make the rubber harder and stronger, and do away with the tackiness of untreated rubber.

latex emulsions. The normal range of percentages of rubber in asphalt rubber is 15 to 25 percent added mainly in the form of powder or crumbs. Rubber is basically of three types: natural, synthetic, or reclaimed. Natural rubber is generally obtained from the sap of several tropical plants (Reference 11) and is supplied in two major forms: liquid latex and powdered or crumb rubber. Synthetic rubber is produced from various types of materials including butyl, styrene-butadiene, and neoprene; it is generally supplied in powder or latex form (Reference 12). Reclaimed rubber is usually ground-up scrap rubber and tire rubber, which is generally vulcanized. Generally, devulcanized scrap rubber is used to produce modifiers for rubberized asphalt, while tire rubber (vulcanized) is used to produce modifiers for asphalt rubber. Devulcanization is a process which alters the material characteristics with heat, pressure, or softening agents. Reclaimed rubber comes from used automobile and truck tires. The rubber in the car tires is usually synthetic rubber; however, truck tires are normally manufactured using a blend of synthetic and natural rubber (References 13,14).

Balanced against the economic costs associated with the use of rubber the following benefits are claimed (References 15,16,17,18,19) for the asphalt cement:

a. Increased softening point

b. Increased toughness

c. Increased elastic recovery

d. Increased ductility

e. Increased retention of aggregates (in surface treatments)

f. Improved low temperature flexibility

g. Improved durability

h. High resistance to compaction under traffic

i. Decreased bleeding tendency

j. Decreased temperature susceptibility.

The following benefits apply to the mechanical/rheological behavior of asphalts:

a. Improved mixture workability

b. Improved sheer susceptibility

c. Improved temperature susceptibility; lower than normal asphalt

d. Improved ultimate responses: tensile strains, high fracture resistance, high elasticity, low rutting.

Factors that affect the rubber-improved-asphalt cement properties include the type and amount of reclaimed rubber, the nature and source of asphalt, temperature and time of heating, amount and time of blending, etc.

3. Fibers Group

Although the use of fibers in other engineering materials has been exploited, not much attention has been given to the use of filamentary fibrous reinforcement in bituminous mixtures. Fibrous materials in filamentary form usually have high tensile strength-to-weight ratios and high tensile stiffness modulus-to-weight ratios, as compared to bituminous mixtures. As the filament diameter decreases, the probability of flaws within the material also decreases. The high ultimate tensile strength of fibers can be useful, if properly harnessed, in increasing the resistance of paving mixtures to cracking. Also, the presence of such high tensile strength reinforcement may increase the amount of strain energy that can be absorbed during the fatigue and fracture process of the mixture. This is the rationale behind employing high-strength fibers in the bituminous mixtures (Reference 20).

Several authors have noted the advantages that can be obtained from fiber reinforcement of plastic and elastic materials. Glass fibers that exhibit elastic behavior up to failure have been used widely in the reinforcement of both types of materials.

When the matrix to be reinforced is plastic and the filamentary fibrous reinforcement is elastic, the balance of forces in the composite can be used to determine the critical length of fiber. For discontinuous fibers randomly distributed in the matrix, fiber reinforcement is most effective when the fiber axis is aligned parallel to the applied tensile stress (Reference 21).

The above theory has been established experimentally for metallic continuous matrices reinforced with metallic or glass fibers. However, it may be only approximately correct for bituminous mixtures, where the particulate character and granular nature of the material is well-recognized.

Earlier work on fiber reinforcement of bituminous mixtures has concluded that:

(1) The resistance of mixtures containing short chrysotile fibers to deflection is significantly greater under concentrated loads than for uniform loading, suggesting improvement of the resistance of mixtures to shear stresses.

(2) For 3 percent fiber addition, the mixtures only retained approximately half of their dynamic load stiffness.

(3) Fiber-reinforced mixtures showed considerably higher flexibility under static loading (than under dynamic loading), as compared to unreinforced mixtures.

a. Polypropylene Fibers

Research results by Majidzadeh et al., (Reference 20) using polypropylene fibers, have indicated that the addition of 0.2 to 0.6 percent of fibers resulted in a high stiffness modulus while increasing the asphalt content.

The addition of fibers increases both the fatigue life of the pavement under load and the amount of asphalt cement required to achieve maximum stability. Mixtures containing 0.2 to 0.6 percent fiber exhibited about the same maximum Marshall stabilities as conventional mixtures but the maximum stability occurred at a higher asphalt content.

b. Polyester Fibers

Research results by Majidzadeh et al., (Reference 20) using polyester fibers, have indicated that the addition of 0.2 to 0.6 percent of fibers resulted in a decrease in Marshall stability of the asphalt-aggregate mixture. This agrees with published research (Reference 22).

The addition of fibers increases the amount of asphalt cement required to achieve maximum stability. Mixtures containing 0.2 to 0.6 percent fibers exhibit about the same maximum Marshall stabilities as conventional mixes; however, the maximum stability occurs at a higher asphalt content.

Slightly higher stabilities and lower flows were obtained with mixtures containing washed fibers as compared to unwashed fibers. However, field tests have shown that washed fibers will cling together, causing difficulties in mixing. Consequently, they are no longer considered for use in asphalt concrete application. The research results also indicate that increasing the fiber content above 0.2 percent decreases the mixture strength. However, tensile strain at failure is shown to increase substantially with increased fiber content when tested at 0.002 inch per minute. This is likely caused by additional asphalt in these high fiber content mixtures. The results of fatigue tests on various polyester fiber mixes, as reported by the Resource International Laboratory, (Reference 20) indicates substantial fatigue life improvement at 0.3 and 0.6 percent fiber content.

c. Steel Fibers

The literature indicates limited experience with the use of steel fibers in asphalt concrete mixtures. Like the polyester and polypropylene fibers, the steel fiber is introduced to the asphalt paving mixture at the pugmill. The resulting asphalt pavement is claimed to display a longer fatigue life, increased resistance to rutting, and resistance to thermally induced reflective cracking.

4. Fillers

The literature indicates that there are two main functions of using fillers in asphalt concrete, namely, to control the voids content and/or to control the asphalt cement oxidation. A typical product for the first type is mineral fillers, some of which are totally inert while others impart limited bonding characteristics. Sulfur, lime, and portland cements are typical examples of these materials that act as fillers, while at the same time introducing limited bonding. Most other siliceous materials passing Number 200 sieve size are examples of the inert mineral filler materials.

Fillers that control oxidation are generally 90 percent or more carbon. A typical example is carbon black, consisting of 97 percent pure carbon diluted in flux oil and pressed to form pellets (References 2,23). Recent developments indicate that carbon black can also be emulsified and pumped, thus eliminating the handling problems. Among other claimed benefits of carbon black are increased moisture resistance, abrasion, and decreased temperature susceptibility.

5. Chemicals

The literature provides a wealth of research regarding the use of chemical additives in bituminous mixtures. Those are metal complexes including antistripping agents, Chemkrete®, antioxidants, and antidegradant (References 2,23,24). Antidegradant additives are not currently used in the asphalt industry but have a wide application in the polymer industry as aging inhibitors. Among the antidegradants' group are diarylamine derivatives, thioesters, phosphites, etc. The antioxidant additives are not used in the asphalt industry because of production problems and/or the use of hazardous material (such as lead) in its manufacturing.

Chemkrete® is an asphalt-soluble complex mix of manganese and organic acid. The recommended dose of addition is 2.0 to 5.0 percent by weight, resulting in an increase in viscosity and rapid controlled hardening. Claimed benefits include increased strength and stiffness, decreased temperature susceptibility, and improved resistance to rutting and cracking. However, field experience with Chemkrete® reveals that the cracking associated with this product limits its present use despite the advantages of controlled oxidation and lower cost (Reference 24).

Two classes of chemical additives for use as antistrip agents are available: (1) asphalt-activated chemicals and (2) aggregate-activated chemicals. The main effect is to increase the aggregate's asphalt bond. The first class consists of a nonpolar hydrocarbon chain with a polar end (usually an amine) that is added in (1.2 to 1 percent) by weight of asphalt. The reduced surface tension of the asphalt improves the bond with the aggregates, while the polar end is attracted to the aggregate. The second class consists of a heavy metal soap which, when dissolved in water and applied to the aggregates, results in deposition of metal cations on its surface and improves the resistance to stripping. A typical example of this class is BA-2000®, a water-activated metallo-amine complex, produced by Carstab Corporation. The second class is not as widely used as the first one.

6. Others

A variety of other modifiers to asphalt cement or asphalt concrete currently exist in the marketplace either on an experimental basis or to solve special problems. It is difficult to encounter every one of these additives, or even those belonging to the above-cited groups, because the industry is rapidly growing and introducing new products and materials with claimed superior properties. However, in the following sections some of these products are mentioned for information purposes, namely, sulfur, Sulphlex®, fly ash, and antistrip agents. The general mechanisms are described below.

Sulfur reacts with the asphalt cement to produce two different competitive reactions: dehydrogenation and introduction of the sulfur into the molecules. At its melting point, sulfur polymerizes into long radical chains that may either extract hydrogen from the hydrocarbons or react to give a carbon-sulfur bond. In effect, the added sulfur may link or remain unreacted as a colloidal solution. Asphalt, upon reaction with sulfur, may become harder and more brittle or softer and more ductile depending mainly on the temperature, i.e., whether or not sulfur enters the molecule. Rheological properties of asphaltic mixtures using sulfur indicate that the addition of a sufficient amount of molten elemental sulfur to hot asphaltic mixes increases their fluidity and compatibility (References 25,26). When the mix cools, the sulfur solidifies in the void spaces between the asphalt-coated aggregate particles in the exact configuration of the voids. Thus, sulfur performs as a conforming filler particle and serves to interlock the aggregate particles, imparting a high degree of mechanical stability to the mix (Reference 27).

Sulphlex® is a trade name for a manufactured material composed of approximately 70 percent by weight elemental sulfur and 30 percent by weight of a blend of three plasticizers or chemical modifiers: 8 percent vinyltoluene, 12 percent dicyclopentadiene, and 10 percent dipentene (Reference 28). Sulphlex® binders are designated as follows: -233 is a flexible asphalt-like binder; -230 is similar to -233, except that it rapidly develops rigidity as Portland cement concrete; and -126 is designated in between grades.

Sulphlex®-233, although composed mainly of sulfur, dissolves 68 percent in trichloroethylene compared to sulfur-extended asphalt (SEA), which has a solubility of about 1.6 percent. Limited research testing indicates that asphalt and Sulphlex®-233 are miscible in all proportions, implying a practical importance of partial substitution. Sulphlex®-233 mixtures are extremely susceptible to water damage except when antistripping agents (such as tall oil pitch) are added (which improves stability as well). Hydrated lime has a contraindicated effect because of its apparent reaction with the Sulphlex®. Other properties of unconfined compressive strength and modulus of resilience indicate harder mixtures below 140° F, as compared to those of AC-20. A critical factor in the Sulphlex® analysis is the simulated aging in the Thin Film Oven Test (TFOT), which indicates a loss of weight of about 3 percent and penetration of about 70 percent; no Sulphlex® recovery procedure exists at present for better evaluation.

Future development of Sulphlex® formulations intended as substitutes for asphalt will focus on the development of softer binders that will produce mixtures with lower stiffness values. Such binders should improve the fatigue and thermal cracking properties of Sulphlex® concrete.

Fly ash, antistrip agents, cement, and lime have all been used as additives to minimize stripping problems. The fly ash and antistrip agents have, however, proven to be cost effective as well (References 29,30). Fly ash improves resistance to stripping from the presence of available calcium in its mineralogical makeup and also from the fact that it increases the density of the mixture by functioning as a filler. Other types of byproduct materials, such as lime kiln dust and clear plant residue (residue from a pilot copper extraction process), have proven equally effective in enhancing stripping resistance of asphaltic mixtures. In fact, limited laboratory field studies indicated that a designed combination of the above with cement and lime performed in a satisfactory manner.

The addition of up to 6 percent by weight of asphalt improved the index of retained strength and increased the density; however, the results varied, depending upon asphalt aggregates' properties as influenced by their sources and types, the calcium oxide content of the fly ash, and the permeability of the mixture. Several other filler-additives are used, such as bottom ash, lignite coal fly ash, limestone dust filler, etc.

7. Commercial Products of the Groups

Appendix A contains a comprehensive list of commercially available modifiers and lists their manufacturer, description, use, and status. However, it is impossible to list each and every modifier available in the marketplace because the technological development of these materials occurs very rapidly. Information on commercial modifiers in each of the six groups was collected in the investigation in Phase I.

B. SPECIFICATION REQUIREMENT AND SCREENING OF ASPHALT MODIFIERS

1. Introduction

The previous section discussed briefly the mechanisms and functions of the modifiers as related to the behavior of asphaltic mixtures. However, two questions must be answered:

(1) Given specific requirements of an asphaltic mixture to be achieved, which modifiers would be most suitable?

(2) Among the suitable ones, which one will give, relatively, the best results with regard to strength and performance?

To answer these questions, an initial feasibility study based on engineering economic factors is to be conducted. One of the main objectives of the feasibility study is to develop an acceptance/rejection screening criterion. This should be followed by establishing an engineering model (discriminating function) that accounts for both short-term and long-term behavior (performance) of the different mixtures. Engineering characterization is receiving a lot of attention at present due to the emergence and introduction of new concepts and technology in the pavement industry. Earlier methods of discriminating between asphaltic mixture behavior were based on short-term behavior such as Marshall criteria, resilient modulus, dynamic modulus, etc. Those parameters reflect the strength or the stiffness and do not necessarily indicate the material toughness, performance, and/or durability. Many researchers are currently investigating long-term behavior (fatigue and rutting). There are two major areas of difficulty with regard to long-term behavior. First, no documented mathematical models exist that can accurately describe field performance or even laboratory simulated test performance.

Rutting and fatigue are major field problems. Rutting has been extensively studied at the empirical and phenomenological levels (References 20,25,31), with no attempt to characterize the asphalt mix as other than linear elastic or viscoelastic. Accumulations of permanent deformation were calculated using elastic and viscous deformation laws. Thus, it is not surprising that poor correlations with actual field performance still exist; however, these correlations could be improved if the appropriate constitutive law is utilized.

Advances in the fields of material characterization and fracture mechanics necessitated more research investigations in the area of flexible pavement structure failures, particularly the development of constitutive relationships that better replicate material responses such as viscoelasticity and viscoplasticity (i.e., viscous elastic-plastic elements combined in a configuration) both with and without yield surfaces. Viscoelastic characterization of asphaltic materials has been investigated (References 32,33), and computer programs that input the creep compliance or relaxation modulus have been implemented (Reference 34). Viscoplasticity with yield surface as a constitutive relationship has been developed in the field of solid mechanics and has recently been applied to soils (References 35,36).

It was not until recently that a sophisticated distress model for rutting was developed for asphaltic mixtures using constitutive laws derived from continuum mechanics (Reference 37). In the next section, an innovative method to deal with rutting, based upon this recent development, is described. Furthermore, another two models have been developed to describe the fatigue behavior of asphaltic mixtures, the first by A. Abdulshafi and K. Majidzadeh using the path-independent contour J-integral (Reference 38) and the second by O. Abdulshafi and Majidzadeh using the time-dependent C*-line integral (Reference 39). Both models utilize the recent development in fracture mechanics to deal with time-independent (e.g., elastic, elastoplastic, plastic) and time-dependent (e.g., viscoelastic) material behavior. The fracture mechanics parameters J and C* have advantages in modeling fatigue over the phenomenological distress functions that are discussed in various sections of this report. Refinement, application, and validation of the above models are in the state-of-the art timeframe.

The second problem area is that the inclusion of performance in the engineering model will require laboratory experimentation that consumes an appreciable amount of time before any result is seen. If these tests are also required for quality control, then these models will be handicapped by the fact that no assurance of meeting their requirements can be forced in the field. This is the typical problem that caused the rationalization for the use of short-term parameters as quality control indicators for materials/construction as well as performance.

However, because the laboratory determination of the J- or C*-integral is as simple as Marshall stability with the added advantage of indicating the fatigue potential, then it is logical to include it as a performance parameter in the quality control program. In fact, the power of using the C*-line integral to differentiate between different sulfur-asphalt mixtures and optimize the percentage of sulfur in the mix has been indicated in the literature (Reference 27). Similarly, a parameter that indicates the potential of mixtures to exhibit rutting should be developed and incorporated in the quality control scheme. Research in that direction is warranted and is expected to develop a breakthrough in this problem area.

2. Building Block of Screening Criteria

A variety of commercial modifiers exist that can solve the problems of rutting, cracking, and raveling caused by increased tire pressure and thrust loading. These modifiers belong to different additive/admixture category types as cited above. There is a need then to develop a rational "screening window or criteria" to either accept or reject these additives. The screening criteria cover three areas of concern, namely, (1) compatibility and aging, set to ensure that the modifier is compatible with the asphalt cement at the initial mixing as well as after aging; (2) potential candidacy, set to ensure that the modified asphalt concrete mixture will perform in the field to meet the objectives of minimizing rutting and fatigue cracking distress; and (3) potential for being cost prohibitive, set to exclude modifiers with ineffective life-cycle cost. The first two areas cover the required engineering characteristics of the modified asphalt concrete (AC) mix and are dealt with in this report, while the third area covers the cost factors and its relation to performance; this area is one of the main focuses of consideration of the Phase II study. In the Phase I study, a cost limit was set based upon the literature review and the researchers' experience. The cost limit was that the selected modifier should not increase the cost of the in-place asphalt concrete mixture by more than 25 percent.

A brief description on the compatibility and aging functions as well as the potential candidacy functions is given next.

a. Compatibility and Aging Functions

Asphalt cement is the cementing agent component in the asphaltic mixture. It is a highly complex organic hydrocarbon material (Reference 40). The most significant fractional oils of petroleum crude (asphalt cement) are asphaltenes and maltenes (Reference 41). Asphaltene is the bodying agent. Maltenes consist of nitrogen bases (N), first acidaffins (A_1), second acidaffins (A_2), and paraffins (P). Asphaltenes (A), due to their high surface activity, absorb a covering sheath of nitrogen bases as a stabilizer (peptizer) as well as the acidaffins acting as a solubilizing agent for the peptized asphaltene. These peptized, solubilized asphaltenes are termed "micelles." The nature and quantity of the absorbed sheath govern the degree of peptization of the asphaltene. When asphaltenes are well-peptized, with sufficient oil (paraffin) content in the asphalt, the dispersion of the micelles is good and the material behaves like a true solution with the Newtonian flow characteristics of a colloidal sol (Reference 42). If asphalt has a high asphaltene content, relative to the nitrogen bases and acidaffins, then the state of peptization is poor, the micelles are not well-dispersed in the oil phase, and the material will have the rheological character of a non-Newtonian gel (Reference 42). In the second case, a linkage or structure compound develops and a viscoelastic mechanical behavior is pronounced in which the elastic effect is attributed to the link structure. Although the sol and gel colloidal states are the limits of a behavior spectrum, true asphalts (intermediate sol-gel structure) behave in either a Newtonian or non-Newtonian manner, depending on the shear rate and temperature conditions.

It has been demonstrated (References 41,43) that asphalt is well-defined by the characteristics of the five primary fractional components: A, N, A_1, A_2, and P, where the groups are well-distinguished and each contributes to a specific behavior of the asphalt cement.

To quantify the effects of these components, two parameters were proposed:

(1) The composition parameter $(N+A_1)/(P+A_2)$, the ratio of more reactive to less reactive fractional components. This parameter has been shown to govern the durability of asphalts as measured by the tendency to harden (embrittle) during aging. The limits are:

$$\text{To control syneresis} \rightarrow 0.4 \le \frac{N + A_1}{P + A_2} \le 1.2 \leftarrow \text{To control durability (pellet abrasion test)}$$

(2) The chemical compatibility parameter, N/P, measures the failure or otherwise of the asphaltene to remain in the homogeneous solution. The limit for these parameters is:

$$\frac{N}{P} \ge 0.5$$

Aging is thought of as a two-part contribution: a physical contribution of losing the oil phase by evaporation, which is measured by a volatilization factor; and a chemical contribution of transformation of the most chemically active component (nitrogen bases and first acidaffins) into asphaltene of low molecular weight. The result is chemical instability reflected by brittle cracking of the pavement. Rheological behavior of the aging process is measured by the change of the asphalt matrix from Newtonian to non-Newtonian characteristics.

Because flash point is related to the amount of volatile material, the flash point test may be used in specification to control volatility. Dunning and Mendenhall (Reference 44) suggest that modifiers should have flash points such that their blends with asphalt equals or exceeds at least 400° F flash point. Hence, they recommend a 392° F Cleveland Open Cup (COC) flash point minimum, which should cause in situ flash points in excess of 400° F Pensky-Martens Closed tester (PMC) when blended with the aged asphalt. This temperature also controls the safety of mixing and handling blend mixtures during processing.

As the asphalt cement ages, the chemical balance changes are mainly in the most reactive components of the maltene phase (N and A_1), where N changes to A and A_1 to N. In fact, the concentration of asphaltene increases because of the components that are instrumental in solvating and dispersing the asphaltene. This results in an asphaltene of increased concentration and polarity dispersed in a maltene of reduced solvent power, thus producing cracking and failure. The specification, however, is concerned with the effect on compatibility and durability. This would affect the two parameters as discussed before: compatibility parameter N/P, which controls syneresis; and composition or reactive parameter $(N + A_1)/(P + A_2)$, which is related to durability. Dunning and Mendenhall (Reference 44) indicated that it is possible to have one asphalt which may oxidize fairly rapidly but does not age because of a relatively low concentration of asphaltenes in a maltene phase of strong solvency power and another asphalt which may oxidize slowly but age rapidly because of a high concentration of asphaltenes dispersed in a maltene phase of weak solvency power. For any given asphaltene composition and concentration, the higher the solubility parameter (the stronger the solvency) of maltenes, the lower the viscosity of the asphalt.

The literature indicates that changes in viscosity and/or penetration could be used as measures for the chemical and physical balance of asphalt cement (or the modified asphalt cement) upon aging. In the area of recycling it has been shown that a reasonable measure of the effect of a modifier on an aged asphalt can be established by observing the change in viscosity and penetration (Reference 25). There is some indication that the viscosity of treated asphalt is a better indicator of the rejuvenating effect than the penetration test (Reference 31).

This idea has been extended to define an aging index as being the viscosity of the modified asphalt cement divided by the viscosity of the referenced asphalt cement, with both aged for the same duration at the same temperature. For modifiers added to the mixture (not preblended with the asphalt cement), the aging index definition is the same except that the test becomes the creep compliance rather than the viscosity. The reason is that creep compliance measures the "mixture" viscosity, which is related to the viscosity of the binder, and represents an indirect measure of blend aging index. Based on the above discussion, the compatibility and aging functions will be measured by:

$$AI = \begin{cases} \left.\dfrac{\mu b}{\mu r}\right|_{TH} & \text{for additives} \\ \\ \left.\dfrac{J_b}{J_r}\right|_{TH} & \text{for admixtures} \end{cases}$$

where:

AI = aging index

μ_b, μ_r = viscosity of AC blends and reference material, respectively

TH = aging of material at temperature T for duration H

J_b = creep compliance at long duration for the modified AC mixtures

J_r = Creep compliance at long duration for the control reference mixture

b. Potential Candidacy Functions

Laboratory and field investigations have shown that the failure of asphaltic mixtures for a given set of loading and environmental conditions could be due to rutting, cracking (fatigue and/or thermal), or a combination of both. In fact, the same material could fail under permanent deformation as easily as under brittle (or ductile) fracture. Failure type will depend upon the prevailing damage mechanisms at the final step of unstable propagation.

(1) The Rutting Problem

Rutting of flexible pavement is defined as the depression in the wheel path of a vehicle caused by one or more of the following mechanisms (Reference 37): densification, viscous flow, and plastic deformation. Some or all of the layers of the flexible pavement contribute to the formation of the surface rut depth. The definition of rutting has been broadened to include various empirical, semiempirical, and stochastic models. However, these procedures fall short of true representation of the pavement response to loading, especially under trends of increased load and pressure tires. Several studies and researchers indicate that the most promising models for rutting are mechanistic. Early mechanistic models have also been developed but they fall short, because accumulation of permanent deformation was calculated, using elastic and, in only one advanced model, viscous deformation laws. A mechanistic model has been developed, accounting for the complete spectrum of material nonlinearity, and has been used to generate rut depth prediction (Reference 45). In this model, a yield surface in stress (or strain) space is hypothesized as a bound to an elastic or viscoelastic region behavior for low stresses, and plastic deformation may commence once stresses reach that surface. Rutting, in this case, is visualized as the accumulation of nonrecoverable viscous deformation for low stress levels and the accumulation of nonrecoverable viscous and plastic deformation for high stress levels. More details about the test method are given in the next section.

(2) The Fatigue Problem

It has been argued that the fatigue life as determined from small laboratory specimens could be misleading in determining the fatigue life of an actual pavement (References

20,46). This is because most of the fatigue life of a small, smooth, unnotched specimen will be consumed in initiating a crack (Reference 20,46). Therefore the final stages of crack propagation and ultimate failure become indistinguishable within the data scatter (References 46,47,48). The question of whether or not these are typical of field observations cannot be directly addressed; however, inconsistent correlations of fatigue life predicted from laboratory testing indicate that more research is yet to be done.

To better simulate the failure conditions or to determine where the importance of fracture toughness lies, one must induce conditions of fracture in the small specimens. Notched specimens must be used to promote early crack growth. A model could then be developed to compare notched and unnotched specimens, and another model could be developed for crack growth.

In the analysis of the unnotched specimens, cyclic plasticity and energy balance should be the tools by which the analysis is effected. On the other hand, the notched specimen should be investigated within the framework of local stress analysis, which will directly introduce the elastoplastic fracture mechanics or alternatively the viscoelastic fracture mechanic approach (Reference 45). Details on the C*-line integral testing are given in the next section.

Based on the above discussion, the potential candidacy functions will be measured by:

- o C*-line integral — To establish the cracking potential
- o CVP-Model — To establish the rutting potential (combo viscoelastic/plastic)

(a) Rutting Potential Parameter

The following development attempts to bridge part of the existing gap in correlation between laboratory and field performance by outlining and discussing the development of a viscoelastic-plastic constitutive relationship to characterize asphalt mixtures and predict rutting.

Rutting, as defined previously, includes the mechanisms of densification, viscous flow, and plastic deformation. If no interaction is assumed between these mechanisms, then the one-dimensional mathematical relationship that describes the permanent deformation will be:

$$\epsilon_p = \epsilon_{po} + c_v(t) + \epsilon_{PL}$$

where:

ϵ_p = permanent total deformation

ϵ_{po} = permanent deformation due to densification; it could be represented by an in-series mechanical relaxing spring with constant $_{po}$

$\epsilon_v(t)$ = time-dependent viscous permanent deformation

ϵ_{PL} = time-independent plastic permanent deformation.

Introduction of the above equation into a permanent deformation phenomenological model such as:

$$\epsilon_{p_{acc}} = N_1 N^{-m}$$

where:

$\epsilon_{p_{acc}}$ = average accumulated permanent deformation

N = number of cycles at measured permanent deformation

m = the slope of log $^{\epsilon}P$ - log N relationship

will result in:

$$\epsilon_p = K_2 (\sigma,t) (\epsilon(t) - K_1 N^{1-m})$$

where:

$$K_2(\sigma,t) = \begin{cases} \dfrac{E'}{E_{po}} + \dfrac{E't}{\eta_2} + \dfrac{E'}{H(W_p)} & \text{if } \sigma > \sigma_{yield},\ t > 0 \\[2ex] \dfrac{E'}{E_{po}} + \dfrac{E'}{\eta_2}\, t & \text{if } \sigma < \sigma_{yield},\ t > 0 \\[2ex] \dfrac{E'}{E_{po}} & \text{if } \sigma < \sigma_{yield},\ t = 0 \end{cases}$$

$$\left\{ \frac{E'}{E_{po}} + n_1^2 \frac{E'}{H(W_p)} \right. \qquad \text{if } \sigma > \sigma_{yield},\ t = 0$$

E' = retarded elastic creep modulus

$$= \frac{1}{\frac{1}{E_2} + \frac{1}{E_1}\left(1 - EXP\left(\frac{-E_1 t}{\eta 1}\right)\right)}$$

This model represents a viscoelastic-plastic model that will lead to a general rutting model with emphasis on a method for distinguishing between the contribution of densification and other permanent deformation mechanisms. This capability to distinguish between densification and shear deformation could enable researchers to identify the unique mechanism pertaining to each additive using K_2 coefficient. However, in this report the method used to investigate the potential for rutting is to examine two parameters: (1) the yield point σ_y, and (2) the creep deformation rate (CR). Both of these parameters are obtained by drawing a curve between the steady-state creep deformation $\dot{\epsilon}_{ss}$ and stress level. At higher stress levels the variation of the creep deformation rate, $\dot{\epsilon}'_{ss}$ (the slope of the line for $\dot{\epsilon}_{ss}$ versus stress levels) is linear. Hence CR will be uniquely defined. The intercept of CR-line with the initial slope on the same graph will define the yield point, σ_y.

(b) The C*-Line Integral

The energy rate interpretation of C* is given as the power difference between two identically loaded bodies having incrementally differing crack lengths by:

$$C^* = \frac{1}{b} \frac{dU^*}{da}\Big|_{\dot{\Delta}}$$

where:

b = thickness of specimen in crack plane

U* = power of energy rate for a load P and displacement rate, $\dot{\Delta}$

a = crack length.

The method of determining the C* parameter experimentally was suggested by Landes and Begley (Reference 49) and is shown schematically in Figure 2. In this method, multiple specimens are subjected to different constant displacement rates. The load (P) per unit crack plane thickness and the crack length (a) are measured as a function of time, as shown in Step 1. This step represents the actual data collected during the test. Because the tests are conducted at a constant displacement rate, time and displacement are the independent variables. Load and crack length are dependent variables. The data in Step 1 are then cross-plotted to yield the load as a function of the displacement rate ($\dot{\Delta}$) (from tests at several displacement rates) for fixed crack lengths, as shown in Step 2. The area under the curve in Step 2 is the rate of work done, U* per unit of crack plane thickness. This is shown plotted against the crack length, as in Step 3. The slope of the curve in Step 3 is C*. Finally, C^* is plotted as a function of the crack growth rate, as shown in Step 4 or the crack length is plotted as a function of C^*, as shown in Step 5. This method of C* determination is called the multiple-specimen method. Adapting this method for use with asphaltic mixtures required the use of the Marshall-type specimen shown in Figure 3 (after Reference 39).

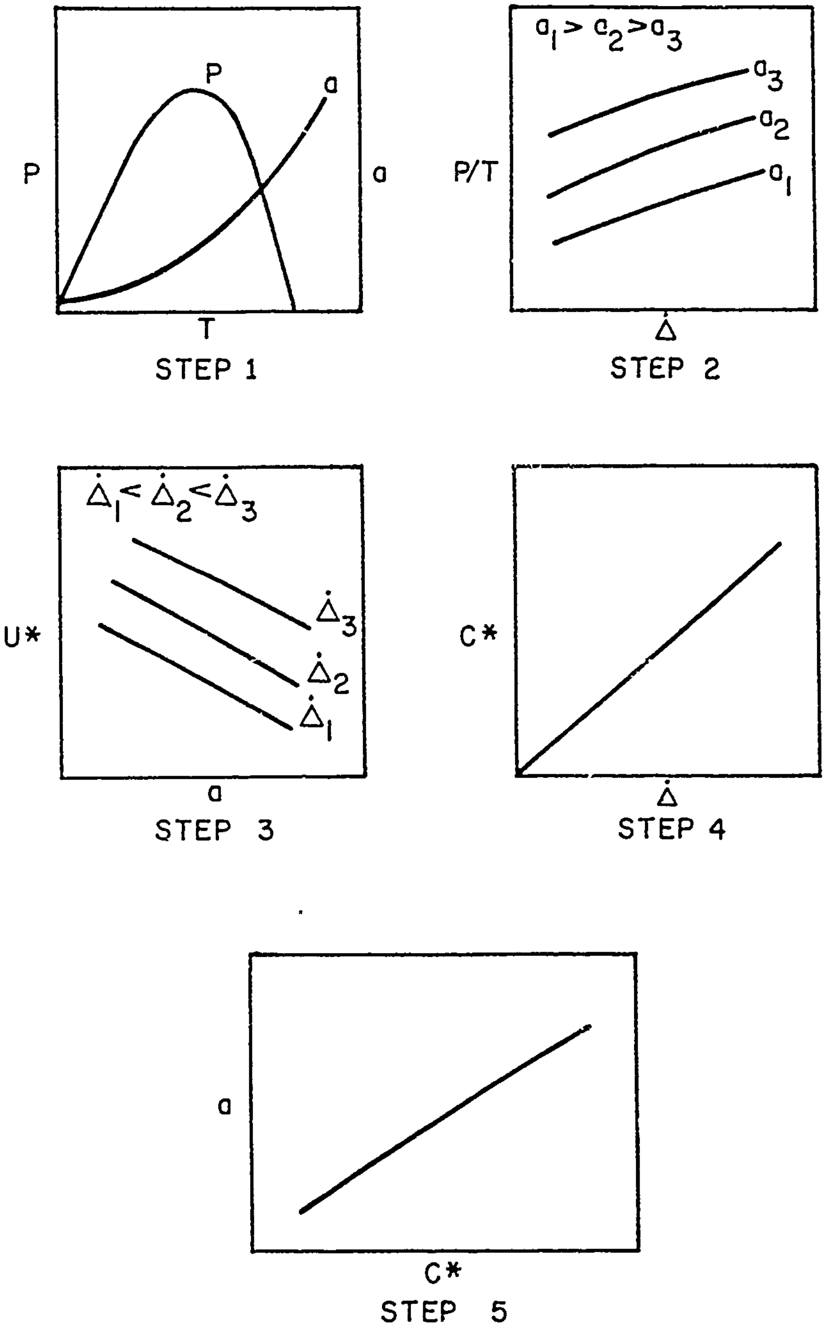

Figure 2. Determining C^* Parameter Schematically.

$$C^* = \frac{1}{b} \frac{du^*}{dc} \Big| \dot{\Delta}$$

b = Sample Thickness

u^* = Power of Energy Rate for a Load p and Displacement Rate

a = Crack Length

$|\dot{\Delta}$: Means with Displacement Rate Held Constant

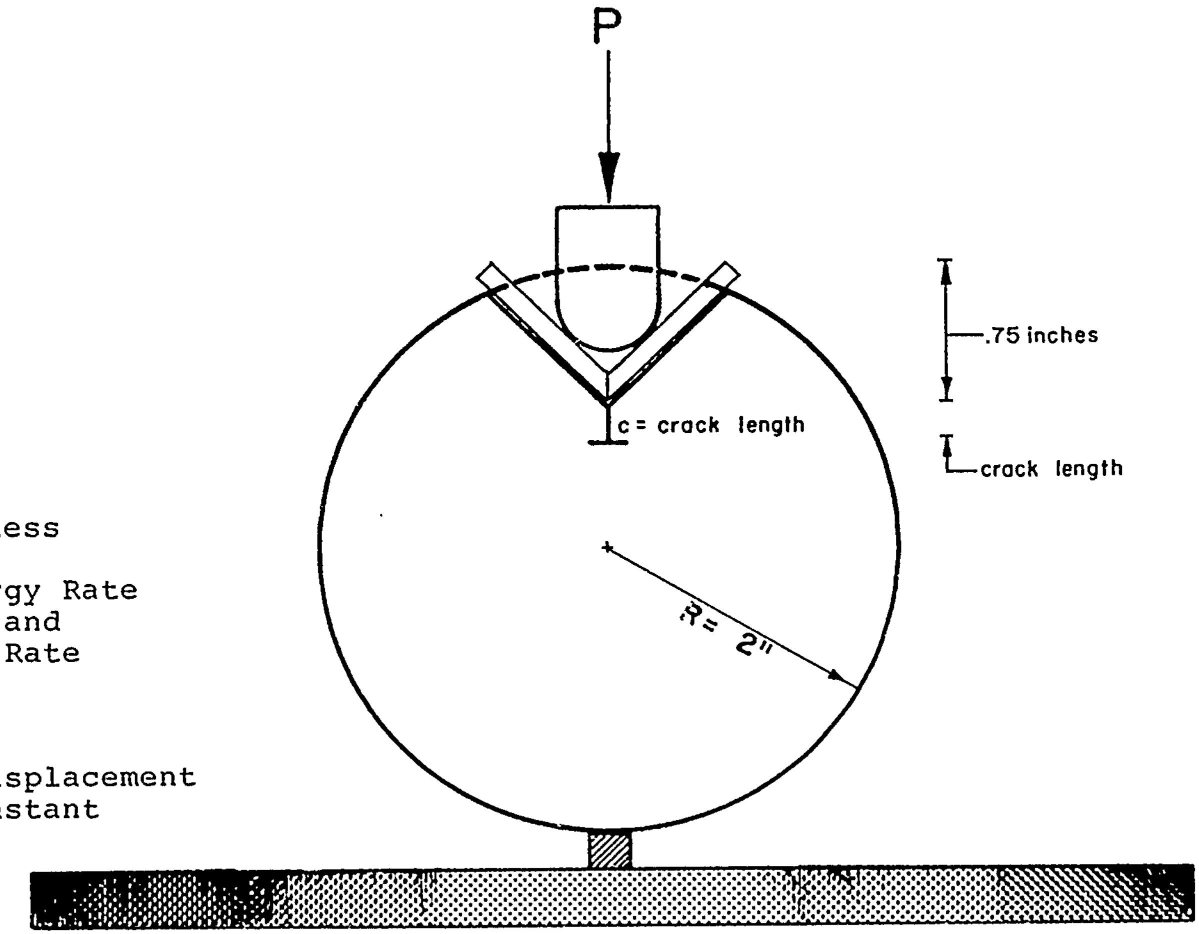

Figure 3. Typical C*- Test Set Up.

SECTION III

RESULTS AND ANALYSES

In this chapter, test results to support the development of a screening criteria will be presented, as well as the analysis of applying the screening criteria to selected modifiers. The results in this phase of study are used to investigate the feasibility of utilizing a screening criteria and not as final measures on the engineering characteristics and performance of the selected modifiers. To be able to investigate and ascertain the performance of the selected modifiers, more samples must be tested in a planned design of the experiment, as outlined in the Phase II followup study proposal.

A. TESTING PROGRAM

In the Phase I investigation, the following six types of modifiers were selected for testing:

	Modifier Type		Abbreviation
o	Elastomer:	Synthetic latex	ESL
o	Block-Co-Polymer:	Styrene-butadiene-styrene	SBS
o	Plastic:	Polyethylene/polypropylene	PP
o	Elastomer:	Rubber	ER
o	Plastic:	Ethylene-vinyl-acetate	EVA
o	Filler:	Carbon Black	FCB

These modifiers were selected, based upon information obtained from the literature review and further confirmed by the manufacturer's technical data. Information on flash points of these modifiers are included in Appendix A, Table A-2. Two types of asphalt cements are used (AC-10 and AC-20). Selection of these types of asphalt cement was based on the manufacturer's recommendation, review of the literature, and the information obtained from the Air Force Standards AFM88-6, Chapter 2, "Flexible Pavement Design for Airfields" for area Zones I and II. Limestone aggregates used were obtained locally and complied with the Air Force specifications for aggregate gradation (cited under wearing-course requirements for the 3/4-inch-down maximum sieve size under the column labeled "high pressures.") The Marshall method of mix design used is also in compliance with the above-cited specification.

Figure 4 presents the Phase I laboratory testing program. The following steps were followed:

1. The six asphalt modifiers were blended with AC-10 and AC-20 separately, and the penetration test was carried out. Two control AC samples were also tested. The viscosity/temperature relationship was established for all the blends and the control samples. The initial viscosity index was calculated. Next, the six blends and the controls were aged in a Thin-Film Oven Test (TFOT) at 325 ^{o}F for a period of 5 hours. The viscosity of the blends was determined, and the aging index was calculated. Results were analyzed, and they and presented in Table 1. Two terms are defined as follows:

   o Aging Factor (AF) = This is the ratio of viscosity of the blend before and after TFOT.

   o Aging Index (AI) = This is the ratio of viscosity of the blend to the viscosity of the control asphalt cement after aging in the TFOT.

2. The Marshall method of mix design was used in accordance with Air Force specifications to determine the optimum asphalt content (in this case binder content) for each of the six modified asphalt blends and the control. Based on the Marshall optimum-mix design, several samples were fabricated to carry out the following tests:

   a. Modulus of resilience, MR

   b. Indirect tensile strength, σ_y

   c. Unconfined compressive strength, q_u

   d. Creep test on unaged and aged samples, J(t)

   e. Rutting potential test using the CVP method

   f. Cracking potential test using the C*-line integral method.

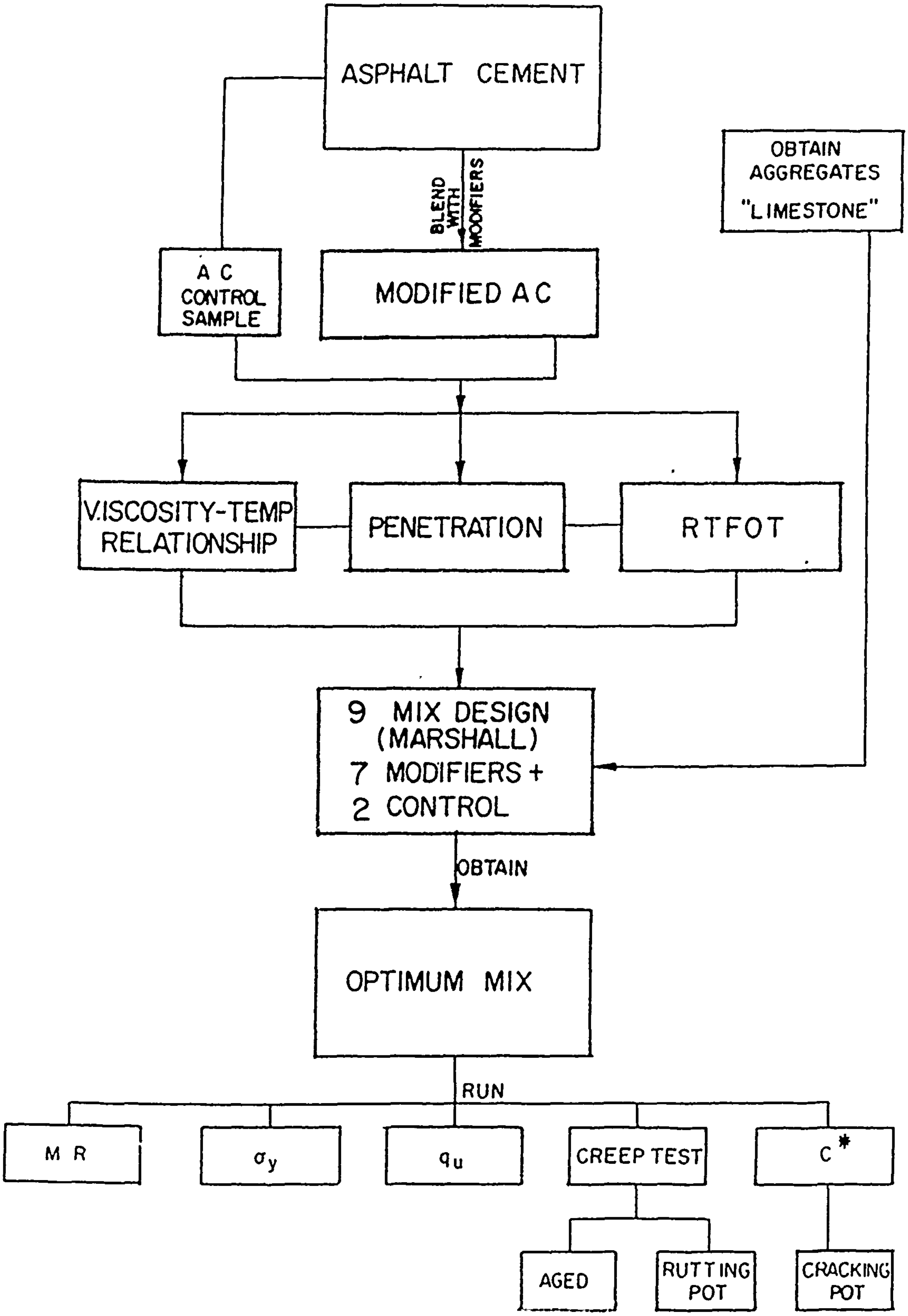

Figure 4. Phase I Laboratory Test Program.

TABLE 1. PENETRATION, ABSOLUTE VISCOSITY-TEMPERATURE TEST RESULTS.

Blend	Penetration 77 °F	Viscosity @ 140 °F B/TFOT	Viscosity @ 140 °F A/TFOT	Viscosity @ 275 °F B/TFOT	Viscosity @ 275 °F A/TFOT	AF 140 °F	AI 140 °F
AC-20	51.4	2443	*	4	15	*	1
AC-10	70.1	1041	14,000	3	8.5	13.4	1
ESL	39.0	6794	16,500	120	19	2.4	.21
SBS	45.3	60,000	*	58	19.5	*	.63
PP	29.4	13,745	200,000	165	23	14.6	2.5
ER	64.8	2522	8,200	6.2	14	3.3	.1
EVA	31.8	8484	*	5	6.5	*	*
FCB/AC-20	36.8	21255	110,000	23	25	5.2	1.4
FCB/AC-10	49.9	5516	21,000	24	24.5	3.8	1.5

B/TFOT: Before aging in Thin Film Oven Test.
A/TFOT: After aging in Thin Film Oven Test.

* Not able to determine/or the result is not reasonable.

AF: Aging Factor.
AI: Aging Index.

Tests a, b, and c are standardized under American Society for Testing and Materials (ASTM) specifications. Test d is detailed in the VESYS IIM User's Manual (Reference 32). Tests e and f are new and thus are outlined in Appendix B.

B. TEST RESULTS AND ANALYSIS

1. Sample Preparation

Initial laboratory work pertained to the preparation of sufficient asphalt-additive mixture quantity to allow completion of all tests in the testing program. Materials sufficient for the test program were obtained based on the estimate of asphalt concrete required for the tests to be performed on each of the selected additives' sample. Sufficient aggregates to complete the testing program and to meet the Air Force gradation specification were also obtained. The specification used was according to Table 7-4 of AFM88-6, "Flexible Pavement Design for Airfields." The maximum sieve size was 3/4 of an inch and the gradation for the high-pressure wearing course was selected.

The first step of the laboratory portion of the program was to mix the asphalt and additive mixtures. In all, nine different asphaltic mixtures (blends) were prepared for various tests. Two of these were regular AC-10 and AC-20 to be used as controls. The remaining seven asphalts would contain the special additives. As recommended by the manufacturer, the additive, FCB, was used in an AC-10 and an AC-20 mix. The remaining five additives were each mixed with AC-20.

Three of the mixes were prepared by an outside test facility at the request of the supplier. The PP and FCB additives were sent to Matrecon, Inc., in California, for mixing. The reason given for the PP was the need for a special blender which Matrecon had, and, according to the manufacturer of FCB, the need was for very thorough blending. The remainder of the additives were mixed in the laboratory at Resource International, Inc., according to the manufacturer's recommendations. Generally, if the asphalt concrete can be kept at 300 ^{o}F, mixing of the polymer and elastomer additives, as was done at Resource International, is no problem. A mixing time of 1/2 to 1-1/2 hours and a mixer providing agitation and turnover are adequate. Complete intermixing of the additive and AC is difficult to visually determine, so overmixing is the best choice if there is any doubt.

The percent addition of each modifier was based on the manufacturer's recommendation. Following are the percent addition used by weight of the asphalt cement:

Modifier Type	% by weight of AC
ESL	4.0
SBS	12.0
PP	5.0
ER	3.5
EVA	4.0
FCB (for both types of AC)	15.0

After all mixing was completed, small quantities of each of the nine samples were set aside for viscosity and penetration tests. Viscosity tests were performed to determine viscosities at 140 ^{o}F and 275 ^{o}F; the tests were done according to ASTM procedure D2171-72 using Cannon-Manning viscometers and constant-temperature bath. Tests to determine viscosity were performed on the new samples and on the same samples that had been aged according to ASTM D1754-85 for Thin-Film Oven Test aging. Penetration tests were performed on the nine samples according to ASTM D5-73. Results of these tests are found in Table 1.

The next step in the laboratory testing program was the preparation of the Marshall Mix Design tablets to optimize the binder content. Procedures for testing and data analysis were taken from Section 7, Bituminous Material Courses, of the U.S. Department of Defense (DOD) "Flexible Pavement Design for Airfields."

A range of 5 to 7 percent binder content by weight was chosen with the binder contents being 5, 5.5, 6, 6.5, and 7 percent. Three samples of each binder content of each of the nine asphalt concrete mixtures were prepared. This makes the total Marshall tablets prepared initially to be 135. The aggregates for the tablet preparation were sieved according to the Air Force specification mentioned previously. After a few tries the proper weight of graded aggregate was found to give the recommended 2.5-inch height for the Marshall tablet. This value was used for the preparation of the 135 Marshall tablets.

Testing according to the Marshall procedure was then performed on the samples, and the data were analyzed to determine the optimum binder content for each of the nine mixtures. For AC-10, ESL, SBS, ER and FCB/AC-20 mixtures, it was necessary to prepare additional samples at binder content percentage less than 5 to determine the optimum stability values. The optimum stability values for these mixtures could not be determined in binder content range that was selected initially. Marshall mix design results are shown in Appendix C. A summary of the results are presented in Table 2. Test specimens at optimum binder content were then prepared to perform the comparison tests for selecting the best asphalt modifier. Test results are summarized in the following section.

TABLE 2. SUMMARY OF MARSHALL CRITERIA TEST RESULTS.

Mixture	Optimum AC%	Stability (lb)	Density PCF	Air Voids %	Flow .01 in.	% Additive in. AC (by wt.)	Specific Gravity of Additive
AC-20	5.6	4040	147.3	3.0	13.0	-	1.02
AC-10	5.4	4200	147.7	3.7	16.0	-	1.02
ESL	5.3	3750	142.5	4.5	11.5	4.0	0.90
SBS	5.4	2950	145.1	4.3	13.0	12.0	0.93
PP	6.0	4000	146.6	4.0	12.0	5.0	1.00
ER	5.6	3250	145.5	4.5	11.0	3.5	0.95
EVA	5.9	4200	145.7	3.7	13.0	4.0	0.94
FCB/AC-20	6.1	5000	146.5	4.0	10.0	15.0	1.74
FCB/AC-10	6.0	4150	146.4	4.2	10.0	15.0	1.74
Specifications	-	>1800	-	3-5	≤16	-	-

2. Viscosity-Temperature Relationship and Penetration Testing and Results

This test was carried out in accordance with the following ASTM standards:

- o D-5 : Penetration test
- o D-2171: Absolute viscosity
- o D-1754: Thin-Film Oven Test (TFOT)

The only deviation from the standard test D-1754 is that the oven shelf rotates about an axis inclined 10^{o} from the vertical axis. This was done to expose more of the sample to test conditions, as well as to aid in stirring. The penetration test was conducted only at the initial conditions, i.e., after blending the modifiers with the asphalt cement. The viscosity test was carried out before and after aging (i.e., before and after TFOT). Each time, the absolute viscosity was determined at two temperatures, 140 ^{o}F and 275 ^{o}F. When it was not possible to test at 140 ^{o}F, viscosity at two other temperatures close to 140 ^{o}F was measured, and the viscosity at 140 ^{o}F was found by curve extrapolation. Before TFOT, all modifiers were tested at 140 ^{o}F and 220 ^{o}F except SBS which was tested at 160 ^{o}F (the SBS modifier was found to be too viscous at 140 ^{o}F). Although the test could have been performed at 140 ^{o}F, very inconsistant results were seen in the initial tests. After TFOT, all modifiers were tested at 160 ^{o}F, and 230 ^{o}F except SBS which was tested at 180 ^{o}F and 230 ^{o}F for the same reason as mentioned above.

a. Analysis

Penetration values for control samples AC-20 and AC-10 were 51.4 and 70.1, respectively. Only FCB was used to modify both AC-20 and AC-10. All other modifiers were blended with AC-20. In all cases, when the modifier was mixed with the asphalt cement, the penetration value was reduced. The most reduction (to a value of 29.4) was associated with the PP, and the least reduction (to a value of 64.8) was associated with ER.

Reduction in penetration values is also associated with the percentage of the additive used and its specific gravity. This information is presented in Table 2.

In examining the results of Table 1, the initial viscosities of the AC-20 and AC-10 were 2443 poise and 1041 poise at 140 ^{o}F, respectively. These values fall within the specification range. In all cases, when the modifier was mixed with the asphalt cement, the viscosity value of the blend was increased. The greatest increase in viscosity (up to 60,000 poise) was associated with the SBS, and the least increase in viscosity (up to 2522 poise) was associated with the ER. The general trend between viscosity and penetration data for the various modifiers is normal (i.e., the lower the penetration the higher the viscosity, and visa versa). All modified blends exhibited increases in viscosity upon aging in TFOT. The aging factor (AF) and the aging index (AI) were calculated and the results are shown in the last two columns of Table 1. The results indicate that PP and FCB age faster than the control samples of asphalt cement while the ESL, SBS, and ER age more slowly than the control sample. However, the aging index alone is not a valid parameter to define the aging characteristics of the modifier, because different modifiers will result in different initial viscosity values of the blends; hence the aging index will include this as an embedded variable. As a better measure of the aging characteristics, the following definition is presented:

$$IAR = \frac{\mu_{Am} - \mu_{Bm}}{\mu_{Ar} - \mu_{Br}} \quad ;\text{where}$$

IAR = index of aging rate

μ_{Bm}, μ_{Br} = the before-aging absolute viscosity of the modified and reference blend, respectively

μ_{Am}, μ_{Ar} = the after-aging absolute viscosity of the modified and reference blend, respectively.

The IAR will have the advantage of normalizing the viscosity data with respect to the variable initial viscosity, as well as being a measure of the effect of the modifier on the change in aging rate.

The aging characteristics using the creep compliance data are presented in Section V. The data pertaining to the aging characteristics are found in Appendix D.

3. Marshall Criteria Results

This test was conducted in accordance with the Air Force specification AFM 88-6. The additive dosage and mixing with asphalt cement was based on the manufacturer's recommendation. Test results are shown in Appendices C and E. Table 2 contains a summary of these results. The last row of Table 2 lists the Air Force specifications.

Graphical representations of the stability, optimum binder content, and specific gravity are presented in Figures 5, 6, and 7.

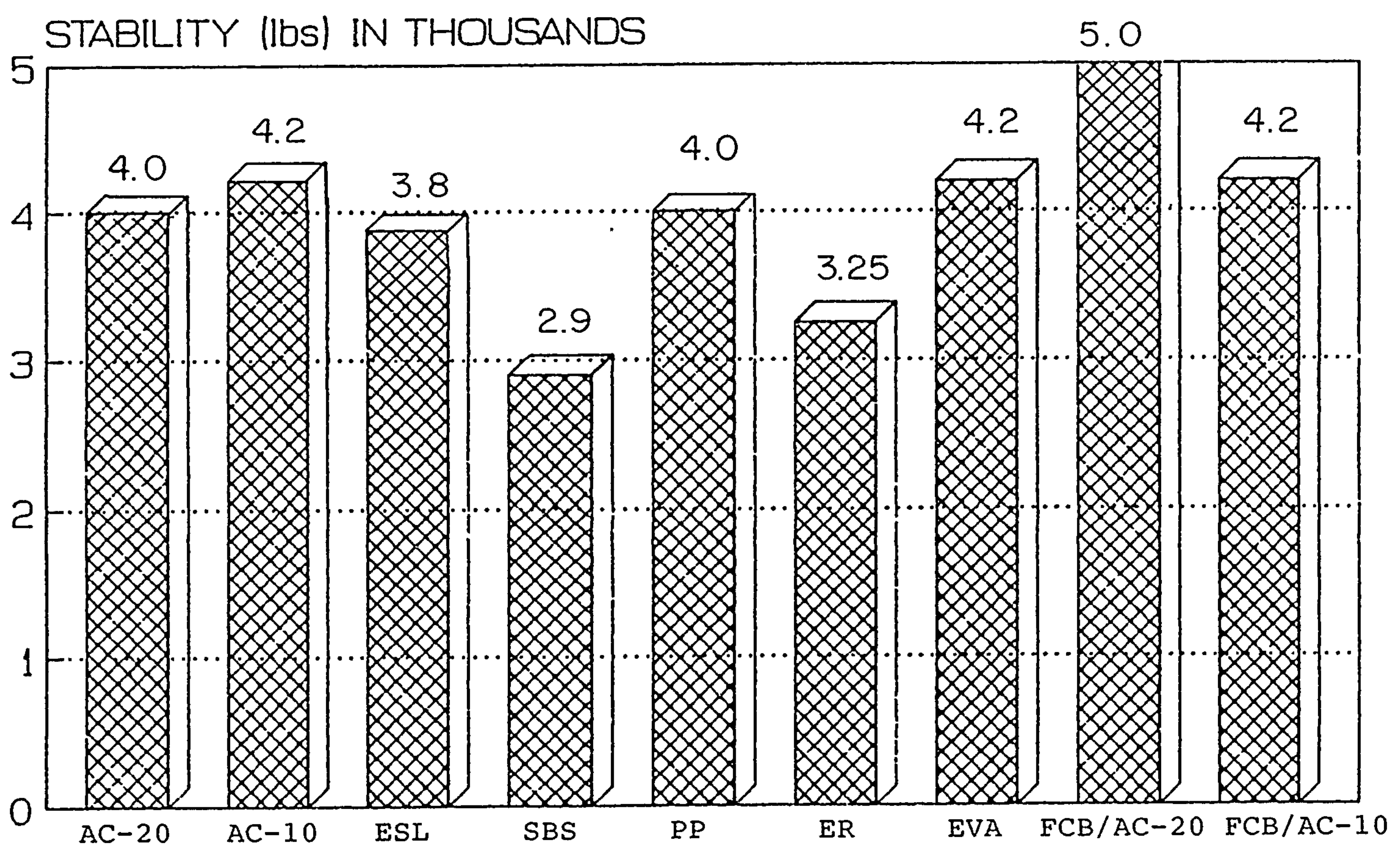

Figure 5. Comparison of Marshall Stability Values for all Additives.

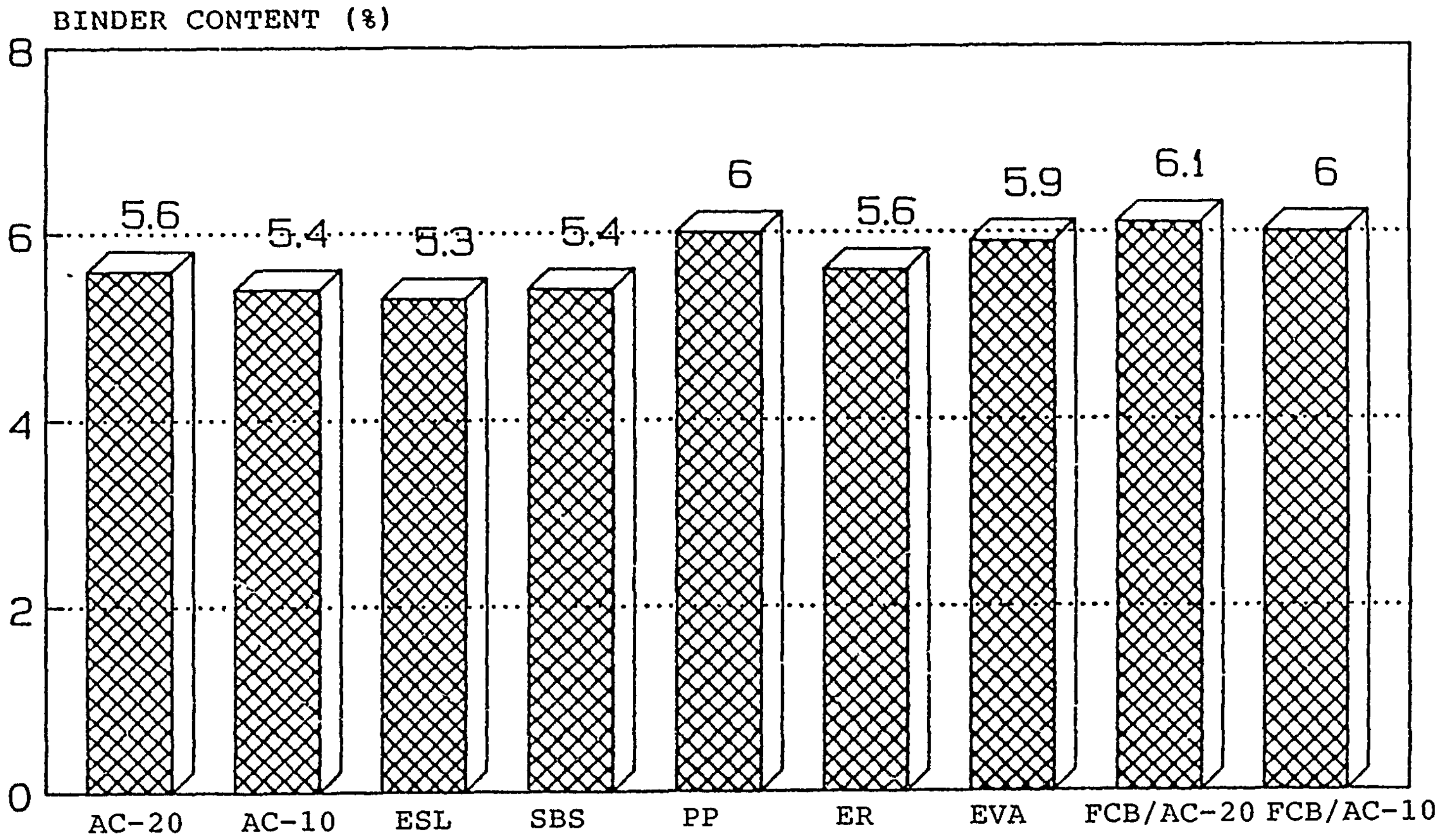

Figure 6. Comparison of Optimum Binder Content for all Additives.

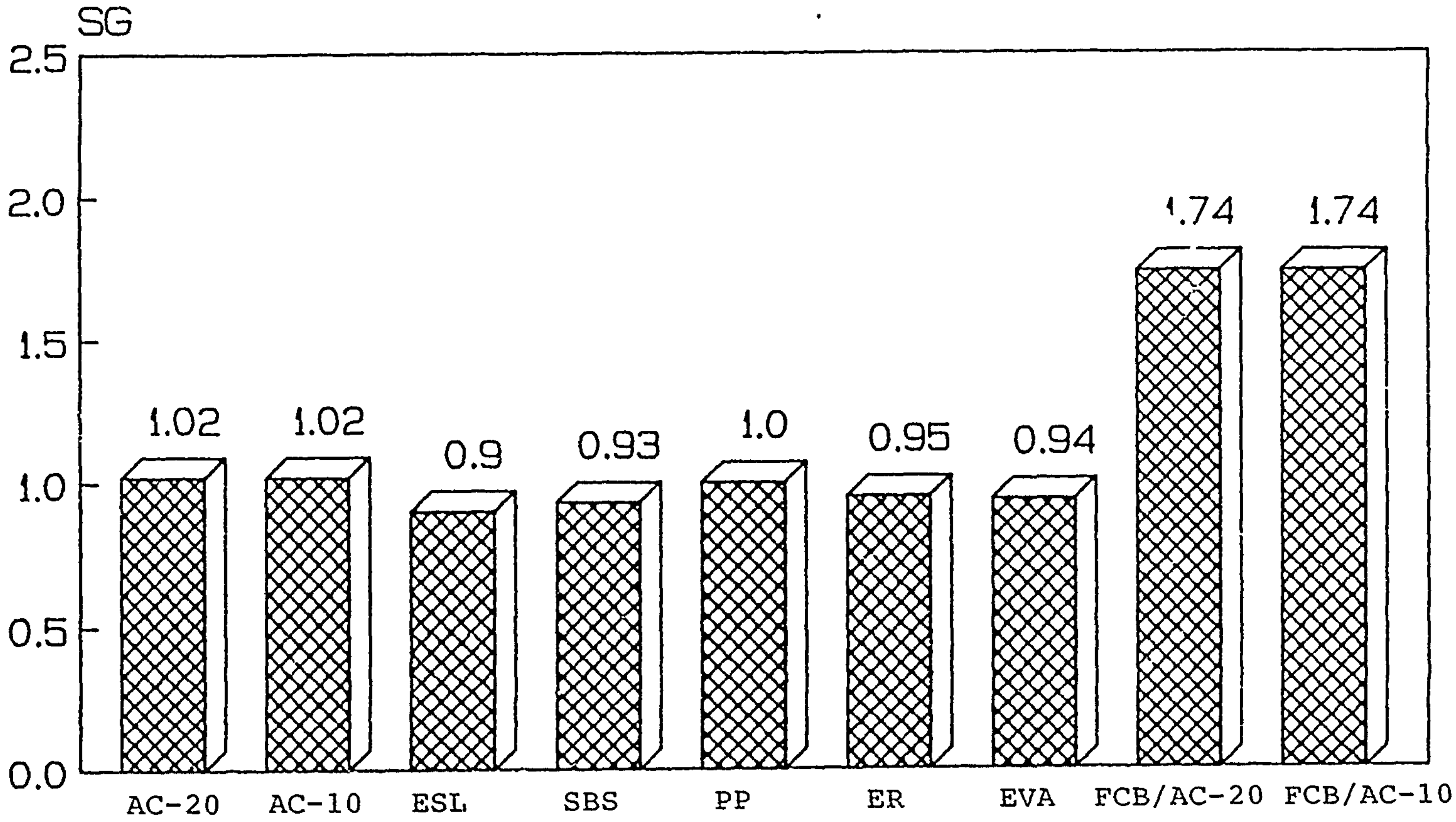

Figure 7. Comparison of Specific Gravity for all Additives.

a. Analysis

Table 2 shows that all results meet the Air Force specification for Marshall criteria. That implies that the Marshall criteria cannot be used to differentiate between bituminous mixtures with different types of additives. Furthermore, most of the results do not vary greatly as the additive type changes. Again, this means that the Marshall criteria parameters, individually or collectively, are not sensitive enough to detect the mixture variation caused by variations in the types of additives used. In fact, the measure that we are looking for is the potential of the mixture to exhibit cracking and/or rutting, compared to conventional asphalt cement mixtures. This measure could not be extracted from the Marshall criteria as all the results meet this standard.

The last column in Table 2 lists the specific gravity of the different modifiers. If the specific gravity is less than that of the asphalt cement, the modifier may float and separate from the blend. This implies that dispersing of the modifier within the asphalt cement matrix by methods such as high shear mixing is essential. For these modifiers, the aging characteristics of the blends are of prime importance.

4. Short-Term Material Characteristics

These tests include the following:

- o Modulus of resilience: MR — ASTM D-4123
- o Indirect tensile strength: σ_y — ASTM D-4123
- o Unconfined compressive strength: q_u — ASTM D-1074

A summary of these results is presented in Table 3. Histograms for comparison of modulus of resilience, indirect tensile strength, and unconfined compressive strength of the various mixtures are presented in Figures 8, 9, and 10.

a. Analysis

No standard specification limits are set for these tests; therefore, comparisons of the above-cited results with the results of the control samples will be made. All modifiers except ESL and ER have increased the modulus of resilience (MR) over that of the control asphaltic mixture. A maximum increase of 27 percent is associated with EVA, and the least increase of about 6 percent is associated with SBS. For all practical reasons, however, this increase is not considered significant. The same trend is noticed for the indirect tensile strength σ_y

TABLE 3. SHORT-TERM MATERIAL CHARACTERISTICS

MIXTURE	Modulus of Resilience MR(psi) $x10^6$	Indirect Tensile Strength σ_y (psi)	Unconfined Compressive Strength of q_u(psi)
AC-20	0.69	219	711
AC-10	0.60	188	725
ESL	0.59	256	772
SBS	0.73	247	719
PP	0.80	217	725
ER	0.67	203	655
EVA	0.88	223	653
FCB/AC-20	0.76	260	1011
FCB/AC-10	0.79	215	683

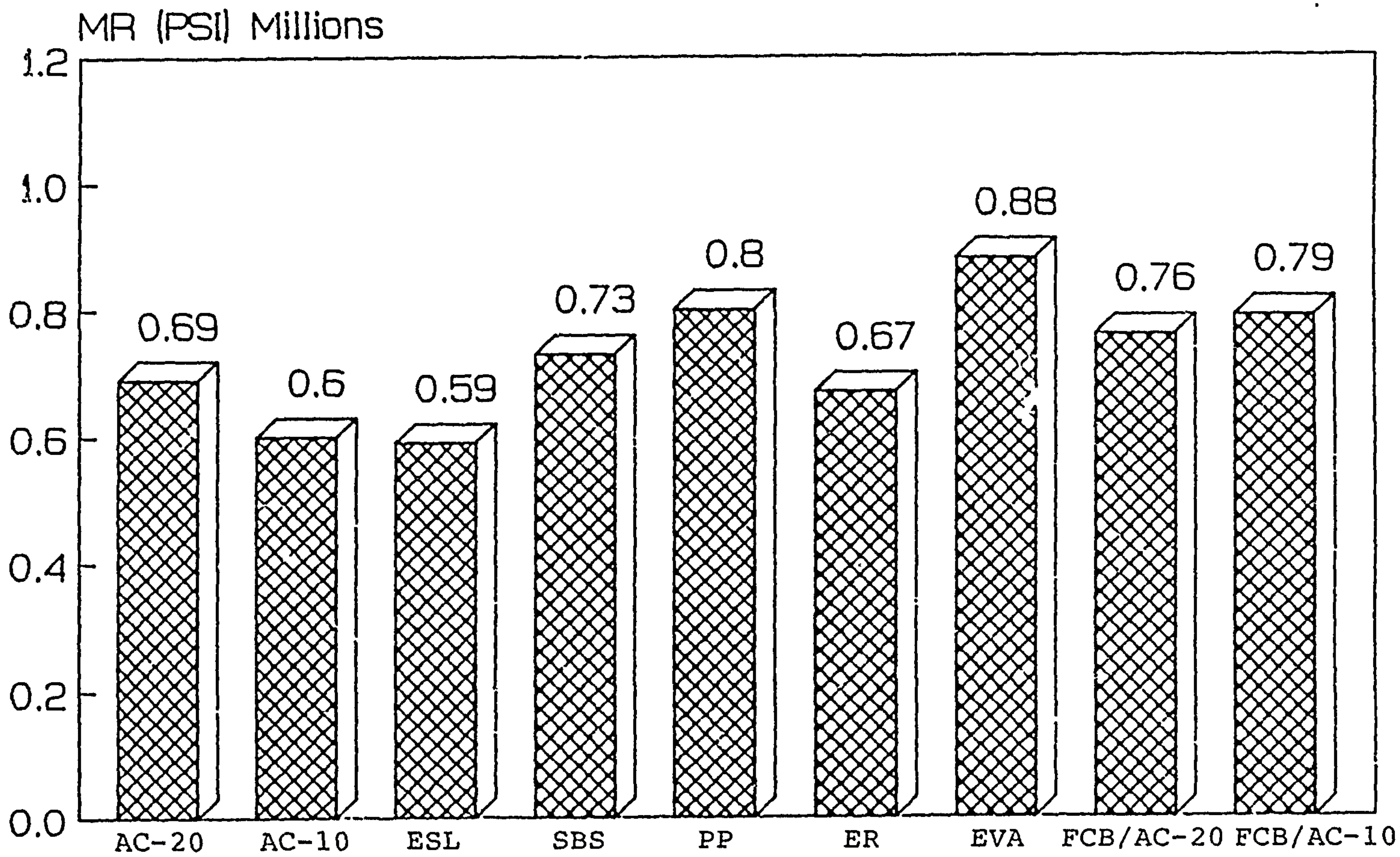

Figure 8. Comparison of Modulus of Resilience.

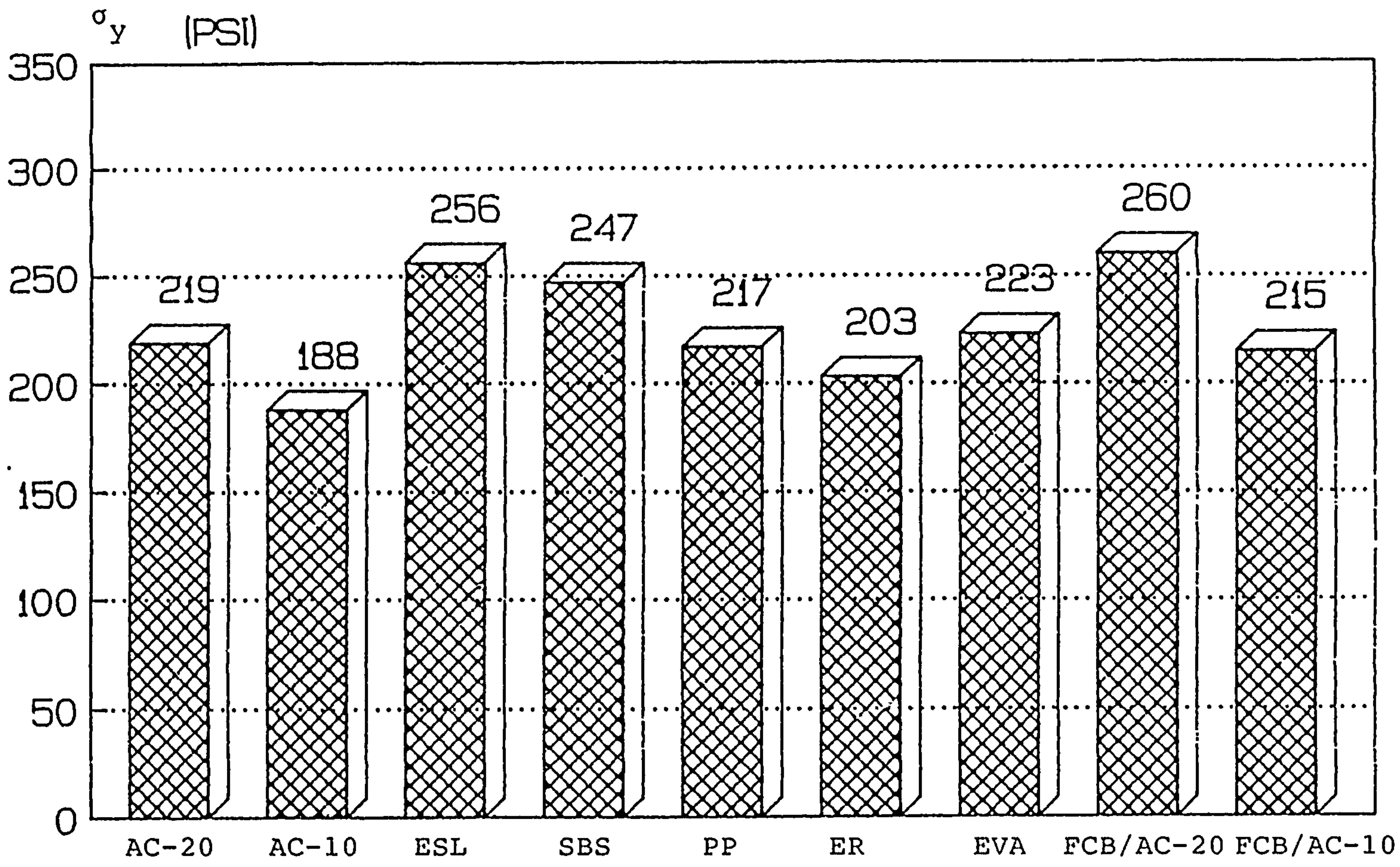

Figure 9. Comparison of Indirect Tensile Strength.

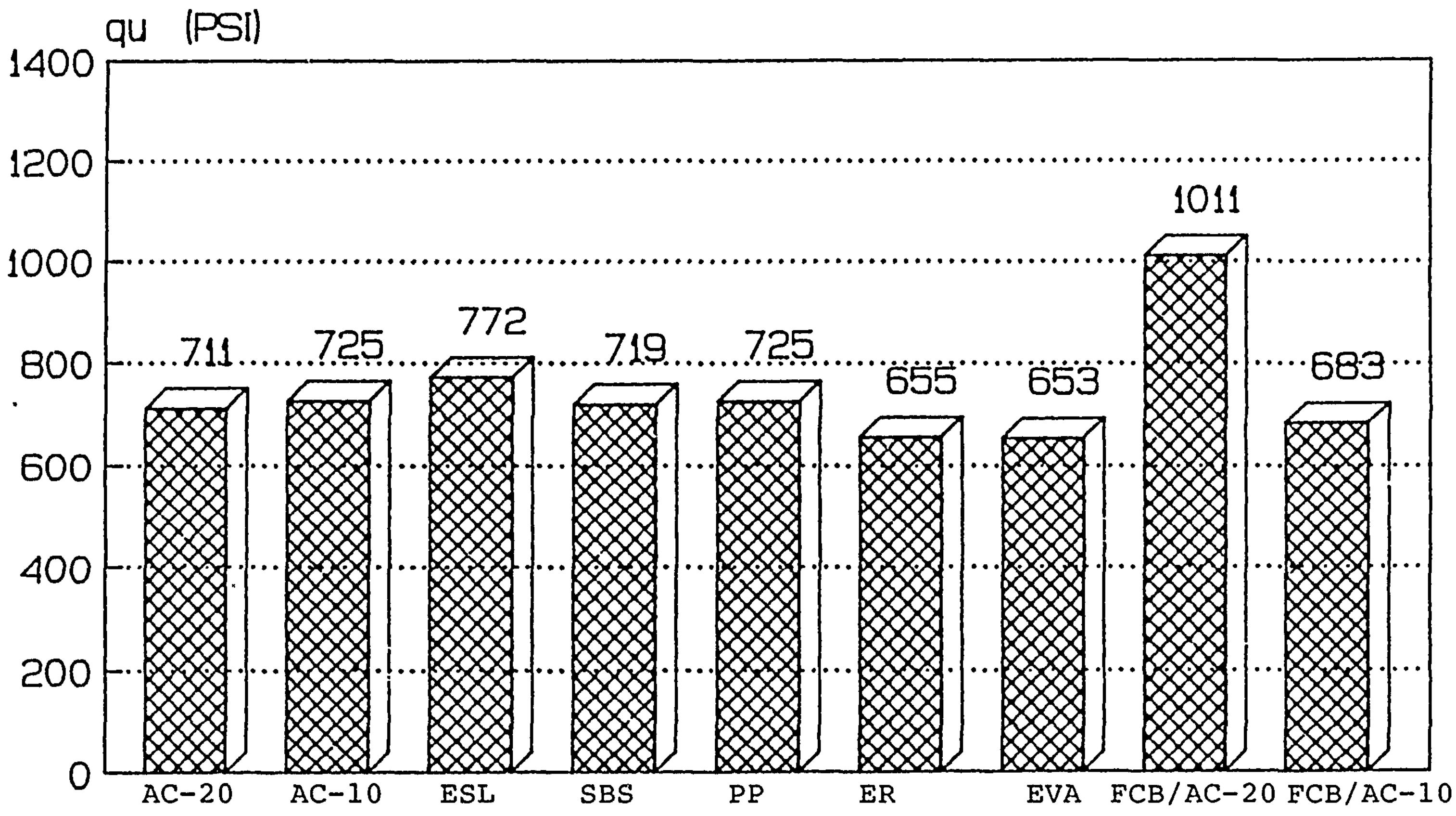

Figure 10. Comparison of Unconfined Compressive Strength.

and unconfined compressive strength q_u, except that additives contributing to the maximum or the least increase are different.

The main conclusions from these results are that these tests cannot be used to distinguish effects of different types of modifiers relative to the control mixtures as the results are comparable to each other. Because these tests do not reflect the mixture performance, they do not indicate whether or not cracking and rutting will be a problem.

5. Long-Term Potential Candidacy Tests

These tests include the following:

- C*-Line integral: new procedure
- Compression rutting-creep: modified procedure based upon the test method presented in VESYS II-M structural subsystem manual.

Detailed results of these tests are found in Appendix C. These results are presented in Figure 11 for the C*-line integral and Figures C-1 through C-9 in Appendix C for the compression rutting-creep data.

a. Analysis

(1) Cracking Potential

A summary of the results of the C*-line integral test is presented in Figure 11. Again, there is no specification limit for compliance with this test; hence the control mixture (designated AC-20) will be used for comparison purposes. Figure 11 is read in terms of the crack speed and the energy required to generate this crack speed. The more energy required and the slower the crack speed the better the mixture resists cracking. Hence, at 70 ^{o}F the FCB, SBS, PP, and ESL are better mixtures to resist cracking compared to AC-20, while EVA and ER are not. Hence, one conclusion would be that C*-line integral could be appropriate measure for the cracking potential of asphaltic mixtures with or without modifiers. This test is part of the proposed screening criteria. The point to be evaluated in a followup study is the temperature-dependence and the effect of aging on the C*-line integral test results.

(2) Rutting Potential

A summary of the compression creep rutting test results at different stress levels is presented in Appendix C.

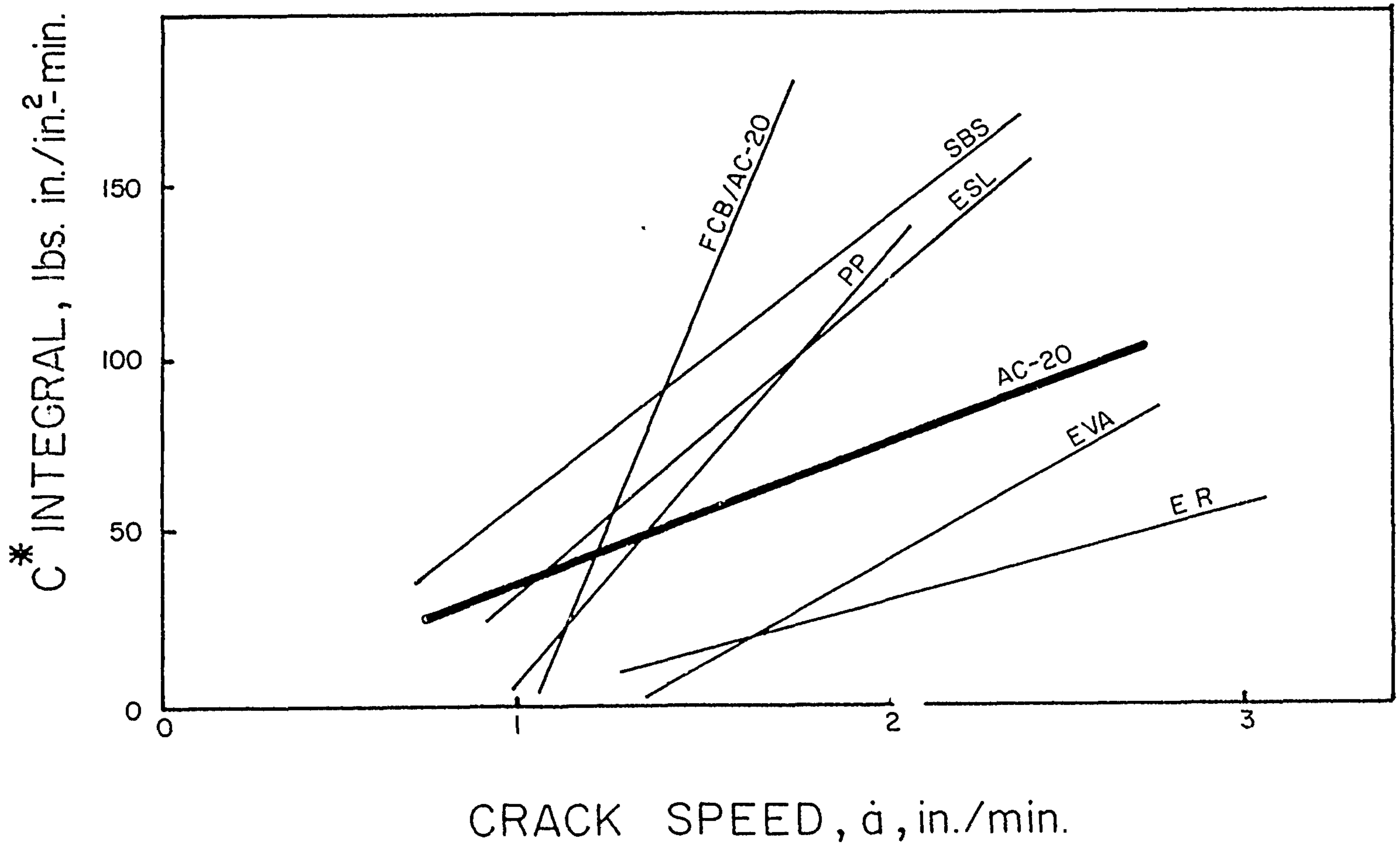

Figure 11. C*-Line Integral

A nonlinear regression equation was used to fit these data. The mathematical statement of this equation which respresents the creep compliance function for the viscoelastic mechanical Burger model for asphaltic mixtures is:

$$J(t,\sigma_o) = \frac{\epsilon(t)}{\sigma_o} = \alpha_1 + \alpha_2 t + \alpha_3 (1 - e^{-\alpha_4 t})$$

$J(t,\sigma_o)$ = creep compliance at stress level σ_o

$\epsilon(t)$ = axial strain as a function of time

σ_o = the applied constant stress

t = time scale

α_i = regression coefficients

Results of the curve fitting are presented in Table 4. The steady-state creep deformation ϵ_{ss} is plotted against the stress levels to enable determination of the yield point of the modified AC mixtures, σ_y. Results of this step are presented in Table 5. σ_y is interpreted as the stress point at which plastic deformation will commence; therefore, the higher the value the better the rutting behavior of the material. Table 5 reveals that all modified mixtures are better than the conventional AC-20 (or AC-10) to various degrees. The best results were with FCB/AC-20 where the yield point almost doubled that of conventional AC-20. ESL, PP, EVA, and ER exhibited yielding characteristics at the same order of magnitude as conventional AC-20 mixtures; however, the low yield point does not mean that the material will exhibit a high creep deformation rate at higher stress levels. To illustrate this fact, the column labeled "creep rate" in Table 5 should be examined. For example, a comparison of values of PP and EVA, shows that both these mixtures have equal yield points, although the EVA will exhibit almost twice the creep deformation as the PP. Accordingly, rutting of AC mixture modified by EVA is expected to be as much as twice that of AC mixture modified by PP. Another interesting example is the comparison between FCB/AC-20 and FCB/AC-10 mixtures. Both mixtures exhibit equal creep deformation rate; however, the FCB/20 mixture is superior because it also has the highest yield point value. Further analysis could be made by comparing the creep data (shown in Appendix C) of the modified mixtures to the control AC-20 mix. All modified mixtures exhibited higher creep deformation than AC-20, except PP and FCB/AC-20. In fact, PP was the only mixture that showed less creep behavior at all stress levels. FCB/AC-20 showed higher creep values initially, but the values decreased at the end of the test period. A comparison of the creep data for any three mixtures, for example PP, SBS and ESL, shows that PP has the

TABLE 4. REGRESSION COEFFICIENTS FOR COMPRESSION-RUTTING-CREEP TEST OF MODIFIED ASPHALT CONCRETE.

Sample	Stress Level (psi)	α_1	α_2	α_3	α_4	ERROR
AC20	15	0.80	.0028	2.21	.053	.014
	40	1.79	.0098	6.21	.050	.214
	80	2.90	.0120	11.90	.050	.670
	160	8.19	.0164	16.80	.0513	3.000
AC10	15	1.06	.0020	2.61	.059	.053
	40	2.76	.0097	8.33	.050	.500
	80	5.94	.0120	12.30	.054	1.070
	160	13.02	.0123	15.00	.059	3.470
ESL	15	1.27	.0020	3.67	.046	.059
	40	2.76	.0060	8.69	.052	.310
	80	6.14	.0060	10.1	.062	1.17
	160	11.50	.0090	12.8	.070	1.54
SBS	15	1.32	.0026	3.68	.0537	.074
	40	4.13	.0069	8.87	.0456	.540
	80	9.11	.0092	11.70	.0517	1.080
	160	15.34	.0100	14.40	.0638	1.700
PP	15	.46	.0014	1.08	.054	.002
	40	1.13	.0061	3.56	.030	.07
	80	2.34	.0093	7.39	.032	.16
	160	3.86	.0140	12.56	.052	1.04
ER	15	1.45	.0015	2.99	.069	.055
	40	3.87	.0060	8.09	.050	.340
	80	6.26	.0076	9.51	.066	.809
	160	9.65	.0092	12.92	.043	2.07
EVA	15	1.206	.0020	2.46	.043	.072
	40	3.37	.0040	6.03	.052	.140
	80	5.00	.0046	7.06	.070	.850
	160	11.50	.0050	7.23	.043	1.26
FCB/AC-20	15	1.02	.0011	1.87	.058	.03
	40	2.45	.0033	4.97	.039	.11
	80	4.89	.0054	8.434	.064	.71
	160	10.24	.0080	9.93	.066	1.62
FCB/AC-10	15	2.04	.0020	3.61	.056	.10
	40	4.57	.0070	9.33	.054	.80
	80	9.15	.0071	13.03	.056	2.93
	160	14.46	.0112	15.36	.066	2.10

TABLE 5. YIELD POINT OBTAINED FROM CREEP COMPLIANCE TEST FOR MODIFIED MIXTURES

Modified Mix	σ_y, psi	Creep Rate[1] CR	Range[2] x 10^{-6}
AC-20	26	.0055	.9 - 1.64
AC-10	20	.00029	.35 - 1.22
ESL	28	.0034	.45 - .9
SBS	44	.00095	.89 - 1.0
PP	30	.0058	.65 - 1.4
ER	34	.0021	.66 - .92
EVA	30	.00077	.4 - .5
FCB/AC-20	46	.0031	.43 - .8
FCB/AC-10	25	.003	.59 - 1.0

[1]creep rate = $\dfrac{\dot{\epsilon}'_{ss}}{\sigma_o}$ micro in/in psi^{-1}

$\dot{\epsilon}'_{ss}$ = variation of the steady state creep deformation

[2]range = (highest $\dot{\epsilon}_{ss}$ - lowest $\dot{\epsilon}_{ss}$) for the evaluated creep rate score. Lowest ϵ_{ss} is taken as the value at the yield point.

least deformation, followed by ESL and SBS respectively. Comparing these findings to the CR values in Table 5, it could be said that higher CR values are generally associated with less creep behavior. The above discussion shows that the screening criteria should account for both parameters in a rutting potential candidacy test, namely, the yield point and the creep deformation rate. Threshold design values for both of these parameters could be established as criteria for acceptance/rejection of modifiers to guard against rutting.

(3) Creep Compliance After Aging

The same procedure for obtaining σ_Y and creep rate (CR) cited above was used to obtain these values after aging the samples in an oven at 140 ^{o}F for 7 days. The test results are presented in Tables 6 and 7. A summary of the compression creep rutting test results at different stress levels is presented in Appendix D. Except for the SBS and FCB/AC-20, σ_Y was increased for all modified mixtures; the maximum value of σ_Y was about 44 psi. All mixtures exhibited less creep behavior after aging. In an analysis similar to the one before aging, it can be concluded that all modified mixtures exhibit better (or slightly better) creep behavior than AC-20 after aging. All the modified mixtures also exhibited greater values of CR after aging. Therefore, the modifiers could be said to be beneficial for resisting the aging behavior of asphaltic mixtures.

C. DEVELOPMENT OF PHASE I SCREENING CRITERIA

Test results in this chapter indicate that it is possible to distinguish between the performance characteristics of modified asphalt concrete mixtures through employing innovative testing techniques.

The most important performance characteristics are resistance to cracking and to rutting; the C*-line integral is a measure of the resistance to cracking and the yield point/creep deformation rate is a measure for resistance to rutting at laboratory scale. To ensure the compatibility of the modifier with AC, an index of aging rate cited in this research could be used as a measure for this behavior. However, it should be pointed out that the results, along with the manufacturers' information, indicate that proper mixing and heating are essential to have consistent viscosity results, if consistency is at all possible. The rheological/chemical characterization will be correlated to viscosity parameters and hence provide the required compatibility acceptance/rejection criteria.

To summarize, the following screening criteria were proposed in this study:

TABLE 6. REGRESSION COEFFICIENTS FOR COMPRESSION-RUTTING-CREEP TEST OF MODIFIED ASPHALT CONCRETE (AFTER AGING).

Sample	Stress Level (psi)	α_1	α_2	α_3	α_4	ERROR
AC20	15	0.80	.0033	1.69	.030	1.081
	40	1.25	.0064	3.40	.032	.048
	80	2.14	.0113	6.72	.033	.215
	160	4.79	.0140	12.17	.040	.719
AC10	15	1.054	.0026	3.27	.030	.0907
	40	1.978	.0082	6.48	.033	.2338
	80	3.902	.0125	9.76	.043	.2749
	160	9.288	.0151	15.01	.043	1.9587
ESL	15	1.00	.0013	1.00	.040	.949
	40	1.00	.0066	2.745	.050	.064
	80	2.41	.0116	6.19	.040	.123
	160	4.92	.0165	12.86	.050	1.653
SBS	15	.547	.0026	1.89	.042	.0026
	40	1.632	.0081	4.95	.040	.1224
	80	4.039	.0114	9.57	.037	.3380
	160	5.879	.0128	12.30	.051	1.1633
PP	15	.305	.0009	.61	.053	.0015
	40	.891	.0031	1.86	.035	.0139
	80	1.972	.0075	3.72	.038	.0866
	160	3.293	.0138	9.04	.044	.4070
ER	15	.443	.0011	.84	.057	.0028
	40	1.161	.0044	2.22	.038	.0250
	80	2.704	.0086	5.834	.035	.1642
	160	5.409	.0130	13.84	.030	.9509
EVA	15	1.00	.0009	1.00	.030	.918
	40	1.00	.0068	2.29	.050	.091
	80	1.55	.0147	6.50	.050	.245
	160	4.67	.0188	15.89	.030	3.451
FCB/AC-20	15	0.80	.0004	1.00	.050	.672
	40	1.00	.0039	2.29	.050	.110
	80	1.87	.0072	5.94	.052	.259
	160	5.55	.0099	8.48	.070	1.159
FCB/AC-10	15	.623	.0019	1.43	.048	.0169
	40	1.594	.0048	3.64	.049	.0371
	80	3.808	.0078	8.05	.046	.5236
	160	6.585	.01108	11.85	.063	1.3646

TABLE 7. YIELD POINT OBTAINED FROM CREEP COMPLIANCE TEST FOR MODIFIED MIXTURES (AFTER AGING).

Modified Mix	σ_y, psi	Creep rate [1] CR	Range [2] x 10^{-6}
AC-20	28	.0034	.5 - 1.4
AC-10	39	.0031	.57 - 1.5
ESL	38	.0061	.80 - 1.65
SBS	44	.0032	.89 - 1.27
PP	44	.0080	.48 - 1.4
ER	43	.0055	.65 - 1.3
EVA	32	.0051	.49 - 1.9
FCB/AC-20	36	.0034	.33 - 1.0
FCB/AC-10	41	.0036	.67 - 1.1

[1] creep rate = $\frac{\dot{\epsilon}'_{ss}}{\sigma_o}$ micro in/in psi^{-1}

$\dot{\epsilon}'_{ss}$ = variation of the steady state creep deformation

[2] range = (highest $\dot{\epsilon}_{ss}$ - lowest $\dot{\epsilon}_{ss}$) for the evaluated creep rate score. Lowest $\dot{\epsilon}_{ss}$ is taken as the value at the yield point.

1. Compatibility:

$$IAR < 1 : IAR = \frac{\mu_{AM} - \mu_{BM}}{\mu_{AR} - \mu_{BR}}$$

where:

IAR	=	Index of aging rate.
μ_{BM}, μ_{BR}	=	The before-aging absolute viscosity of the modified and reference blend, respectively.
μ_{AM}, μ_{AR}	=	The after-aging absolute viscosity of the modified and reference blend, respectively.

The IAR value is obtained from running absolute viscosity test on the conventional and the modified asphalt cements before and after aging. Whenever possible, this value should be correlated to rheological/chemical behavior of the modifier, as suggested in the Phase II proposal.

2. Optimum mixture design:
Currently use Marshall criteria.

Furthermore, the following screening procedures were developed in this study:

1. Rutting potential:

$[\sigma_{yield}]_m >$ spec.

$[CR]_m <$ spec.

where:

$[\sigma_{yield}]_m$	=	the yield point of the modified mix, psi.
$[CR]_m$	=	creep deformation rate of the modified mix, micro in/in psi^{-1}.

Both $[\sigma_{yield}]_m$ and $[CR]_m$ are obtained from modified creep compliance testing.

2. Cracking potential:

$[C^*]_m$ > spec.

$[A]_m$ < spec.

where:

$[C^*]_m$ = the energy line integral value
$[A]_m$ = the crack speed of the modified mix

Both $[C^*]_m$ and $[A]_m$ are obtained from the C^*-line integral testing.

SECTION IV

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

A. SUMMARY

A literature search for information on modifiers to asphalt concrete resulted in the identification of more than 300 materials for different applications. Those materials were screened to identify modifiers claimed to be able to solve the rutting and cracking distress of asphalt concrete. In addition, modifiers were classified by type in six groups, namely, polymer, elastomer, fiber, filler, chemical, and miscellaneous. The literature, manufacturers' data, and recent studies indicate that modifiers belonging to the polymer, elastomer, and filler groups were the most promising to solve rutting and cracking.

In this phase of study, six different types of modifiers of those three groups were selected and analyzed, as well as used to develop screening criteria that are able to distinguish among the modifiers' performance. The screening criteria contain three major factors: (1) compatibility and aging, set to ensure that the modifier is compatible with the asphalt cement (AC) at the initial mixing, as well as after aging; (2) potential candidacy, set to ensure that the modified AC mixture will perform in the field to meet the objectives of minimizing rutting and fatigue cracking distress; and (3) cost prohibition, set to exclude modifiers with ineffective life-cycle cost. The first two areas cover the required engineering characteristics of the modified AC mix and are dealt with in this report, while the third area covers the cost factor and its relation to performance; this area is recommended as a main focus of consideration in a future study. In the Phase I study, a cost limit was set, based upon the literature review and the researchers' experience. The cost limit was that the selected modifier should not increase the cost of the in-place AC mixture by more than 25 percent.

Conventional testing methods including Marshall criteria and compressive strength, as well as nonconventional testing methods such as modulus of resilience and indirect tensile strength, have been conducted on the modified asphaltic mixtures and the control samples (AC-20 and AC-10). As expected, test results indicate that the cited conventional and nonconventional testing methods cannot differentiate between characteristics of the modified mixtures, and it would be difficult to judge performance; this problem led to the development of the study.

Two innovative testing methods with sound theoretical backgrounds were used in this study: (1) the C*-line integral method to measure the potential for cracking, and (2) the modified compression creep-rutting method to measure the potential for creep and rutting. Test results using these two methods have shown their potential to distinguish performance of the different modifiers, as related to cracking and rutting.

The greatest advantages of these methods are that they relate directly to performance and require simple testing procedures with no special equipment. The latter may be of prime importance if these methods are to be adopted in the field as quality control/quality assurance methods.

In effect, the screening criteria developed in Phase I contain:

1. Compatibility parameter: measured by index of aging rate (IAR).

2. Rutting potential parameters: measured by the yield point σ_y and creep deformation rate (CR).

3. Cracking potential parameters: measured by the energy line integral [C^*] and the crack speed [$\dot{a}$].

B. CONCLUSIONS

1. The marketplace is full of modifiers to asphalt concrete that are claimed to solve rutting and cracking problems. There is an urgent need to be able to screen out these modifiers and select those appropriate to withstand high-pressure tires, thrust vectoring on the airfield pavement, and temperature blast effects.

2. Conventional test methods such as absolute viscosity, Marshall criteria, and unconfined compressive strength, as well as nonconventional test methods such as the indirect tensile strength and the modulus of resilience, are not able to clearly distinguish the characteristics of the asphalt concrete modified by the different types of additives/admixtures.

3. Two innovative testing techniques used in this study can distinguish between modifiers on the basis of their performance. These two methods are:

   - C^*-line integral

   - The yield point and modified creep deformation rate.

   Test procedures for these two methods are documented in this report in Appendix B.

C. RECOMMENDATIONS

1. To utilize the screening criteria developed in this study for screening a wider base of modifiers through a factorial design of experiment.

2. To investigate the rheological/chemical characteristics of the modified blends and correlate these with compatibility/aging parameters such as IAR.

3. To develop a data base for modifiers that contain engineering and cost-effectiveness information.

4. To direct part of a future followup investigation toward more studies on rheological and chemical characterization of commercially available modifiers for proper categorization.

REFERENCES

1. Askelaud, Donald R., The Science and Engineering of Materials, Brooks/Cole Engineering Division, A Division of Wadsworth, Inc., 1984.

2. Phillips, David K., Asphalt Additive Workshop, NAPA 31st Annual Convention, Honolulu, Hawaii, January 18-23, 1986.

3. Winters, W.F., "Barytes in Rubber-Asphalt Mixtures," Proceedings, AAPT, 25, 1956.

4. Thompson, D.C., "Rubber Modifiers," Bituminous Materials, Interscience Publishers, 1964.

5. Thompson, D.C., and Hagman, J.F., "The Modification of Asphalt with Neoprene," Proc., AAPT, Vol. 27, 1958.

6. Rice, J.J., Field Laboratory Experience with Natural Rubber as an Additive for Asphalt, Asphalt Institute Symposium on Rubber in Asphalt, 1960.

7. Gregg, L.E. and Alcoke, W.F., "Investigations of Rubber Additives in Asphalt Paving Mixtures," Proc., AAPT, Vol. 23, 1954.

8. Moavenzadeh, F. and Alexander, J.A., Effects of Rubber Additives on Properties of Asphalts, Second Inter-American Conf. on Materials Technology, ASME, 1970.

9. Mack, C., "Physical Aspects of Hardening on Paving Asphalts," Proc., AAPT, Vol. 27, 1958.

10. Little, D.N., Batton, J.W., White, R.M., Ensley, E.K., Kim, Y., and Ahmed, S.J., Investigation of Asphalt Additives, Texas Transportation Institute, Texas A&M, FHWA/RD-87-001, November 1986.

11. Natural Rubber Bureau, Natural Rubber and You, Washington, D.C., 1951.

12. Gregg, L.E., "Additional Observation on the Use of Rubber in Bituminous Paving Mixtures," Technical Bulletin No. 194, American Road Builders Association, pp. 19-30, 1953.

13. LaGrone, B.D., "Rubber Used in Asphalt-Rubber Applications," Proc., National Seminar on Asphalt-Rubber, FHWA, pp. 241-256, October 1981.

14. Oliver, J.W.H., "Research on Asphalt-Rubber at the Australian Road Research Board," Proc., National Seminar on Asphalt-Rubber, FHWA, pp. 241-256, October 1981.

15. Berry, J.P., "Brittle Behavior of Polymeric Solids," Fracture Processes in Polymeric Solids, Interscience Publishers, 1964.

16. Benson, J.R., "New Concepts in Rubberized Asphalts," Roads and Streets, Vol. 28, No. 4, 1955.

17. Cannon, C.R. and Majidzadeh, K., "A Laboratory and Field Study on the Use of Elastomers in Hot-Mix Emulsified Asphalt," Highway Research Record 404, pp. 33-41, 1972.

18. Pavlovich, R.D., "Asphalt-Rubber, An Overview and Some Observations," Proc., Pacific Coast User/Producer Conference, San Francisco, California, May 1981.

19. Brand, B.G., Scrap Rubber Tire Utilization in Road Dressings, U.S. Environmental Protection Agency, Cincinnati, Ohio, March 1974.

20. Majidzadeh, et al., Application of Fracture Mechanics for Improved Design of Bituminous Concrete, Vol. 2, Final Report No. FHWA-RD-76-92, 1976.

21. Kelly, A., Strong Solids, Clarendon Press, 1966.

22. McGarry, F.J., Willner, A.M., and Sultan, J.N., "Relationships Between Resin Fracture and Composite Properties," AFML-TR-67-381, December 1967.

23. Schuler, Scott, Executive Summary of Asphalt Additives, New Mexico Engineering Research Institute, July 1986.

24. Resource International, Inc., A Preliminary Study of Chemkrete Additives, Final Report, Ohio Department of Transportation, June 1987.

25. Abdulshafi, A., Rheological Behavior of Rejuvenated Aged Asphalt, MSc. Thesis, OSU, 1981.

26. Majidzadeh, K., et al., Evaluation of Sulfur-Asphalt Paving Mixtures in Ohio: A Field and Laboratory Investigation, EES-590, ODOT, 1979.

27. Majidzadeh, K., Abdulshafi, A., and Elaithy, A., Sulphur-Extended Asphalt Mixtures in Ohio, Second Arab Regional Conference on Sulphur and Its Uses in the Arab World, Riyadh, Saudi Arabia, 1985.

28. Richey, Barry L. and Little, Dallas, N., "A Sulphlex Mixture Design Method Based on the Indirect Tensile Test," TRR 911, December 1983.

29. Majidzadeh, K., et al., "Material Chacteristics and Performance of Bottom Ashes in Bituminous Materials," Paper presented in the TRB Annual Meeting, 1979.

30. Majidzadeh, K., Bokowski, G., and El-Mitiny, R., "Material Characteristics of Power Plant Bottom Ashes and their Performance in Bituminous Mixtures: A Laboratory Investigation," Proc., Atlanta Ash Conference, 1979.

31. Air Force Civil Engineering Center, Evaluation of Rejuvenators for Bituminous Pavements, Technical Report 76-3, Tyndall Air Force Base, Florida, 1976.

32. Kenis, W.J., Predictive Design Procedure: VESYS User Manual, FHWA-RD-77-154, Final Report, 1978.

33. Moavenzadeh, F., Findakly, H.K., and Sousson, J.E., Synthesis for Rational Design of Flexible Pavements, FHWA Report 75-29, Washington, D.C., 1975.

34. Beckedahl, H., Gerlach, A., Lucke, H., and Schwaderer, W., "On Improvements of the Existing VESYS-Concepts," Sixth International Conference, Structural Design of Asphalt Pavements, 1987.

35. Valanis, K.C., "A Theory of Viscoplasticity Without a Yield Surface, Part I: General Theory; Part II: Applications to Mechanical Behavior of Metals," Arch. Mech. Stosowanej, No. 24, 1971.

36. Zienkiewicz, O.C., Norris, V., and Naylor, D.J., "Plasticity and Viscoplasticity in Soil Mechanics with Special Reference to Cyclic Loading Problems," Paper presented at the International Conference on Finite Elements in Nonlinear Solid and Structural Mechanics, Proc., Norway: Tapir Publisher, Norway, pp. 455-485, August 1977.

37. Abdulshafi, A., and Majidzadeh, K., "Comboviscoelastic/Plastic Modelling and Rutting of Asphaltic Mixtures," TRR No. 968, December 1984.

38. Abdulshafi, A. and Majidzadeh, K., "J-Integral and Cyclic Plasticity Approach to Fatigue and Fracture of Asphaltic Mixtures," TRR No. 1034, December 1985.

39. Abdulshafi, O., Rational Material Characterization of Asphalt Concrete Pavements, Ph.D. Dissertation, The Ohio State University, 1983.

40. Heislich, Herbert, et al., Theory and Problems of Organic Chemistry, New York, McGraw-Hill Book Company.

41. Dabin, J., Rapport de Recherche, No. 58/JPD/1958, Publ. Centre de Recherche, Routiers, Bruxelles, Belgium, 1958.

42. Rostler, F.S. and White, R.M., Symposium on Road and Paving Materials, 1959 ASTM-STP, No. 277, p. 64, 1960.

43. Barth, S.J., Asphalt Science and Technology, Gordon and Erenth, London and New York, 1962.

44. Dunning, R.L., and Mendenhall, R.L., Design of Recycled Asphalts and Selection of Modifiers, ASTM, STP 662, 1978.

45. Abdulshafi, A., Viscoelastic/Plastic Characterization, Rutting and Fatigue of Flexible Pavements, Ph.D., Dissertation, The Ohio State University, March, 1983.

46. Manson, S.S., "Interfaces Between Fatigue, Creep, and Fracture," International Journal of Fracture Mechanics, Vol. 1-2, pp. 327-363, 1965-1966.

47. Morrow, Jo Dean, "Cyclic Plastic Strain Energy and Fatigue of Metals," International Friction, Damping and Cyclic Plasticity, ASTM-STP378, pp. 45-87, 1965.

48. Weibull, W., Fatigue Testing and Analysis of Results, New York, Pergamon Press Ltd., 1960.

49. Landes, J.D. and Begley, J.A., Mechanics of Crack Growth, ASTM, STP 590, pp. 128-148, 1976.

APPENDIX A

INVENTORY LIST OF MODIFIERS AND SELECTED FLASH POINT DATA TO ASPHALT CONCRETE

TABLE A-1. INVENTORY LIST OF MODIFIERS TO ASPHALT CONCRETE (REFERENCE 34).

Product	Manufacturer	Description and Use	State/Status	
ARM-R-SHIELD	Arizona Refining Company P.O. Box 1453 Phoenix, Arizona 85001	Asphalt Rubber Compound	Oklahoma Pending	10/81
			Colorado Not Accepted	08/80
ASPHADUR	Minnesota Mining & Manufacturing Company St. Paul, Minnesota	Stability Additive for Asphalt Hot Mixes	Illinois Not Accepted	07/82
ASPHADUR (ADD-ITIVE 5990)	3M Company 3M Center St. Paul Minnesota 55101	Addive for Asphaltic Concrete	Iowa Accepted	12/78
ASPHDUR	3M Company 3M Center St. Paul, Minnesota 55101	Asphalt Additive	Missouri Not Accepted	10/80
BA-2000-D	Morton Thiokol Inc. Carstab Division West Street D Cincinnati, Ohio 45215	Asphalt Anti-Stripping Agent	Arizona Accept	09/84
BA-2000	Morton Thiokol Inc.	Anti-Strip Additive	Colorado Accepted	09/834
BA-2000	Carstab Corporation West Street Cincinnati, Ohio 45215	Asphalt Anti-Stripping Agent	Arizona Accepted	03/84
BONIFIBERS	Kapejo Inc. 3 Peirce Road Wilmington, DE 19803	Polyester Fibers to Asbestos Fibers in Asphaltic Concrete	Missour Pending	
BONIFIBERS		Bituminous Conctrete Reinforcing Fibers	Indiana Pending	11/80
CARSTAB BA-2000	Carstab Co. West Street Cincinnati, OH 45215	Anti-Stripping Agent for Open Graded Friction Coarse and Dense Graded Mixtures	Oklahoma Accepted Oregon Pending	01/89 08/84

TABLE A-1. INVENTORY LIST OF MODIFIERS TO ASPHALT CONCRETE (CONTINUED).

Product	Manufacturer	Description and Use	State / Status	
CHEM-CRETE	Chem-Crete Corp. 2180 Sand Hill Road Menlo Park, CA 94025	An Asphalt Additive to Increase Stability and Durability	Missouri Pending	
CHEM-CRETE BITYUMEN	Chem-Crete Corp. 2180 Sand Hill Road Menlo Park, CA 94025	To Improve the Stregth and Stability of Asphalt Concrete	Iowa Not Accepted	10/81
		Processed and Refinied to Increase Stability & Durability of Asphalt-Aggregate Mixtures	Oklahoma Pending	12/83
CRS-2S ASPHALT Emulsion	Bitucote Products Co. 100 Executive Pkwy P.O. Box 27327 St. Louis, MO 63141	Asphalt Emulsion With Styrelf Styrene Butadiene Polymer for Seal Coats	Illinois Pending	04/82
CRS-2S		Polymer Modified Asphalt	Oklahoma Pending	08/84
DOW LATEX	Dow Chemical Co. 1691 Swede Road Midland, MI 48640	Latex for Hot Mix Asphalt Concrete	Pennsylvania Pending	09/84
ES-6 FORTASHALT	Forta Fibre Inc. 100 Forta Drive Grove City, PENN 16127	80% Polypropylene Fibre & 20% Nylon, Carbon or Aramide Fibers for Bituminous Concrete Hot Mix	Pennsylvania Pending	03/84
EVA-POX #12	E-Poxy Industries Inc. 14 West Shore Street Ravena, New York 12143	Coaltar/Asphalt Mortar Mix	Pennsylvania Pending	05/83
FIBER PAVE	Hercules, Inc 910 Market Street Wilmington, DE 19889	Polypropylene Fiber Additive for Asphalt	Illinois Accepted	08/83
			Louisiana Pending	06/82

TABLE A-1. INVENTORY LIST OF MODIFIERS TO ASPHALT CONCRETE (CONTINUED).

Product	Manufacturer	Description and Use	State / Status	
FIBERCON REINFORCING FIBERS	Mitchell Fibercon, Inc. 9800 McKnight Road Pitt., Penn 15237	Steel Fibers for Bituminous Concrete	Pennsylvania Pending	05/83
FLO MIX AND G-274	US Rubber Reclaiming Co. P. O. Box 54 Vicksburg, MISS 39180	Powdered Devulcanized Rubber Mixture for Asphalt	Indiana Not Accepted	07/78
HERCULON FIBER PAVE	Hercules Incorporated 910 Market Steet Wilmington, DE 19899	Polypropylene Fibers Added to Hot & Cold Mixes to Improve Toughness Reflective Cracking	Alabama Accepted	03/79
KAY-O-CEL	Amer. Fillers & Abrasives 14 Industrial Park Drive Bangor, MI 49013	Fiber Reinforcement for Asphalts (Asbestos Alternative)	Pennsylvania Pending	09/81
MICROFIL 8	Cabot Corp. Billerica, MA	Carbon Black Additive for Bituminous Mixtures	Illinois Pending	12/84
MINERAL FILLER	Anderson-Dunham, Inc. P. O. Box 1028 Baton Rouge, LA 70821	Mineral Filler-Hot Mix Asphalt	Louisiana Pending	08/76
NOPHALT	Chem-Crete Corp. Menlo Park, CA	Speciallity Processed Asphalt for High Stability and Reduced Temperature Susceptibility	Illinois Pending	03/80
NOPHALT			Pennsylvania Pending	04/80
NOPHALT			Indiana Pending	11/80
OVER-FLEX	Sahuaro Petroleum & Asphalt Co. 731 North 19th Avenue Phoenix, Arizona 85005	Asphalt-Rubber Mixture for SAM, SAMI, and Joint and Crack Filling	Illinois Pending	09/79

TABLE A-1. INVENTORY LIST OF MODIFIERS TO ASPHALT CONCRETE (CONTINUED).

Product	Manufacuter	Description and Use	State / Status	
OVERFLEX	Crafco P.O. Box 20133 Phoenix, Arizona 85036	23 Plus or Minus 3 % Granulated Rubber & 77 Plus or Minus 3 % Asphalt Cement	Oklahoma Pending	10/84
OVERFLEX MS	Crafco Inc. Phoenix, Arizona 85036	Rubber Asphalt	Arizona Accepted	04/78
PAVE BOND	Thiokol/Garstab Corp. West Street Cincinnati, OH 45215	Anti-Stripping Agent	Arizona Accepted	03/76
PAVE BOND AP	Thiokol/Garstab Corp. Cincinnati, OH 45215	Anti-Stripping Agent	Arizona Accepted	08/80
PLIOPAVE L-170	Goodyear Tire & Rubber Co. Akron, Ohio	Synthetic Rubber Latex Additive for Asphalt Hot Mixes	Illinois Accepted	04/73
PLIOPAVE MS	Goodyear Tire & Rubber Co. Akron, Ohio	Ashalt Modification for Any Type Asphalt Application	Michigan Pending	
PLUSRIDE	All Seasons Surfacing Corp. Bellevuae, WA 98004	Rubberized Asphaltic Cement	Oklahoma Pending	10/81
POLYESTER FIBER P-221	E I DuPont De Nemours & Co. Wilmington, DE	Polyester Fiber Additive for Asphalt Mixes	Illinois Not Accepted	04/81
POLYESTER FIBERS P-262	E I DuPont De Nemours & Co Centre Road Building Wilmington, DE 19898	Replacement for Asbestos in Hot Mix Hot Laid Bituminous Concrete Curb Mixes	Delaware Accepted	11/75
POLYF-REINFILLER # 164	Bonner-Ply Chemical 3505 Pomona Blvd. Pomona, CA 91768		Louisiana Pending	12/82
PLYSAR LATEX	Polysar, Inc Chattanooga, TN	Latex Modifier for Asphalt Cement	Illinois Accepted	07/81

TABLE A-1. INVENTORY LIST OF MODIFIERS TO ASPHALT CONCRETE (CONTINUED).

Product	Manufacturer	Description and Use	State / Status
POLYSAR LATEX PL275, PL298, PL420 & D9-2217	Polysar Latex 3805 Amnicola Hwy Chattanooga, TN 37406	Latex for Bituminous Mixes	Pennsylvania Pending 06/84
POLYSAR LATEX RUBBER	Polysar Latex Corp. 2200 Polymer Drive Chattanooga, TN 37421	S. B. R. Latex Rubber as a Asphalt Overlay Modifier	Delaware Pending 06/83
POLYSAR LATEX XE-261	Tex-Crete Inc 422 Delany Road Zion, IL 60099	Latex Modifer for Asphalt Cement	Missouri Pending
RECOPAVE	Mulco, Inc Mid Western Admixture Corp. P. O. Box 594 Park Ridge, IL 60068	Admixture for Thin Bituminous Surface courses	Louisiana Not Accepted 02/83
			Pennsylvania Pending 02/83
ROSPHALT 50	Royson Laboratories Inc. Pittsburgh, Penn	Rubberized Bitumen Additive for Low Void Sand Asphalt Hot Mixes	Illinois Pending 12/83
SOLAR-LAGLUGEL	NHI, Ltd. Chicago, Illinois	Nylon Gel Additive for Asphalt Cement	Illinois Pending 07/80
STYRELF CRS-25 EMULSION	Bitucote Products 1824 Knox Avenue St. Louis, Missouri 63139	Polymer Asphalt Emulsion for Seal Coats	Missouri Pending
SULPHUR EXTENDED ASPHALT		Sulphur-Asphalt Blend Designed to Reduce the Amount of Asphalt Necessary in a Conventional Asphaltic Concrete Roadway	Delaware Pending

TABLE A-1. INVENTORY LIST OF MODIFIERS TO ASPHALT CONCRETE (CONCLUDED).

Product	Manufacuturer	Description And Use	State / Status
ULTRAPAVE	Textile Rubber & Chemical Company, Inc. 1300 Tiarco Drive S.W. Dalton, GA 30720		Louisiana Pending 06/83
	Textile Rubber & Chemical	Styrene/Butadiene Rubber Latex for Adding to Asphalt	Pennsylvania Pending 08/83
XE-261 LATEX	Polysar Latex Chattanooga, Tenn 37406	Latex for Latex Modified Asphalt Paving	Oklahoma Pending 10/84

TABLE A-2. FLASH POINTS DATA FOR SELECTED MODIFIERS AS PROVIDED BY THE MANUFACTURER.

MODIFIER TYPE	FLASH POINT INFORMATION
ESL	N/A - Material safety data sheet (MSDS) rating zero for fire hazard. Non-flammable unless all of water is evaporated and the dry polymer is heated substantially over 350 ^{o}F for extended time or exposed to open ignition source.
SBS	400 - 450 ^{o}F (electrostatic buildup to be avoided).
PP	450 ^{o}F
ER	N/A - (Flash ignition temperature 500 ^{o}F).
EVA	430 ^{o}F - (Anti-ignition 480 ^{o}F).
FCB	600 ^{o}F (500 ^{o}F oil used in product only -6%).
AC-20	450 ^{o}F
AC-10	450 ^{o}F

APPENDIX B

TEST METHODS AND PROCEDURES

APPENDIX B

TEST METHODS AND PROCEDURES

A. The CVP Method

This test is an extension to the creep-rutting test cited under the incremental static-dynamic series of the VESYS II M User's Manual (Reference 32). The modification to this test is in Step 4 of static-creep portion as follows:

4. Incremental Static Loading:

   (a) Apply one ramp load of 20 psi to the specimen as quickly as possible and hold load for 0.1 second. Release the load and measure total permanent deformation after two minutes of unload. See Figure B-1 for a description of the loading function. If the deformation under load starts to exceed 2500 micro-units of strain, immediately reduce the maximum stress level by 5 psi. If the deformation starts to exceed 2500 microunit strain, then reduce the stress level by another 5 psi. Wait 30 minutes and repeat Step 4(a) at this level.

   (b) Apply a second ramp load to the specimen at the same stress level used above and hold for 1 second. Release the load and measure the total permanent deformation after 2 minutes of unload.

   (c) Apply a third ramp load to the specimen at the level used in 4(a) and hold for 10 seconds. Release the load and measure the permanent deformation after 2 minutes of unload or when rebound becomes negligible.

   (d) Apply a fourth ramp load to the specimen at the level used in 4(a) above and hold for 100 seconds. Release the load and measure the total permanent deformation remaining after four minutes of unload or when rebound becomes negligible.

   (e) Apply a fifth ramp load to the specimen at the level used in 4(a) above and hold for 1000 seconds. Measure the magnitude of the creep deformation during loading after 0.03, 0.1, 1.0, 3.0, 10.0, 30.0, 100.0 and 1000.0 seconds. Release the load and measure the total permanent deformation after eight minutes of unload or when rebound becomes negligible.

σ_2 = 0.5 ultimate strength

σ_3 = 0.75 ultimate strength

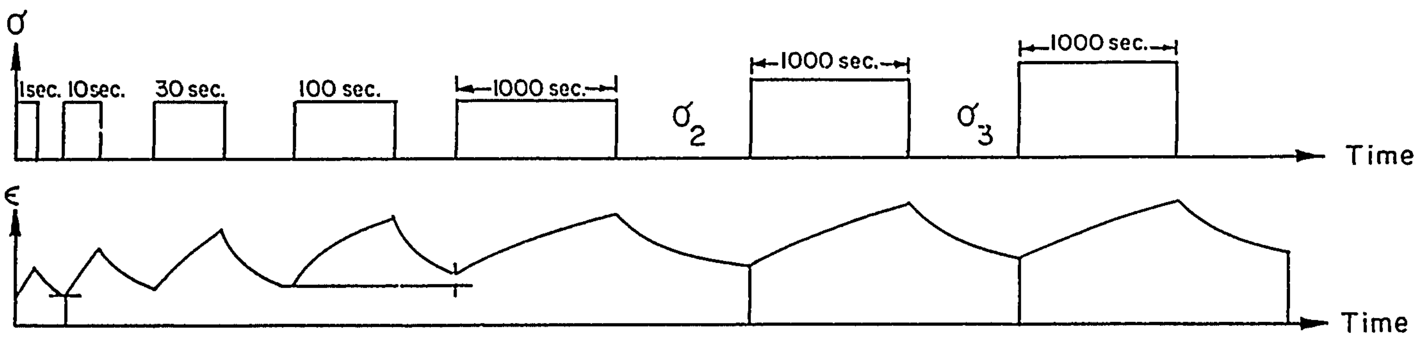

Figure B-1. Incremental Static Rutting-Creep Series.

5. Apply a sixth ramp load to the specimen at a level equal to 0.5 σ_y obtained from the indirect tensile test and hold for 1000 seconds. Measure the magnitude of creep deformation, release the load, and measure the permanent deformation as in Step 4(e) above.

6. Apply a seventh ramp load to the specimen at a level equal to 1.5 times that of Step 5 above and hold for 1000 seconds. Measure the magnitude of creep deformation, release the load, and measure the permanent deformation as in Step 4(e) above.

NOTE: Loading and response simulations are shown in Figure B-1.

B. THE C*-LINE INTEGRAL TEST

This test procedure follows the method described below (Reference 33). However, the sample preparation and testing is identical to the method developed by the Dr. Abdulshafi for the J-integral; the only difference is the requirement to measure both the load, displacement, and time simultaneously, while the J-integral is required to measure the load and displacement simultaneously. The C*-line integral test procedure is as follows:

1. Assumptions

- Crack tip stress-strain singularity for large-scale yielding exists.
- Two-dimensional space (or less) problems only should be considered; mainly plane strain problems are considered.
- Deformation theory of plasticity is assumed; i.e., unloading is not permitted.

2. Specimens

A Marshall-type specimen is used. This is a cylindrical disk with a 4-inch diameter and a 2.5-inch thickness. These dimensions are compatible with the requirement of plane strain condition to be achieved. Field- extracted cores could also be processed to have the same dimensions; however, a minimum thickness of 2 inches should not be violated.

A right-angled wedge is cut into the disc specimen to accommodate the loading device. The wedge should be cut to a depth of 0.75 inch along the specimen diameter and extended over the whole thickness, as shown in Figure 3. Care should be exercised to ensure symmetry of the wedge about the vertical axis and smoothness of cut surfaces for proper contact with the loading steel wedges. A very small, artificially made crack should be sawed at the tip of the wedge (notch) to channelize crack initiation. It is preferable that the vertical strip that includes the notch tip be painted a lighter color to clearly distinguish crack initiation and propagation processes. A vertical line extending from the notch tip to the contact point of the seating rod should be marked and scaled. It is preferable to paint the two faces of the specimens along the vertical line with light color paint.

A gradually and slowly increasing monotonic load is applied to the sample until a crack is noticed. The load should be maintained until the required crack size is reached. Identical samples with different crack sizes should be made as above.

3. Experimental Setup

The experimental setup is similar to the indirect tensile strength test method, ASTM D-4123. The sample is seated on a steel bar of 1-inch-by-1-inch cross-section and 2.5-inch length. The steel bar face in contact with the specimen should have a circular groove along the whole length with such a diameter as to assure proper contact with the specimen. The steel bar should be placed over the testing machine base plate. The notched part of the specimen should be pointing towards the loading head of the testing machine. Two steel plate wedges matching the notch surfaces are placed in their respective positions while a semicircular piece of road of sufficient length and rigidity is used to transmit the vertical load to the plate wedges. The dimensions of the wedge, plates, and semicircular rod are such that symmetry of loading is maintained about the vertical axis. Alignment of the sample is such that the tip of the wedge is exactly lined up with the point of the contact with the seating rod and is also lined up with the applied load. This alignment is of great importance and will affect test results if not achieved.

4. Test Procedure

a. Set up the sample to have proper alignment.

b. Bring the machine loading head into contact with the loading device and apply a slow ramp loading and observe the crack developed to reach the required size, at which point loading should be released. The crack size should then be measured accurately.

c. The test procedure from this point on is identical to the indirect tensile test with the following modification:

(1) Apply a load at constant stroke rate.

(2) Monitor and record the load and crack length at 0.2-inch intervals until failure.

(3) Repeat steps (1) and (2) on a new specimen with different stroke rate.

(4) At least three stroke rates should be chosen and three specimens for each stroke rate tested.

C. INTERPRETATION OF TEST RESULTS

This section outlines how interpretation of test results will be made. Actual interpretation will be given in the final report.

1. Aging Index

$IAR \leq 1$

2. The CVP Testing

$[\sigma_{yield}]_m > [\sigma_{yield}]_r$

$[CR]_m < [CR]_r$

where:

σ_{yield} = The yield point of the mix; i.e., the stress at which plastic deformation commences.

m, r = Refer to modified and reference mixture, respectively.

$[CR]_m$ = The creep deformation rate of the modified mixture, micro in/in psi.

3. The C*-Line Integral

$[C^*]_m > [C^*]_r$

$[a]_m < [a]_r$ for the same C*

where:

[C*] = The energy release rate line integral for time-dependent material

[a] = The crack growth rate

m,r As previously defined

APPENDIX C

PHASE I TEST RESULTS

TABLE C-1. CREEP COMPLIANCE DATA BEFORE AGING.

AC-20	HEIGHT (in)	LOAD (lbs)	STRESS (psi)	$J(t) \times 10^{-4}$ (psi^{-1})					
				1	3	10	30	100	1000
	2.00	188	15	0.054	0.077	0.122	0.170	0.221	0.390
	2.00	502	40	0.049	0.072	0.111	0.160	0.231	0.444
	2.00	1005	80	0.037	0.064	0.101	0.148	0.199	0.334
	2.00	2010	160	0.048	0.072	0.102	0.135	0.167	0.258

AC-10	HEIGHT (in)	LOAD (lbs)	STRESS (psi)	$J(t) \times 10^{-4}$ (psi^{-1})					
				1	3	10	30	100	1000
	2.00	188	15	0.070	0.107	0.158	0.206	0.264	0.380
	2.00	502	40	0.071	0.110	0.167	0.228	0.325	0.533
	2.00	1005	80	0.073	0.106	0.148	0.192	0.246	0.376
	2.00	2010	160	0.077	0.106	0.129	0.157	0.186	0.252

TABLE C-1. CREEP COMPLIANCE DATA BEFORE AGING (CONTINUED).

ESL	HEIGHT (in)	LOAD (lbs)	STRESS (psi)	$J(t) \times 10^{-4}$ (psi^{-1})					
				1	3	10	30	100	1000
	2.00	188	15	0.067	0.120	0.191	0.259	0.345	0.445
	2.00	502	40	0.070	0.109	0.169	0.233	0.304	0.427
	2.00	1005	80	0.074	0.109	0.141	0.176	0.214	0.274
	2.00	2010	160	0.070	0.095	0.112	0.141	0.158	0.206

SBS	HEIGHT (in)	LOAD (lbs)	STRESS (psi)	$J(t) \times 10^{-4}$ (psi^{-1})					
				1	3	10	30	100	1000
	2.00	188	15	0.088	0.135	0.204	0.276	0.356	0.517
	2.00	502	40	0.096	0.143	0.195	0.262	0.344	0.498
	2.00	1005	80	0.111	0.144	0.181	0.223	0.274	0.362
	2.00	2010	160	0.095	0.119	0.141	0.166	0.196	0.249

TABLE C-1. CREEP COMPLIANCE DATA BEFORE AGING (CONTINUED).

PP	HEIGHT (in)	LOAD (lbs)	STRESS (psi)	$J(t) \times 10^{-4}$					(psi^{-1})
				1	3	10	30	100	1000
	2.00	188	15	0.030	0.045	0.062	0.090	0.112	0.198
	2.00	502	40	0.026	0.039	0.057	0.080	0.126	0.269
	2.00	1005	80	0.018	0.040	0.060	0.086	0.129	0.237
	2.00	2010	160	0.023	0.040	0.060	0.089	0.112	0.188

ER	HEIGHT (in)	LOAD (lbs)	STRESS (psi)	$J(t) \times 10^{-4}$					(psi^{-1})
				1	3	10	30	100	1000
	2.00	188	15	0.098	0.150	0.199	0.266	0.311	0.398
	2.00	502	40	0.096	0.135	0.186	0.248	0.318	0.450
	2.00	1005	80	0.077	0.109	0.141	0.176	0.211	0.292
	2.00	2010	160	0.056	0.076	0.190	0.229	0.148	0.199

TABLE C-1. CREEP COMPLIANCE DATA BEFORE AGING (CONTINUED).

EVA	HEIGHT	LOAD	STRESS	$J(t) \times 10^{-4}$					(psi^{-1})
	(in)	(lbs)	(psi)	1	3	10	30	100	1000
	2.00	188	15	0.071	0.116	0.146	0.195	0.259	0.375
	2.00	502	40	0.084	0.112	0.152	0.200	0.247	0.340
	2.00	1005	80	0.067	0.084	0.120	0.134	0.165	0.211
	2.00	2010	160	0.074	0.081	0.095	0.105	0.120	0.148

FCB AC-20	HEIGHT	LOAD	STRESS	$J(t) \times 10^{-4}$					(psi^{-1})
	(in)	(lbs)	(psi)	1	3	10	30	100	1000
	2.00	188	15	0.066	0.098	0.129	0.165	0.204	0.268
	2.00	502	40	0.058	0.084	0.115	0.147	0.193	0.269
	2.00	1005	80	0.060	0.087	0.117	0.145	0.178	0.267
	2.00	2010	160	0.060	0.083	0.096	0.114	0.134	0.176

TABLE C-1. CREEP COMPLIANCE DATA BEFORE AGING (CONCLUDED).

FCB AC-10	HEIGHT (in)	LOAD (lbs)	STRESS (psi)	$J(t) \times 10^{-4}$ (psi^{-1}) 1	3	10	30	100	1000
	2.00	188	15	0.135	0.184	0.255	0.319	0.398	0.517
	2.00	502	40	0.110	0.163	0.228	0.290	0.371	0.520
	2.00	1005	80	0.105	0.158	0.193	0.236	0.292	0.366
	2.00	2010	160	0.090	0.115	0.141	0.169	0.197	0.257

TABLE C-2. C*-LINE INTEGRAL TEST RESULTS, (DISPLACEMENT RATE .01 IN./MIN.).

Modifer	Crack Length, in.	.4 (1 Cm)	.8 (2 Cm)	1.2 (3 Cm)	1.6 (4 Cm)	2.0 (5 Cm)	2.4 (6 Cm)	2.8 (7 Cm)
AC-10 #1	Time, Min.	4.09	4.30	4.48	5.40			
	Load, Lbs.	200	150	125	75			
AC-10 #2	Time, Min.	2.34	2.42	2.57	3.06	3.55	5.12	5.58
	Load, Lbs.	450	375	250	187	62	25	12
AC-10 #3	Time, Min.	3.16	3.28					
	Load, Lbs.	225	125					
AC-20 #1	Time, Min.	2.59	3.07	3.15	3.28	3.47	5.10	
	Load, Lbs.	650	575	350	125	100	0	
AC-20 #2	Time, Min.	3.30	3.36	3.47	3.52	3.58	4.50	8.03
	Load, Lbs.	688	650	620	588	525	212	20
AC-20 #3	Time, Min.	3.28	3.33	3.41	3.47	4.03	5.18	9.00
	Load, Lbs.	750	725	675	600	475	88	25
FCB/ AC-10 #1	Time, Min.	2.39	2.99	2.52	2.58	3.50	5.35	7.07
	Load, Lbs.	750	625	250	250	75	50	20
FCB/ AC-10 #2	Time, Min.	2.22	2.30	2.40	2.52	3.20	3.59	
	Load, Lbs.	575	450	350	275	175	112	

TABLE C-2. C*-LINE INTEGRAL TEST RESULTS, (DISPLACEMENT RATE .01 IN./MIN.), (CONTINUED).

FCB/ AC-10 #3	Time, Min.	2.10	2.15	2.28	2.48	3.12	3.34	3.50
	Load, Lbs.	838	700	550	275	125	100	62
PP* #1	Time, Min.	3.30	3.40	3.58	4.58	6.02	7.48	13.40
	Load, Lbs.	325	300	175	75	62	25	0
PP* #2	Time, Min.	2.55	3.07	3.19	3.40			
	Load, Lbs.	700	450	200	75			
PP* #3	Time, Min.	3.04	3.10	3.20	3.32	3.59	4.09	6.05
	Load, Lbs.	712	625	550	412	262	225	100
ESL #1	Time, Min.	3.07	3.21	3.43	4.02	4.43	5.45	8.40
	Load, Lbs.	875	900	625	450	250	175	25
ESL #2	Time, Min.	4.03	4.10	4.18	4.33	4.52	6.09	
	Load, Lbs.	875	700	500	350	225	75	
FCB/ AC-20 #1	Time, Min.	2.58	3.20	3.40	3.51	4.03	6.45	8.37
	Load, Lbs.	1200	900	325	300	275	75	25
FCB/ AC-20 #2	Time, Min.	2.22	2.30	2.40	2.52	3.20	3.59	
	Load, Lbs.	575	450	350	275	175	112	

TABLE C-2. C*-LINE INTEGRAL TEST RESULTS, (DISPLACEMENT RATE .01 IN./MIN.), (CONTINUED).

SBS #1	Time, Min.	2.20	2.56	3.06	3.14	3.52	5.30	6.50
	Load, Lbs.	950	225	175	150	100	50	0
SBS #2	Time, Min.	4.11	4.19	4.35	4.52	5.21	5.38	6.59
	Load, Lbs.	725	725	700	600	300	200	50
SBS #3	Time, Min.	3.09	3.17	3.34	3.45			
	Load, Lbs.	600	425	262	188			
EVA #1	Time, Min.	2.35	2.44	2.54	3.13	3.24	3.35	5.21
	Load, Lbs.	825	850	850	800	525	500	125
EVA #2	Time, Min.	2.34	2.38	2.45	3.07	3.18	3.39	4.05
	Load, Lbs.	750	725	575	175	100	60	40
ER #1	Time, Min.	2.20	2.27	2.37	2.50	3.15	4.10	8.04
	Load, Lbs.	525	450	425	325	200	125	0
ER #2	Time, Min.	2.09	2.13	2.19	2.28	2.39	3.04	3.49
	Load, Lbs.	825	825	825	750	575	250	50
ER #3	Time, Min.	2.31	2.42	2.54	3.08	3.52	5.08	
	Load, Lbs.	700	700	650	575	275	125	

TABLE C-2. C* - LINE INTEGRAL TEST RESULTS, (DISPLACEMENT RATE .013 IN./MIN.).

Modifer	Crack Length, in.	.4 (1 Cm)	.8 (2 Cm)	1.2 (3 Cm)	1.6 (4 Cm)	2.0 (5 Cm)	2.4 (6 Cm)	2.8 (7 Cm)
AC-10 #1	Time, Min.	5.45	6.04	6.34	6.54	7.14	8.59	13.35
	Load, Lbs.	575	400	225	125	125	75	0
AC-10 #2	Time, Min.	4.41	5.00	5.14	5.37	6.09	8.01	
	Load, Lbs.	312	262	225	187	137	37	
AC-10 #3	Time, Min.	5.13	5.27	5.50	6.08	7.04	9.02	
	Load, Lbs.	200	175	125	120	87	12	
AC-20 #1	Time, Min.	4.25	4.42	5.04	6.00	7.05	8.18	13.39
	Load, Lbs.	575	525	500	300	175	112	25
AC-20 #2	Time, Min.	4.28	4.42	4.52	5.58	7.02		
	Load, Lbs.	700	725	700	550	200		
AC-20 #3	Time, Min.	4.55	5.35	6.42	7.40	8.00	8.35	13.20
	Load, Lbs.	700	625	288	150	125	100	25
FCB/ AC-10 #1	Time, Min.	3.35	4.53	5.20	5.54	7.24	8.46	
	Load, Lbs.	600	175	150	100	50	25	

TABLE C-2. C*-LINE INTEGRAL TEST RESULTS, (DISPLACEMENT RATE .013 IN./MIN.), (CONTINUED).

FCB/ AC-10 #2	Time Min.	4.47	5.15	5.44	6.22	7.11	9.30	
	Load, Lbs.	625	525	350	250	112	37	
FCB/ AC-10 #3	Time, Min.	2.44	2.55	3.06	3.15	3.51	4.34	5.54
	Load, Lbs.	400	375	350	275	150	88	12
PP* #1	Time, Min.	5.55	6.11	6.28	6.45	7.35	8.54	
	Load, Lbs.	900	900	800	525	250	0	
PP* #2	Time, Min.	4.55	5.07	5.19	5.33	6.15	8.36	
	Load, Lbs.	625	375	300	225	137	12	
PP* #3	Time, Min.	3.04	3.18	3.35	4.00	4.22	6.33	10.25
	Load, Lbs.	425	412	388	300	275	75	25
ESL #1	Time, Min.	5.00	5.12	5.33		8.04	9.08	14.20
	Load, Lbs.	1000	975	875	625	225	162	25
ESL #2	Time, Min.	4.08	4.17	4.36	4.49	6.03	6.58	7.36
	Load, Lbs.	1100	1075	950	500	188	125	100
ESL #3	Time, Min.	4.14	4.26	4.45	5.25	6.43	7.03	
	Load, Lbs.	875	875	850	750	250	200	

TABLE C-2. C*-LINE INTEGRAL TEST RESULTS, (DISPLACEMENT RATE .013 IN./MIN.), (CONTINUED).

FCB/ AC-20 #1	Time, Min.	4.02	4.17	4.38	5.21	6.11	6.50	7.12
	Load, lbs.	950	975	950	750	375	225	200
FCB/ AC-20 #2	Time, Min.	4.16	4.30	5.04	5.30	5.55	6.58	8.04
	Load, lbs.	925	925	875	575	375	225	112
FCB/ AC-20 #3	Time, Min.	4.28	4.36	5.25	6.04	6.28	7.30	8.20
	Load, Min.	800	800	650	475	338	175	100
SBS #1	Time, Min.	4.20	4.36	4.59	5.22	6.39	7.40	9.03
	Load, lbs.	1050	1075	900	300	125	75	50
SBS #2	Time, Min.	4.17	4.32	4.51	5.19	6.46	7.25	9.05
	Load, lbs.	850	750	425	188	88	60	20
SBS #3	Time, Min.	4.22	4.37	4.44	4.55	5.26	6.33	7.55
	Load, lbs.	725	500	325	260	175	100	25
EVA #1	Time, Min.	4.54	5.09	5.36	5.55	6.20	8.40	10.22
	Load, lbs.	625	600	550	350	225	100	62
EVA #2	Time, Min.	4.02	4.16	4.27	4.50	5.16	6.03	7.30
	Load, lbs.	700	650	600	250	110	62	12

TABLE C-2. C*-LINE INTEGRAL TEST RESULTS, (DISPLACEMENT RATE .013 IN./MIN.), (CONTINUED).

EVA #3	Time, Min.	3.57	4.15	4.29	4.40	4.52	5.30	7.28
	Load, lbs.	750	725	550	500	350	200	25
ER #1	Time, Min.	4.28	4.42	5.17	5.54	7.02		
	Load, lbs.	525	500	450	250	0		
ER #2	Time, Min.	3.40	3.55	4.56	6.36	7.10	7.58	8.30
	Load, lbs.	662	660	462	137	75	50	12
ER #3	Time, Min.	4.06	4.30	5.23	6.07	7.27	8.45	
	Load, lbs.	450	350	225	175	75	12	

TABLE C-2. C* - LINE INTEGRAL TEST RESULTS, (DISPLACEMENT RATE .019 IN./MIN.).

MODIFER	Crack Length, in.	.4 (1 cm)	.8 (2 cm)	1.2 (3 cm)	1.6 (4 cm)	2.0 (5 cm)	2.4 (6 cm)	2.8 (7 cm)
AC-10 #1	Time, Min.	7.00	7.09	7.22	7.37	7.53	9.40	10.50
	Load, lbs.	300	300	225	200	125	75	50
AC-10 #2	Time, Min.	4.40	5.08	5.39	6.45	7.32	8.29	
	Load, lbs.	300	262	250	200	150	625	
AC-10 #3	Time, Min.	5.57	6.12	6.38	8.18	7.18	9.03	11.09
	Load, lbs.	375	350	275	100		75	37
AC-20 #1	Time, Min.	5.07	5.17	6.03	6.43	7.03	7.47	10.43
	Load, lbs.	550	525	375	240	200	150	62
AC-20 #2	Time, Min.	6.00	6.15	6.41	7.10	7.58	8.40	10.02
	Load, lbs.	850	875	825	575	225	100	50
AC-20 #3	Time, Min.	5.57	6.04	6.14	6.54	7.42	9.22	10.36
	Load, lbs.	375	350	325	200	125	62	25
FCB/ AC-10 #1	Time, Min.	6.38	7.02	7.53	8.44	9.22		
	Load, lbs.	375	275	200	125	100		
FCB/ AC-10 #2	Time, Min.	4.40	4.56	5.20	5.55	6.40	8.30	10.12
	Load, lbs.	600	450	325	188	125	75	50

TABLE C-2. C*-LINE INTEGRAL TEST RESULTS, (DISPLACEMENT RATE .019 IN./MIN.), (CONTINUED).

FCB/ AC-10 #3	Time, Min.	5.50	5.25	5.51	6.25	6.34	6.25	6.10
	Load, lbs.	788	750	700	300	225	300	
PP* #1	Time, Min.	9.02	9.18	9.39	10.01	11.27	12.30	12.40
	Load, lbs.	650	625	575	525	225	150	125
PP* #2	Time, Min.	5.34	6.40	7.58	8.30	9.20	10.30	12.40
	Load, lbs.	725	600	225	150	100	50	
PP* #3	Time, Min.	5.42	5.52	6.28	6.46	7.26	8.40	13.58
	Load, lbs.	650	600	375	275	188	125	25
ESL #1	Time, Min.	6.56	7.08	7.20	7.42	8.45	10.09	14.52
	Load, lbs.	900	875	850	825	600	350	125
ESL #2	Time, Min.	6.29	6.42	7.05	8.16	9.29	11.22	
	Load, lbs.	700	588	450	150	100	75	
ESL #3	Time, Min.	6.06	6.23	6.39	6.58	7.24	10.38	13.59
	Load, lbs.	575	525	475	425	350	150	25

TABLE C-2. C*-LINE INTEGRAL TEST RESULTS, (DISPLACEMENT RATE .019 IN./MIN.), (CONTINUED).

FCB/ AC-20 #1	Time, Min.	5.26	6.21	6.32	6.42	6.56	7.28	14.39
	Load, Lbs.	650	375	350	340	275	225	75
FCB/ AC-20 #2	Time, Min.	4.40	5.02	5.30	6.04	6.44	8.09	11.04
	Load, Lbs.	725	700	562	350	200	75	12
FCB/ AC-20 #3	Time, Min.	4.17	4.47	5.20	5.56	6.46	7.44	9.52
	Load, Min.	788	712	588	300	162	88	25
SBS #1	Time, Min.	5.32	6.03	6.20	6.30	8.32	9.43	10.50
	Load, Lbs.	825	775	625	550	150	125	100
SBS #2	Time, Min.	6.39	6.45	6.57	7.18	7.59	8.53	12.14
	Load, Lbs.	625	600	500	400	150	112	12
SBS #3	Time, Min.	6.28	6.35	6.50	7.20	8.04	9.06	
	Load, Lbs.	725	700	638	425	238	138	
EVA #1	Time, Min.	6.30	6.42	6.58	7.11	7.57	9.07	9.15
	Load, Lbs.	475	450	375	350	150	100	80
EVA #2	Time, Min.	6.13	6.32	6.50	7.08	7.36	8.14	9.04
	Load, Lbs.	575	312	175	138	100	75	25

TABLE C-2. C*-LINE INTEGRAL TEST RESULTS, (DISPLACEMENT RATE .019 IN./MIN.), (CONCLUDED).

EVA #3	Time, Min.	5.37	5.51	6.12	6.38	7.07	8.03	8.59
	Load, Lbs.	600	575	500	400	250	150	100
ER #1	Time, Min.	5.21	5.36	5.44	6.01	6.26	9.29	
	Load, Lbs.	450	400	350	330	200	25	
ER #2	Time, Min.	6.42	6.50	7.02	7.20	8.16	9.37	
	Load, Lbs.	500	475	400	275	125	37	
ER #3	Time, Min.	7.07	7.14	7.22	7.42	8.41	10.20	11.44
	Load, Lbs.	512	450	412	338	188	112	75

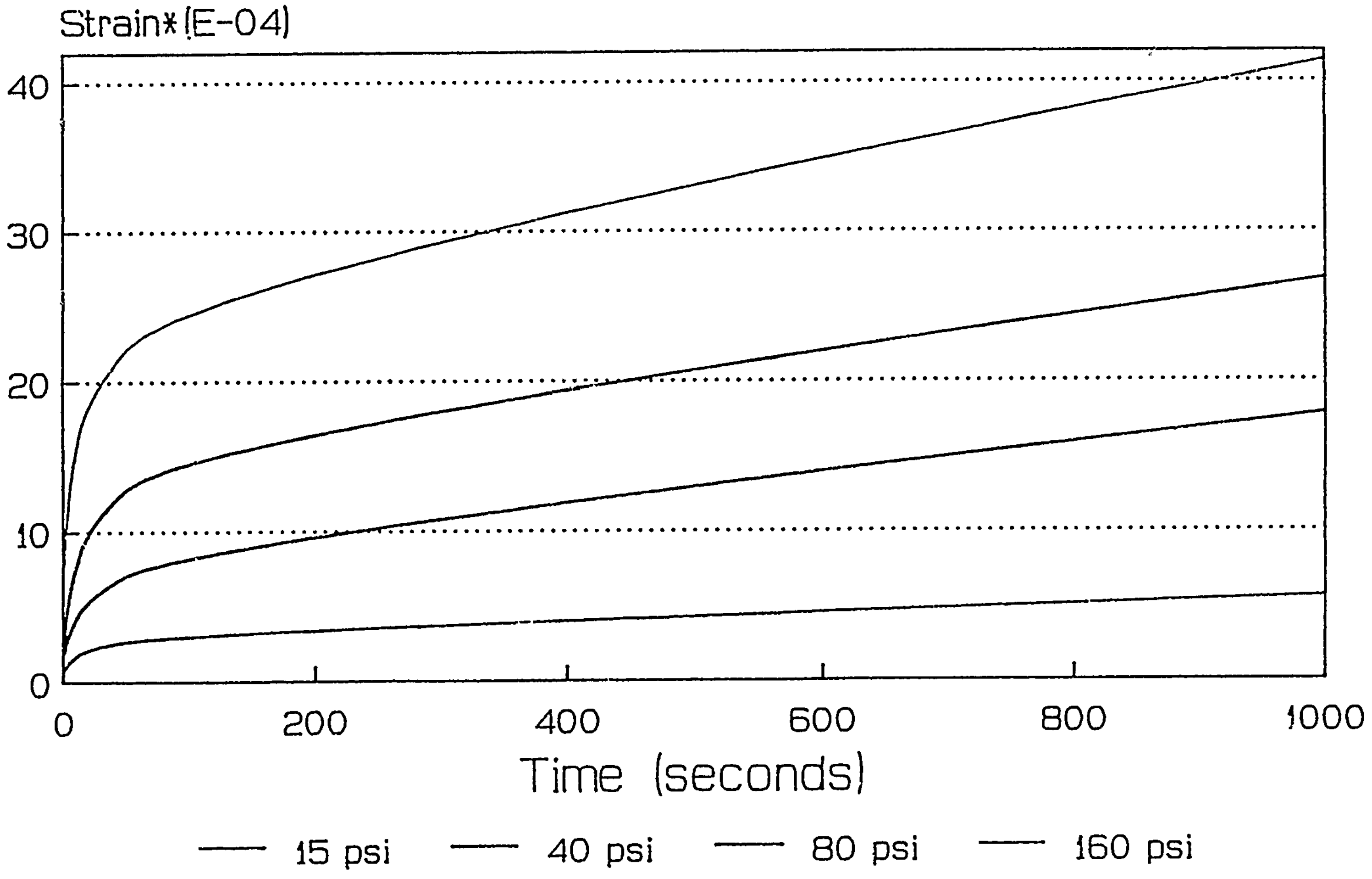

Figure C-1. Compression Rutting-Creep for AC-20.

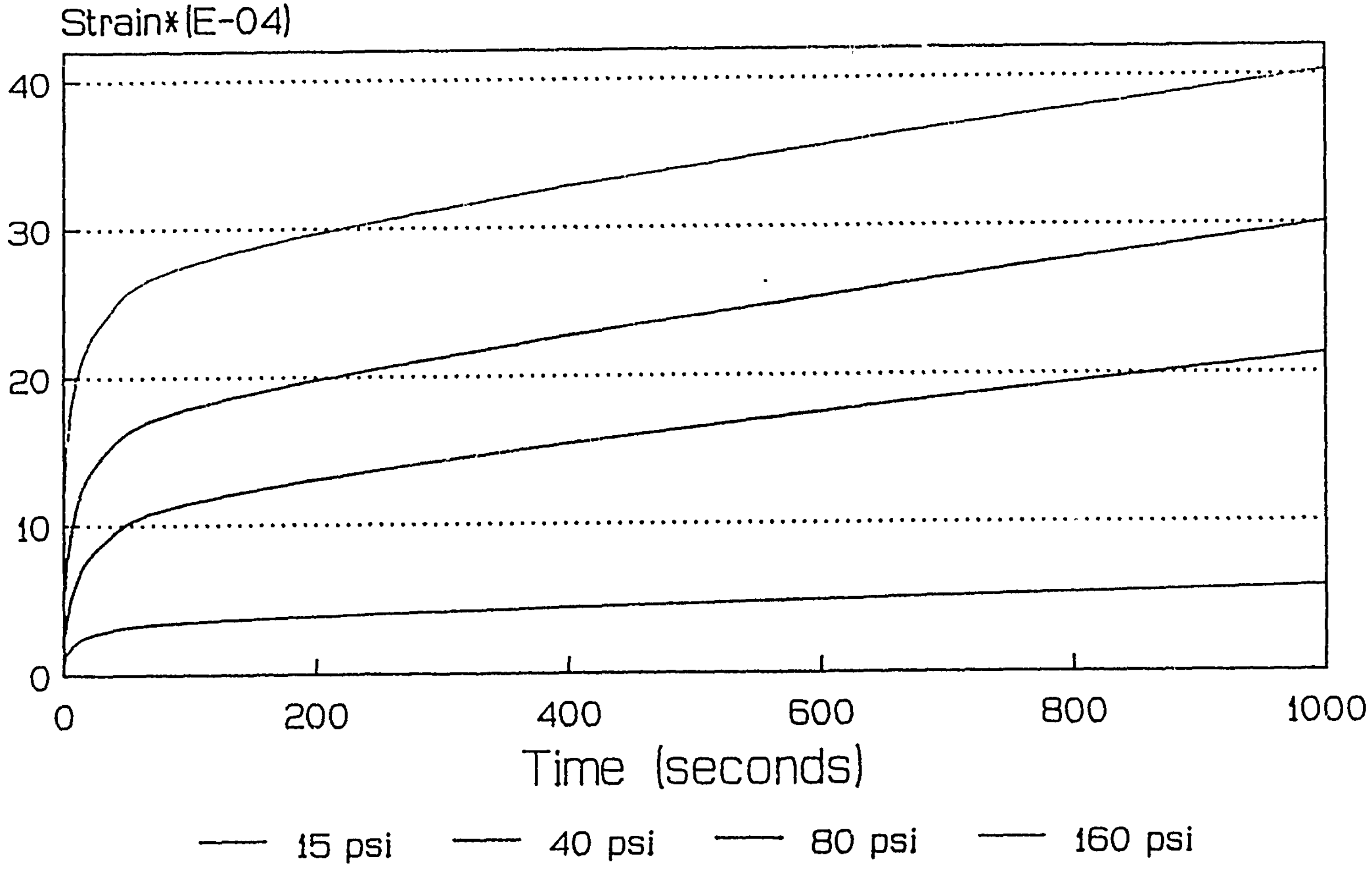

Figure C-2. Compression Rutting-Creep for AC-10.

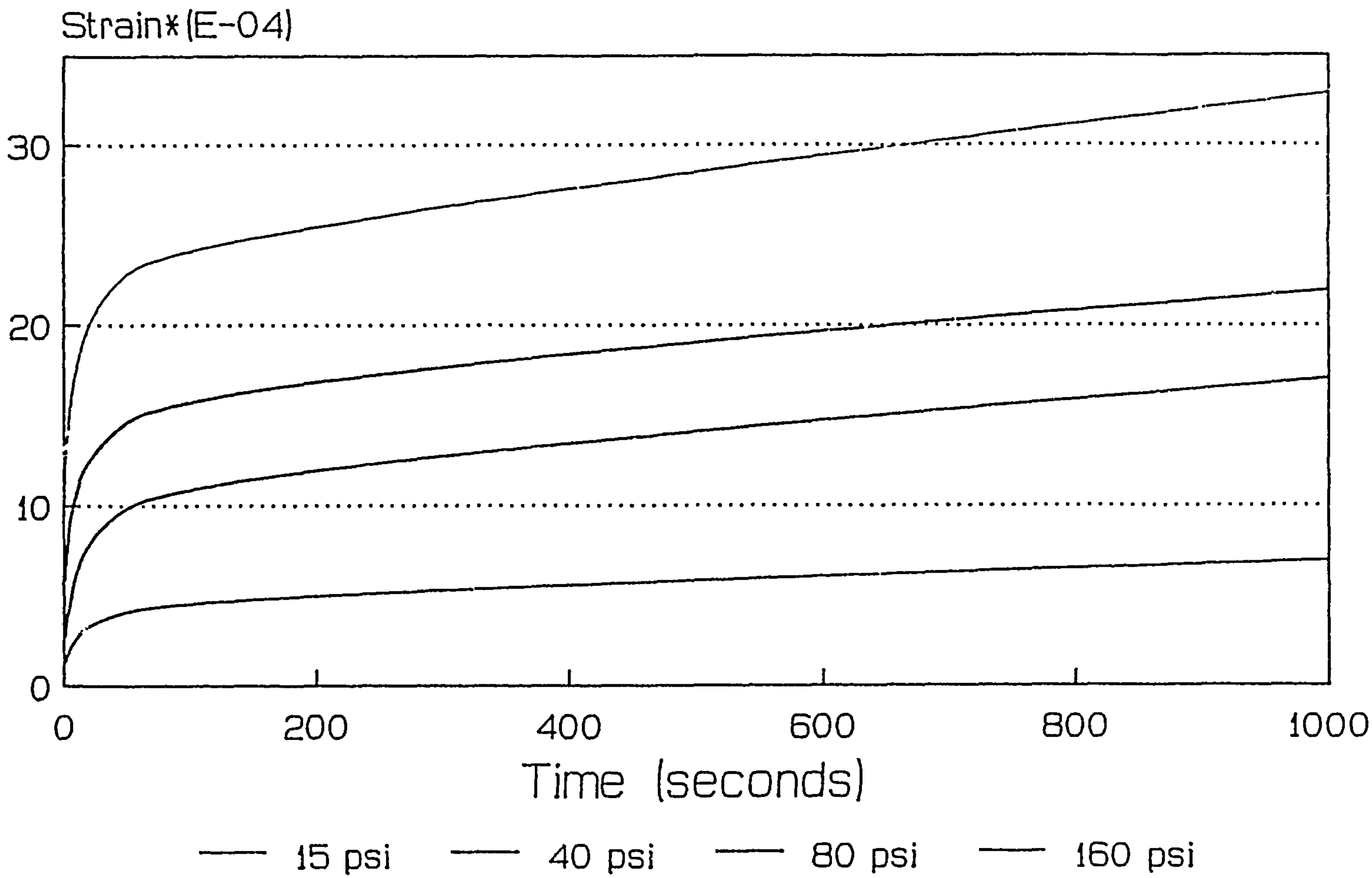

Figure C-3. Compression Rutting-Creep for ESL Mixture.

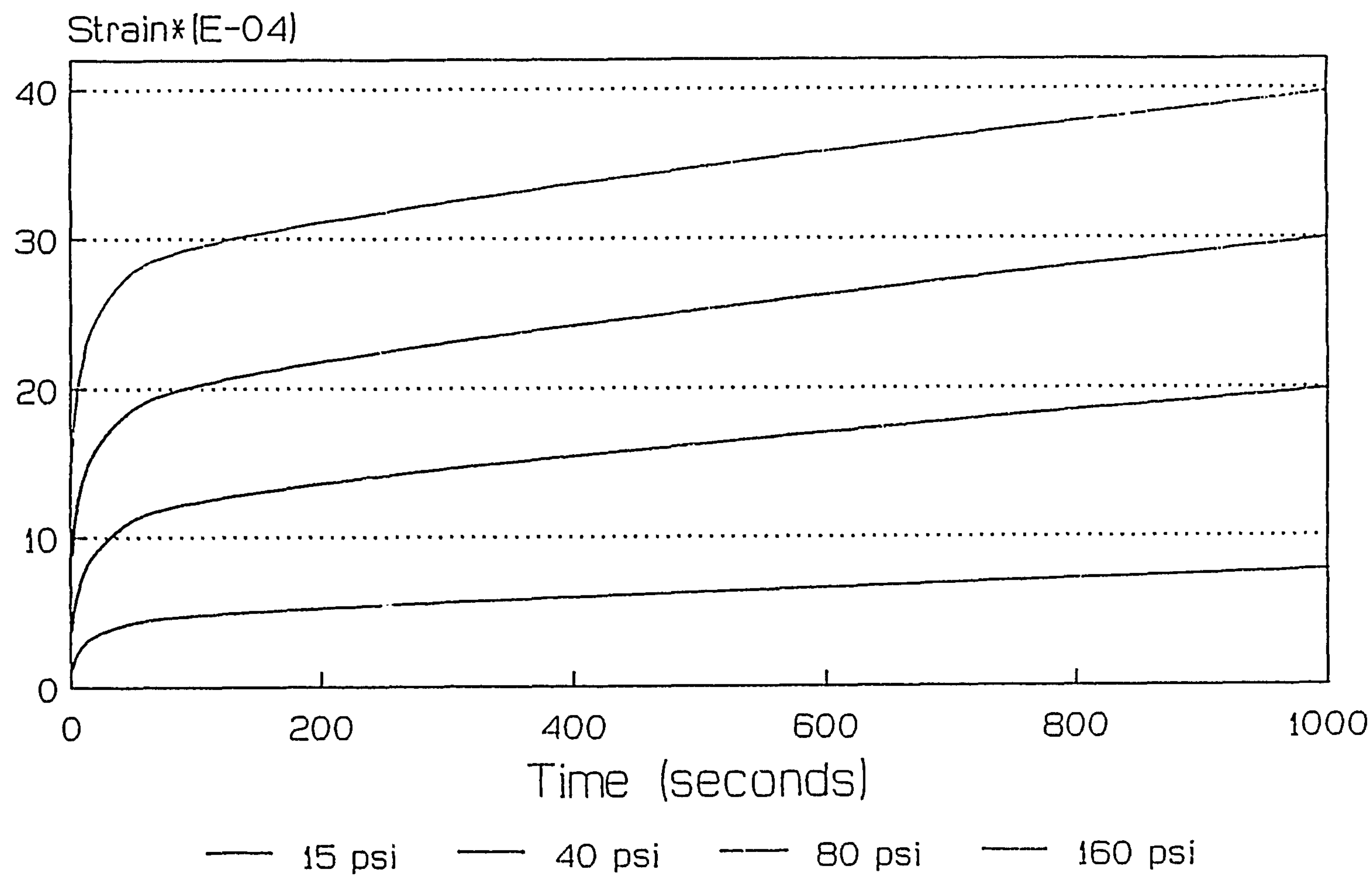

Figure C-4. Compression Rutting-Creep for SBS Mixture.

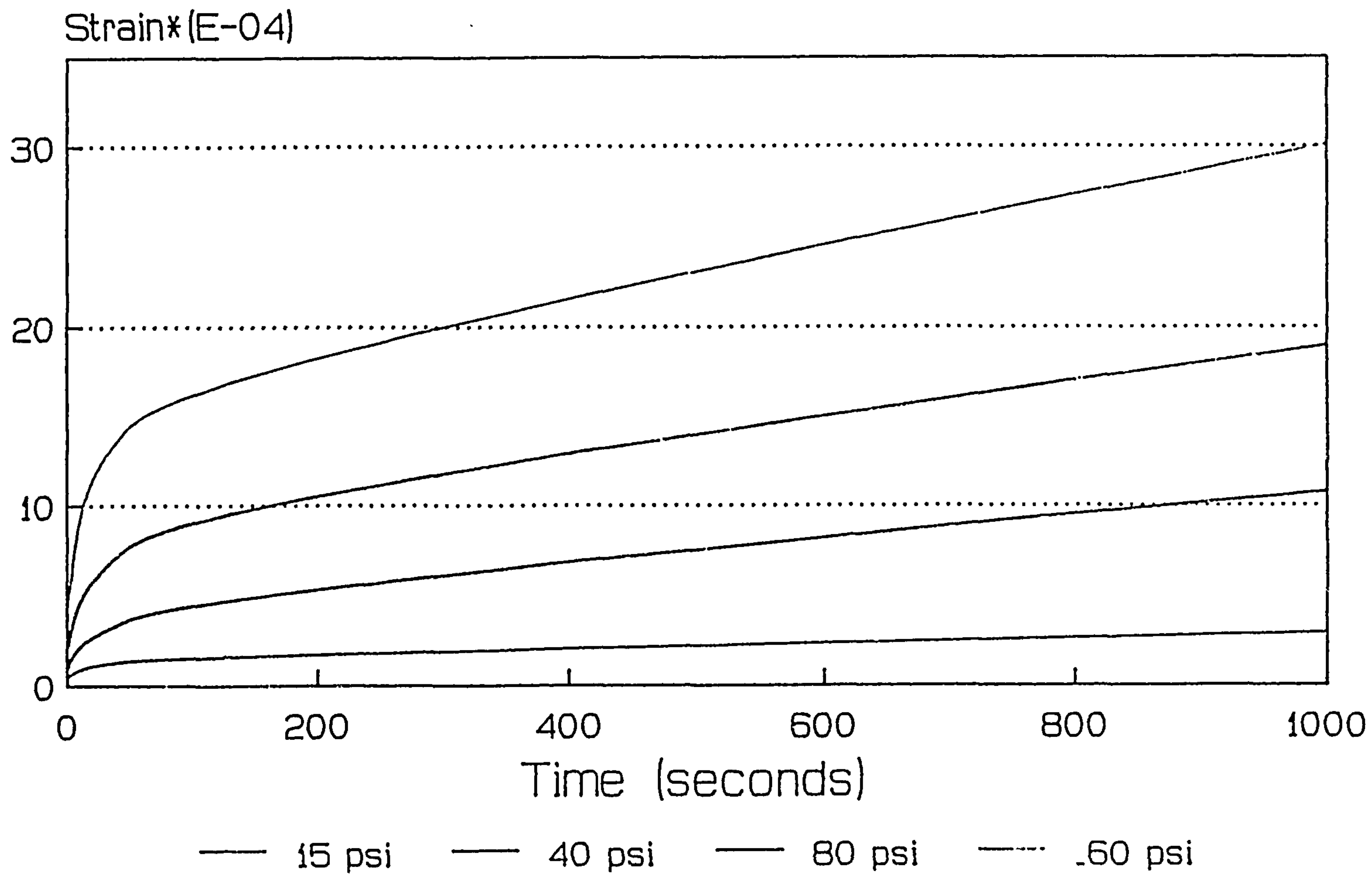

Figure C-5. Compression Rutting-Creep for PP Mixture.

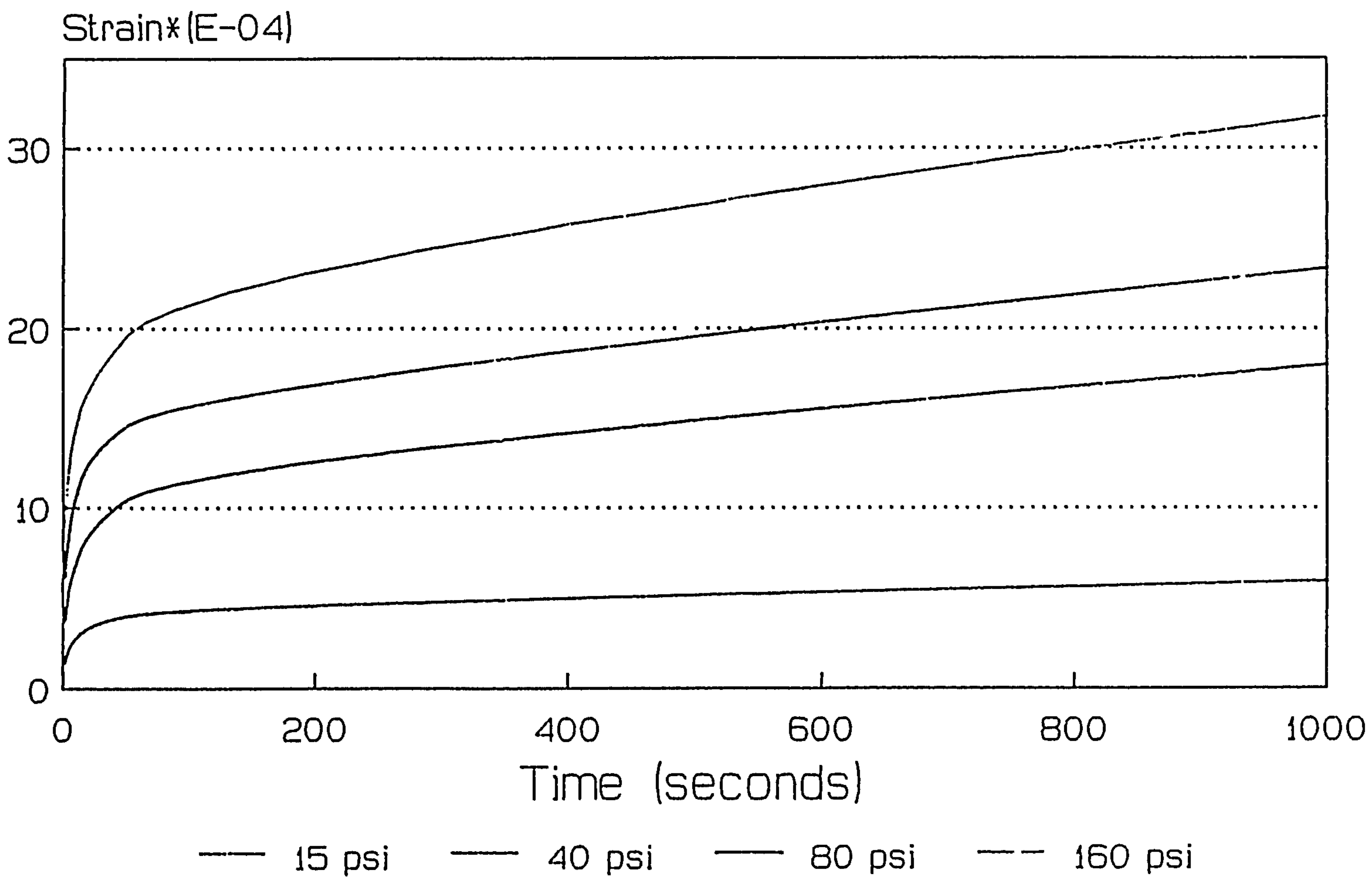

Figure C-6. Compression Rutting-Creep for ER Mixture.

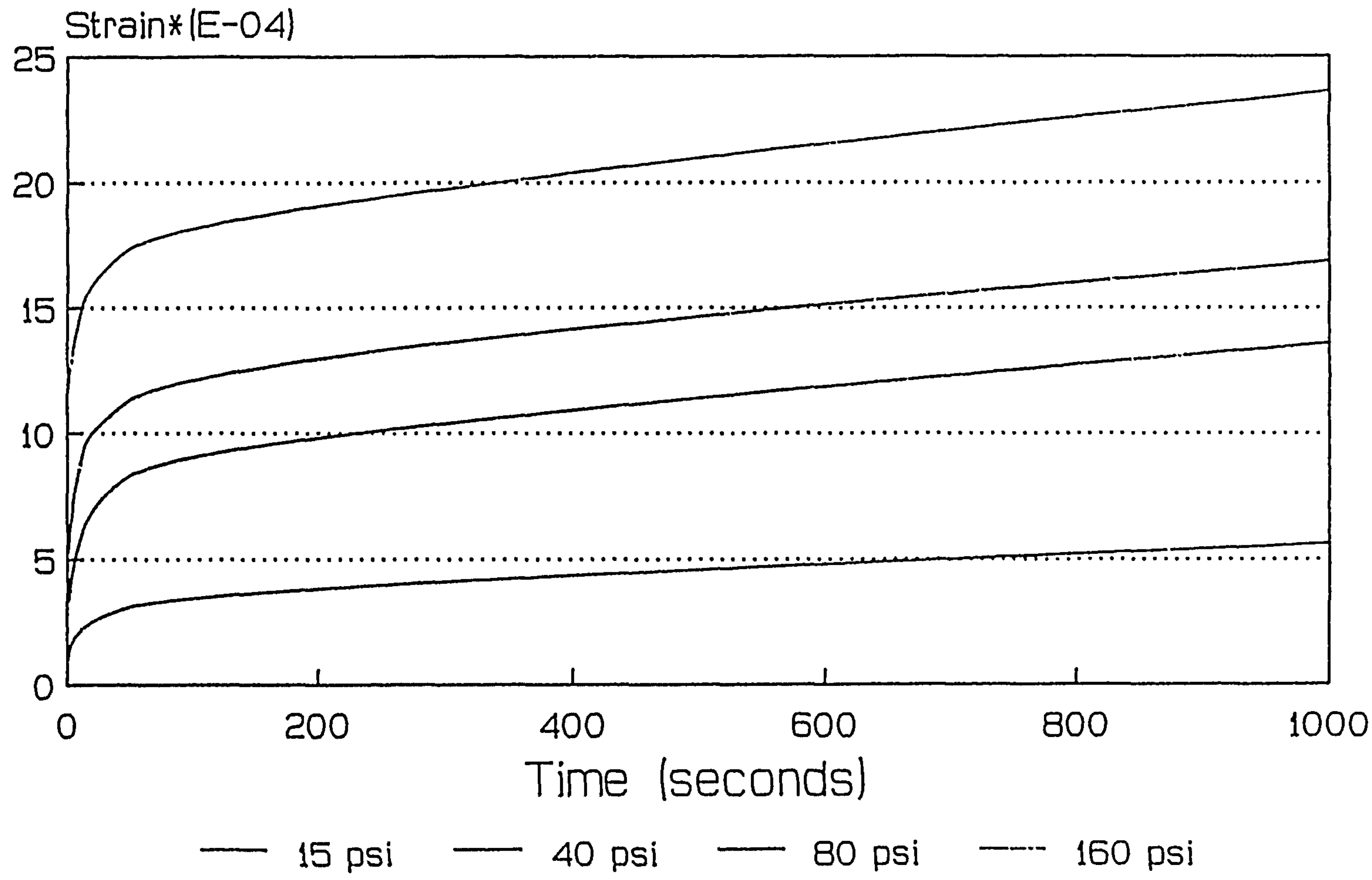

Figure C-7. Compression Rutting-Creep for EVA Mixture.

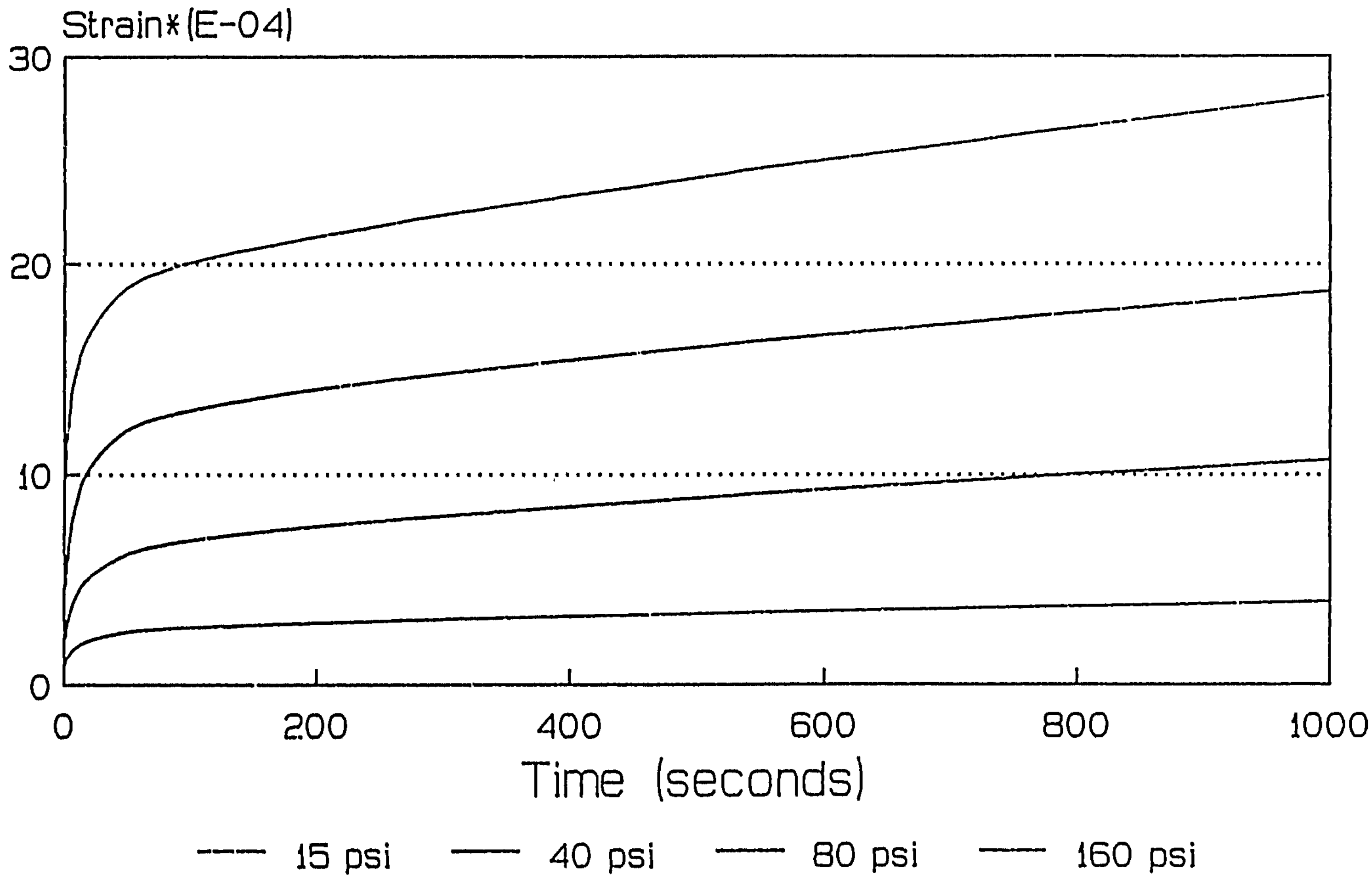

Figure C-8. Compression Rutting-Creep for FCB/AC-20.

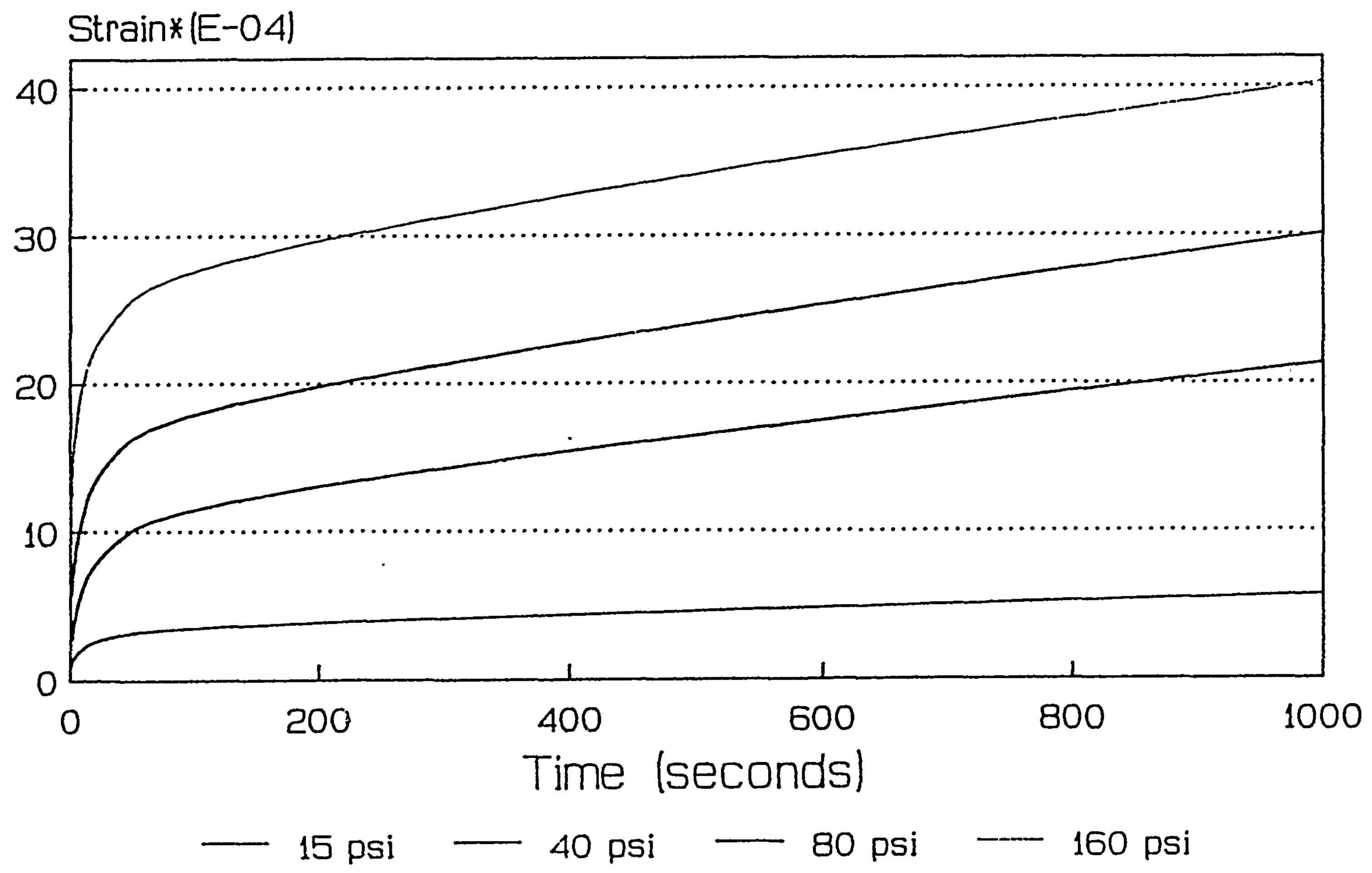

Figure C-9. Compression Rutting-Creep for FCB/AC-10.

1. MARSHALL MIX DESIGN DATA FOR AC-20.

TABLE C-3. INFORMATION OF MARSHALL MIX DESIGN DATA, AC-20

No.	% A.C.	Specimen Ht. (in)	Weight (grams) Air	SSD	Water	Specific Gravity (gm-cc) Actual	Maximum	Air Voids %	Unit (pcf)	Stability Load (lb)	Flow (.01 in)
1	5.0	2.529	1224.7	1229.3	708.8	2.353			146.82	3433	11
2	5.0	2.557	1231.5	1231.7	707.6	2.350			146.62	3986	12
3	5.0	2.530	1227.2	1227.2	706.5	2.357			147.07	4251	13
AVERAGE							2.481	5.2	146.84	3890	12
1	5.5	2.551	1239.4	1241.0	715.6	2.359			147.20	4306	13
2	5.5	2.565	1243.5	1243.8	716.5	2.358			147.15	3985	13
3	5.5	2.526	1235.4	1236.1	709.4	2.346			146.76		12
AVERAGE							2.455	4.1	147.04	4146	12.66
1	6.0	2.551	1247.0	1247.2	720.7	2.368			147.79	3003	
2	6.0	2.565	1247.1	1247.4	718.7	2.359			147.19	2908	13
3	6.0	2.584	1244.4	1244.8	718.4	2.364			147.51	3804	13
AVERAGE							2.419	2.3	147.50	3238	13
1	6.5	2.585	1246.1	1246.3	715.7	2.348			146.54	2020	20
2	6.5	2.589	1245.1	1245.1	713.7	2.343			146.21	1944	17
3	6.5	2.591	1243.6	1243.8	715.2	2.353			146.80	2095	22
AVERAGE									146.52	2020	19.67
1	7.0	2.623	1254.3	1254.7	719.7	2.344			146.30	2042	28
2	7.0	2.606	1252.2	1252.2	720.5	2.360			147.29	2773	23
3	7.0	2.619	1259.1	1259.2	724.1	2.363			146.83	2458	24
AVERAGE									146.81	2424	25

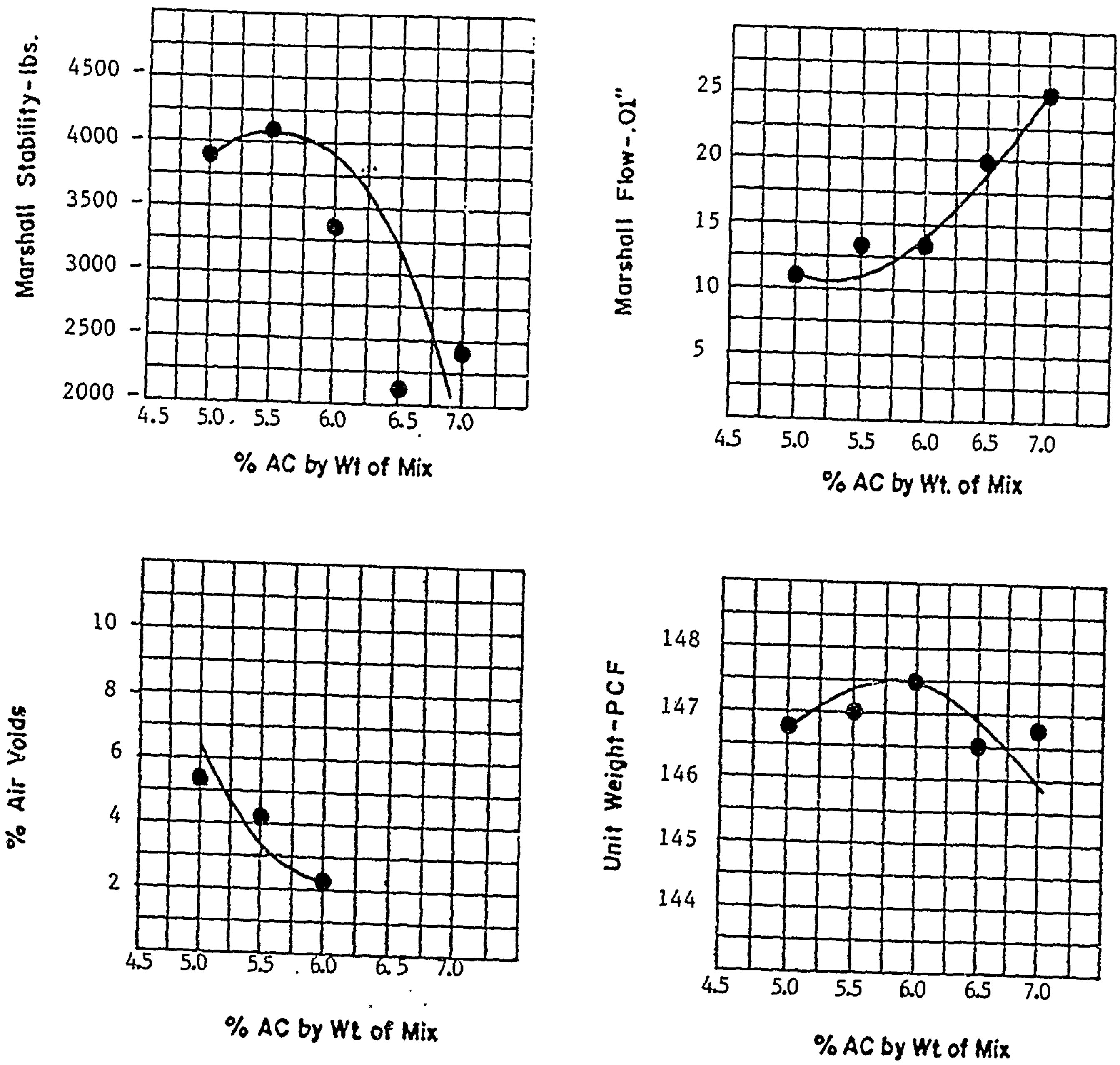

Figure C-10. Marshall Mix Design Curves for AC-20.

2. MARSHALL MIX DESIGN DATA FOR AC-10

TABLE C-4. INFORMATION OF MARSHALL MIX DESIGN DATA, AC-10

No.	% A.C.	Specimen Ht. (in)	Weight (grams) Air	Weight (grams) SSD	Weight (grams) Water	Specific Gravity (gm-cc) Actual	Specific Gravity (gm-cc) Maximum	Air Voids %	Unit (pcf)	Stability Load (lb)	Stability Flow (.01 in)
1	4.5	2.601	1243.7	1244.4	707.2	2.315			144.47		
2	4.5	2.576	1234.2	1235.3	698.8	2.300			143.55	3692	8
3	4.5	2.587	1230.7	1231.5	694.9	2.294			143.12	3421	7
AVERAGE						2.303	2.430	5.2	143.71	3556	7.5
1	5.0	2.526	1232.1	1232.1	709.6	2.358			147.14	3481	6
2	5.0	2.530	1232.0	1232.0	709.1	2.359			147.02	4164	19
3	5.0	2.537	1230.5	1231.4	709.2	2.356			147.04	5648	21
AVERAGE						2.358	2.460	4.1	147.1	4431	15.3
1	5.5	2.553	1236.4	1236.4	714.2	2.368			147.74	3154	21
2	5.5	2.510	1227.9	1228.5	710.5	2.370			147.92	3653	16
3	5.5	2.561	1241.5	1241.5	718.3	2.373			148.07	4662	15
AVERAGE						2.370	2.460	3.7	147.91	3823	17.3
1	6.0	2.555	1242.9	1243.4	719.0	2.370			147.99	2907	21
2	6.0	2.585	1235.3	1235.4	714.0	2.370			147.84	4818	26
3	6.0	2.534	1238.6	1239.0	717.0	2.373			148.06	4097	19
AVERAGE						2.371			147.93	3941	22
1	6.5	2.570	1244.0	1244.2	720.4	2.375			148.20	2917	24
2	6.5	2.551	1236.9	1237.1	713.8	2.364			147.49	2584	21
3	6.5	2.569	1242.8	1243.0	715.5	2.356			147.02	2012	23
AVERAGE						2.365			147.57	2504	22.7
1	7.0	2.608	1241.7	1241.9	715.2	2.358			147.11	2048	
2	7.0	2.594	1240.9	1241.4	711.0	2.340			145.99	1840	
3	7.0	2.580	1248.8	1248.9	715.0	2.339			145.95	1679	
AVERAGE						2.346			146.35	1856	

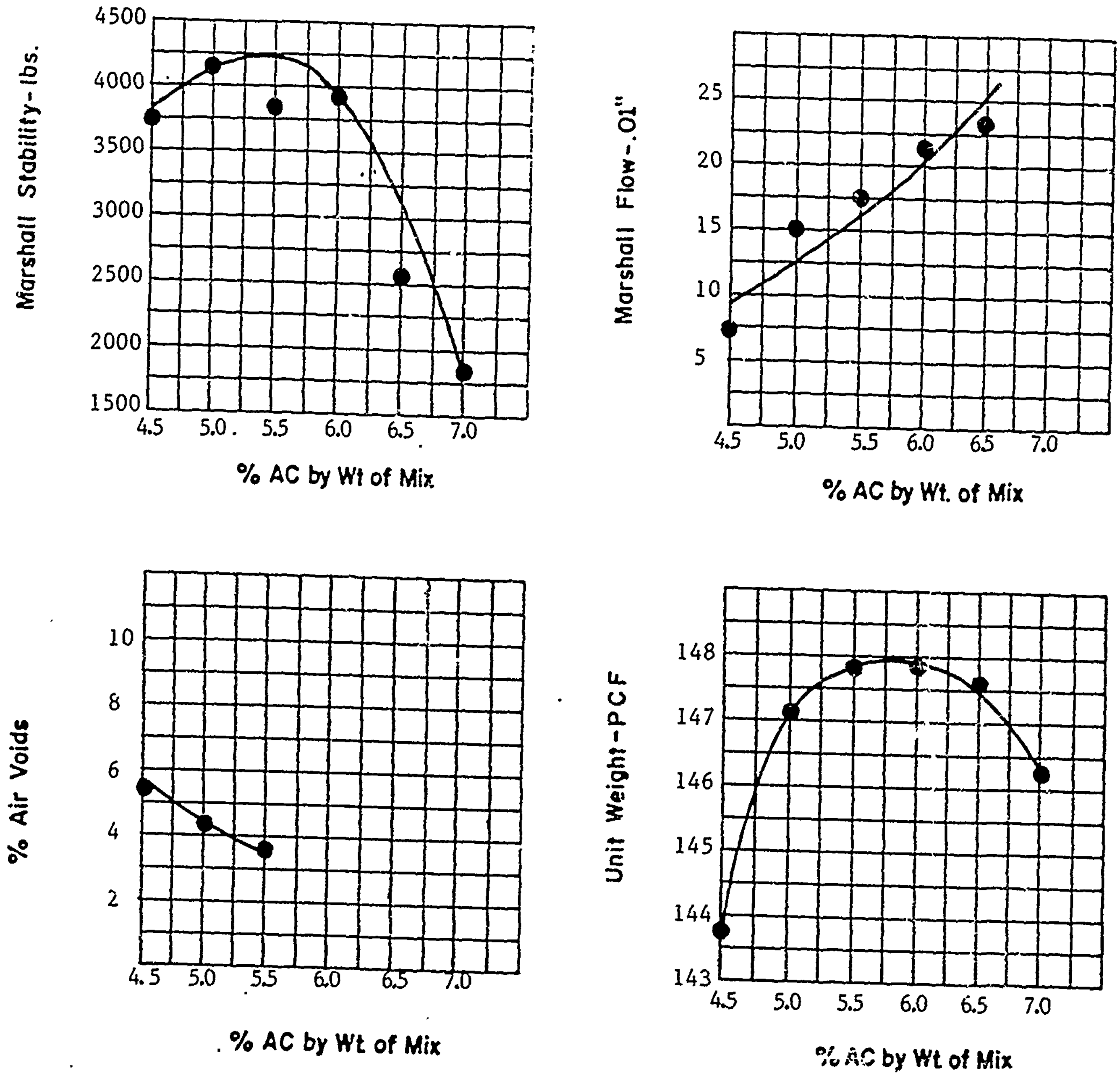

Figure C-11. Marshall Mix Design Curves for AC-10.

3. MARSHALL MIX DESIGN DATA FOR ESL

TABLE C-5. INFORMATION OF MARSHALL MIX DESIGN DATA, ESL

No.	% A.C.	Specimen Ht. (in)	Weight (grams) Air	Weight (grams) SSD	Weight (grams) Water	Specific Gravity (gm-cc) Actual	Specific Gravity (gm-cc) Maximum	Air Voids %	Unit (pcf)	Stability Load (lb)	Stability Flow (.01 in)
1	4.0	2.555								4606	5
2	4.0	2.551								3941	7
AVERAGE							2.520	10.3		4273	6.0
1	4.5	2.576	1229.7	1232.5	692.8	2.278			142.15	3929	7
2	4.5	2.577	1229.0	1230.0	696.7	2.294			143.12	4906	10
3	4.5	2.601	1228.3	1229.2	691.6	2.285			142.57	3847	11
AVERAGE						2.286	2.463	7.2	142.62	4227	9.3
1	5.0	2.575	1228.9	1229.4	696.7	2.307			143.95	3391	11
2	5.0	2.579	1234.3	1234.5	702.2	2.319			144.69		
3	5.0	2.598	1230.1	1230.6	698.1	2.310			144.15	4056	17
AVERAGE						2.312	2.445	5.4	144.26	3723	14.0
1	5.5	2.565	1233.7	1234.0	703.1	2.324			145.00	3495	16
2	5.5	2.675	1241.6	1241.8	708.0	2.326			145.14	3657	
3	5.5	2.595	1241.3	1242.0	705.6	2.314			144.40	3320	13
AVERAGE						2.321	2.422	4.2	144.85	3491	14.5
1	6.0	2.624	1246.1	1246.6	710.2	2.323			144.96	3001	17
2	6.0	2.569	1243.9	1244.4	708.7	2.322			144.89	3315	13
3	6.0	2.619	1241.1	1241.6	706.5	2.319			144.73	3010	19
AVERAGE						2.321			144.86	3109	16.3

TABLE C-5. INFORMATION OF MARSHALL MIX DESIGN DATA, ESL (CONCLUDED)

No.	% A.C.	Specimen Ht. (in)	Weight (grams) Air	SSD	Water	Specific Gravity (gm-cc) Actual	Maximum	Air Voids %	Unit (pcf)	Stability Load (lb)	Flow (.01 in)
1	6.5	2.615	1240.6	1241.1	703.6	2.308			144.02	2098	16
2	6.5	2.609	1248.4	1249.0	709.0	2.312			144.26	2698	18
3	6.5	2.579	1244.9	1245.8	708.1	2.315			144.47	2432	18
AVERAGE						2.312			144.25	2409	17.5
1	7.0	2.636	1253.7	1253.9	709.1	2.301			143.60	1929	24
2	7.0	2.640	1253.6	1253.9	707.9	2.296			143.27	1626	21
3	7.0	2.655	1252.9	1253.5	706.8	2.292			143.00	1681	25
AVERAGE						2.296			143.23	1745	23

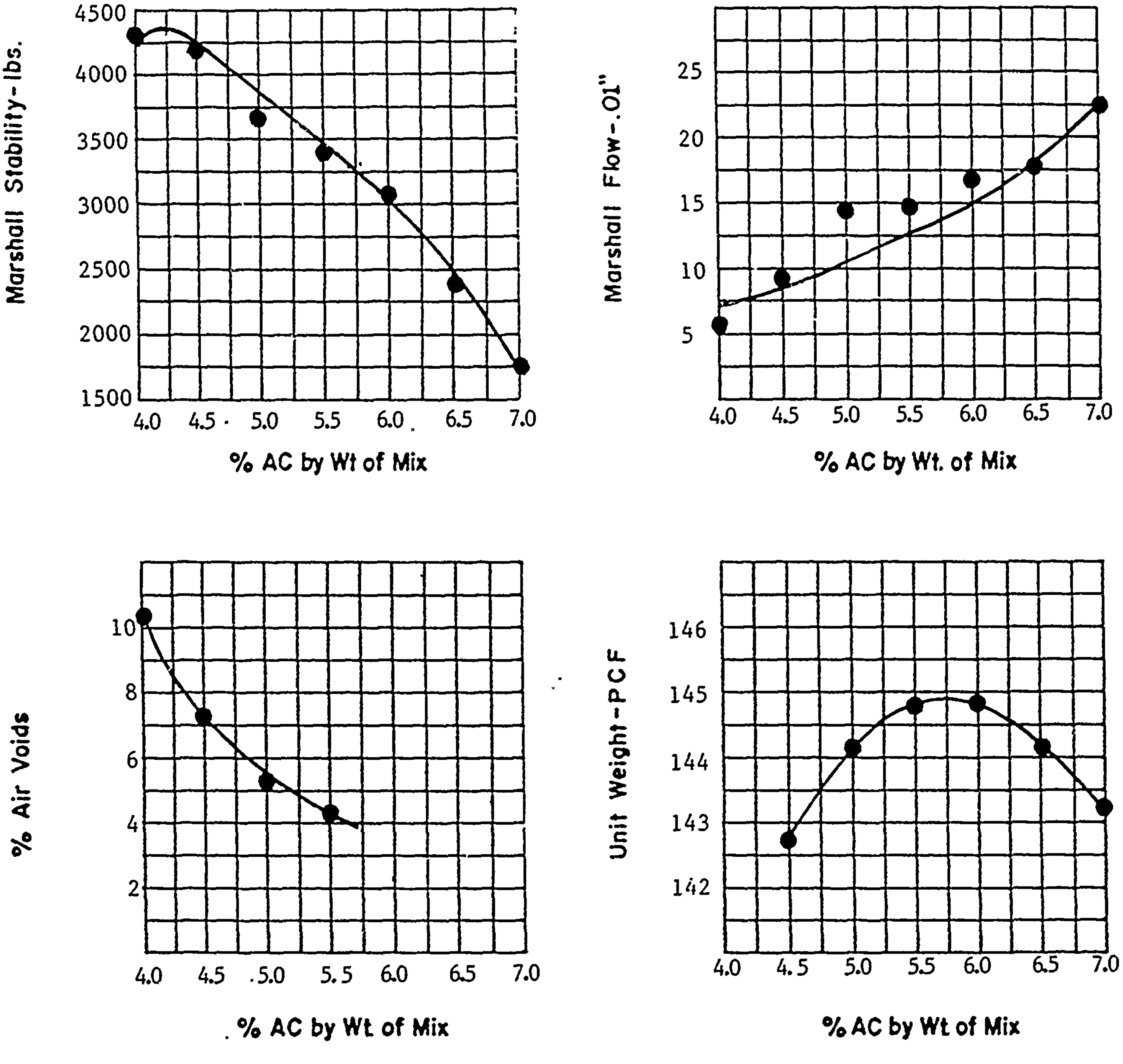

Figure C-12. Marshall Mix Design Curves for ESL.

4. MARSHALL MIX DESIGN DATA FOR SBS

TABLE C-6. INFORMATION OF MARSHALL MIX DESIGN DATA, SBS

No.	% A.C.	Specimen Ht. (in)	Weight (grams) Air	SSD	Water	Specific Gravity (gm-cc) Actual	Maximum	Air Voids %	Unit (pcf)	Stability Load (lb)	Flow (.01 in)
1	4.0	2.551								3342	
2	4.0	2.535								3286	
AVERAGE						2.346			146.36	3314	
1	4.5	2.607	1227.4	1228.7	687.8	2.269			141.60	3358	11
2	4.5	2.581	1222.3	1224.4	685.2	2.267			141.45	3515	11
3	4.5	2.601	1227.6	1229.0	688.7	2.272			141.78	3607	9
AVERAGE						2.269	2.488	8.8	141.61	3493	10.33
1	5.0	2.574	1233.7	1234.0	699.4	2.308			144.0	3328	8
2	5.0	2.576	1235.0	1235.6	700.5	2.308			144.0	3318	12
3	5.0	2.581	1233.9	1234.7	700.0	2.308			144.0	3159	14
AVERAGE						2.308	2.448	5.7	144.0	3268	11.33
1	5.5	2.606	1242.3	1243.0	708.9	2.326			145.14	2726	12
2	5.5	2.646	1247.1	1247.5	712.3	2.330			145.40	2978	14
3	5.5	2.581	1242.2	1242.8	709.9	2.331			145.46	2813	14
AVERAGE						2.329	2.431	4.19	145.33	2839	13.33
1	6.0	2.654	1254.2	1254.9	715.8	2.326			145.17	2504	14
2	6.0	2.561	1244.7	1245.3	714.3	2.344			146.27	3050	21
3	6.0	2.596	1248.6	1249.3	712.8	2.327			145.22	2407	21
AVERAGE						2.332			145.55	2654	18.67
1	6.5	2.601	1250.5	1251.2	715.5	2.334			145.66	2447	16
2	6.5	2.611	1253.5	1254.3	714.2	2.321			144.82	2419	20
3	6.5	2.626	1255.4	1255.8	717.3	2.331			145.45	2079	21
AVERAGE						2.329			145.30	2315	19.0
1	7.0	2.607	1248.3	1248.4	711.0	2.323			144.95	1961	28
2	7.0	2.631	1255.8	1255.8	715.8	2.326			145.11	2033	22
3	7.0	2.617	1251.4	1251.9	713.8	2.326			145.12	1913	22
AVERAGE						2.325			145.06	1969	24

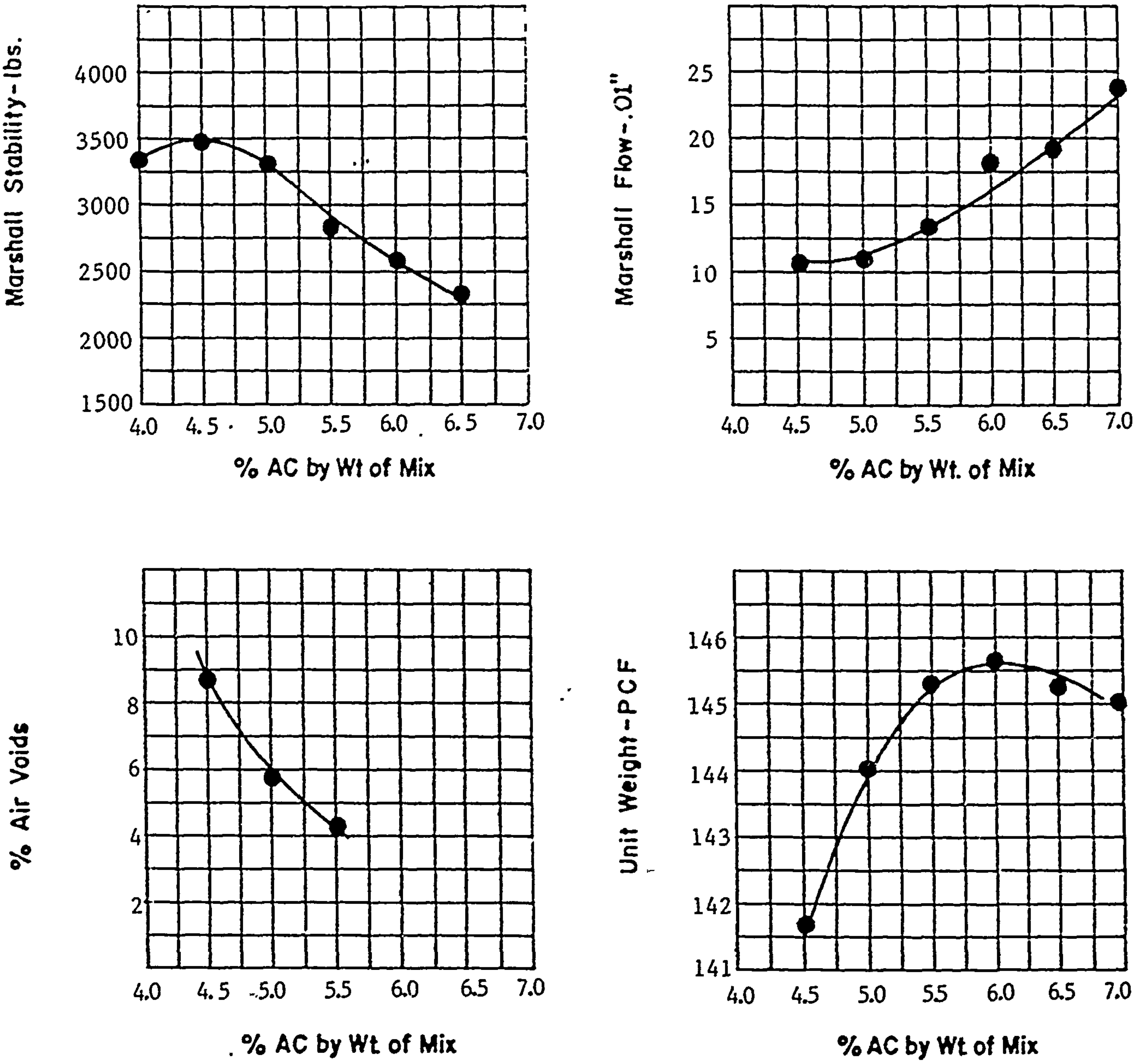

Figure C-13. Marshall Mix Design Curves for SBS.

5. MARSHALL MIX DESIGN DATA FOR PP

TABLE C-7. INFORMATION OF MARSHALL MIX DESIGN DATA, PP

No.	% A.C.	Specimen Ht. (in)	Weight (grams) Air	SSD	Water	Specific Gravity (gm-cc) Actual	Maximum	Air Voids %	Unit (pcf)	Stability Load (lb)	Flow (.01 in)
1	5.0	2.551	1232.5	1233.6	704.8	2.331			145.44	3426	7
2	5.0	2.590	1232.5	1233.8	701.8	2.317			144.56	3449	11
3	5.0	2.639	1234.9	1235.9	697.1	2.292			143.02	3056	11
AVERAGE						2.313			144.30	3310	10
1	5.5	2.595	1242.0	1242.3	711.6	2.340			146.03	3122	9
2	5.5	2.575	1239.0	1239.1	707.9	2.332			145.55	3299	12
3	5.5	2.570	1248.4	1248.6	719.7	2.360			147.29	5133	
AVERAGE						2.344	2.490	5.9	146.29	3851	10.5
1	6.0	2.605	1242.1	1242.6	708.1	2.324			145.01	3709	12
2	6.0	2.591	1247.6	1248.1	717.4	2.351			146.69	4437	10
3	6.0	2.548	1248.8	1249.2	719.1	2.356			147.00	3970	12
AVERAGE						2.344	2.460	4.7	146.23	4039	11.33
1	6.5	2.579	1256.5	1257.0	721.9	2.348			146.53	2962	16
2	6.5	2.609	1246.1	1246.6	714.1	2.340			146.02	2335	17
3	6.5	2.590	1251.5	1251.7	717.9	2.345			146.30	2473	16
AVERAGE						2.344	2.400	2.4	146.18	2590	16.33
1	7.0	2.608	1254.9	1255.1	716.8	2.331			145.47	2027	17
2	7.0	2.626	1256.2	1256.2	715.7	2.324			145.03	2402	17
3	7.0	2.629	1259.5	1259.6	716.9	2.321			144.82	2513	16
AVERAGE						2.325			145.11	2314	16.66

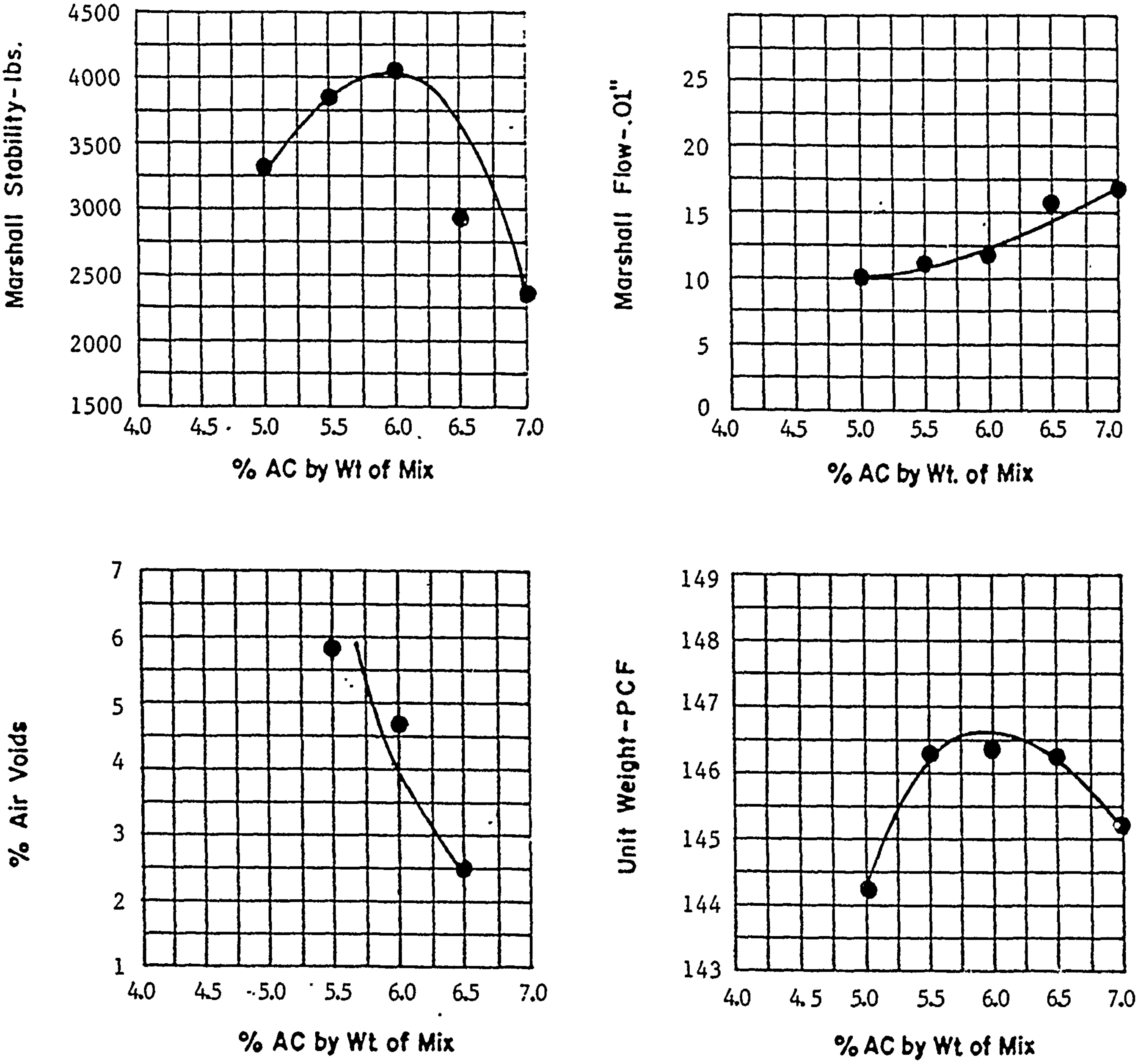

Figure C-14. Marshall Mix Design Curves for PP.

6. MARSHALL MIX DESIGN DATA FOR ER

TABLE C-8. INFORMATION OF MARSHALL MIX DESIGN DATA, ER

No.	% A.C.	Specimen Ht. (in)	Weight (grams) Air	SSD	Water	Specific Gravity (gm-cc) Actual	Maximum	Air Voids %	Unit (pcf)	Stability Load (lb)	Flow (.01 in)
1	4.5	2.590	1223.6	1224.2	691.7	2.298			143.39	3571	7
2	4.5	2.605	1226.9	1227.8	690.1	2.282			142.38	3037	10
3	4.5	2.585	1222.9	1223.5	690.4	2.294			143.14	2925	8
AVERAGE						2.291			142.97	3178	8.33
1	5.0	2.585	1240.5	1241.0	707.6	2.326			145.12	3459	9
2	5.0	2.569	1234.8	1235.1	702.4	2.318			144.64	3126	11
3	5.0	2.577	1232.1	1232.4	702.8	2.326			145.12	3429	8
AVERAGE						2.323	2.470	6.0	144.96	3338	9.8
1	5.5	2.580	1237.6	1237.6	707.6	2.335			144.71	3150	14
2	5.5	2.599	1236.2	1236.9	702.1	2.312			144.24	3328	8
3	5.5	2.590	1235.7	1236.3	704.1	2.322			144.88	3533	8
AVERAGE						2.323	2.434	4.6	144.94	3337	10
1	6.0	2.577	1241.2	1241.5	709.1	2.331			145.47	2783	10
2	6.0	2.600	1244.5	1245.0	712.1	2.325			145.72	2379	13
3	6.0	2.595	1245.3	1245.8	710.1	2.325			145.06	2671	15
AVERAGE						2.330	2.410	3.3	145.42	2611	12.66
1	6.5	2.589	1240.0	1240.2	704.2	2.313			144.36	1850	13
2	6.5	2.595	1248.4	1248.7	711.1	2.322			144.90	2341	10
3	6.5	2.595	1249.2	1249.4	712.4	2.326			145.16	2539	19
AVERAGE						2.320			144.81	2243	14

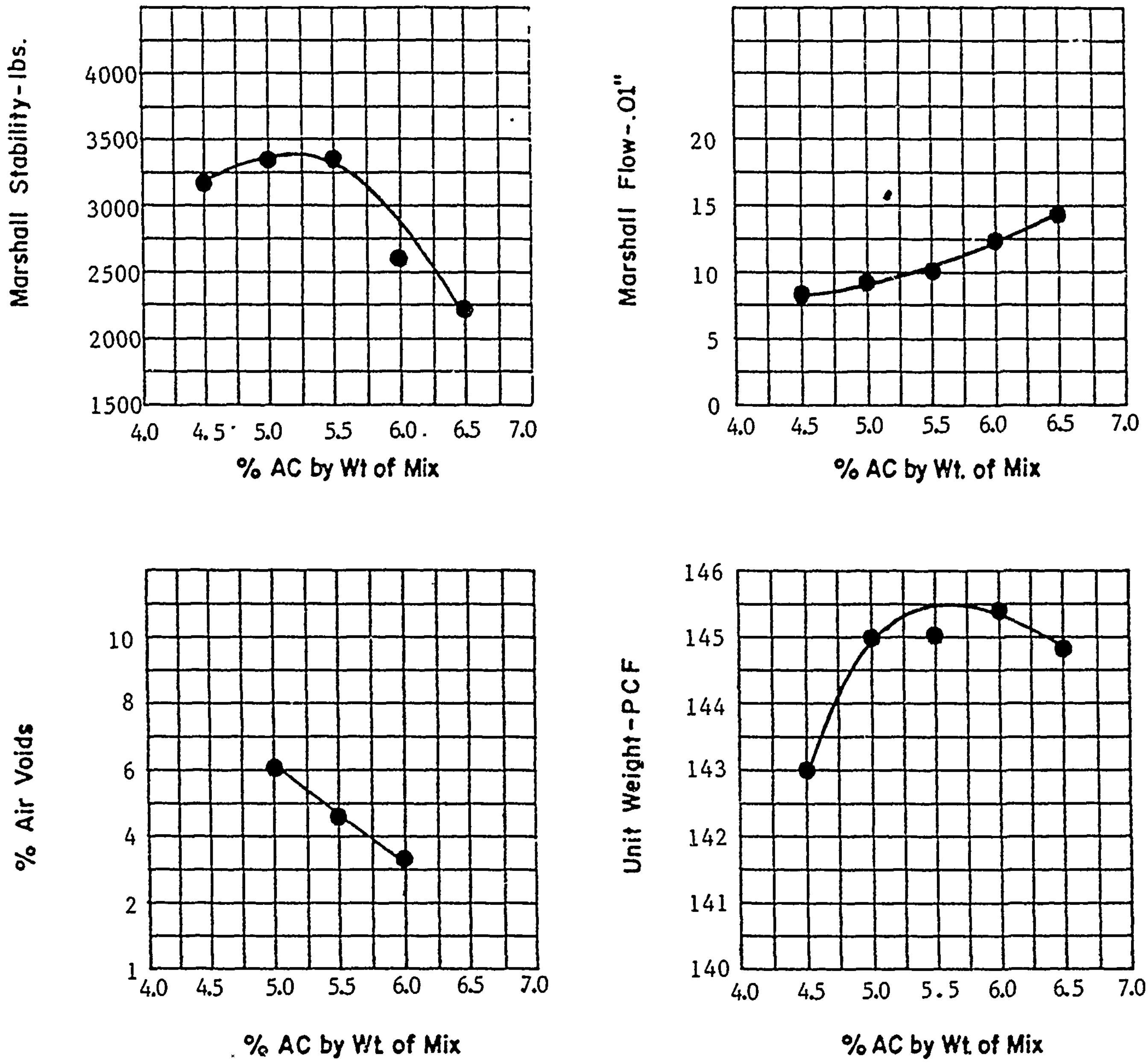

Figure C-15. Marshall Mix Design Curves for ER.

7. MARSHALL MIX DESIGN DATA FOR EVA

TABLE C-9. INFORMATION OF MARSHALL MIX DESIGN DATA, EVA

No.	% A.C.	Specimen Ht. (in)	Weight (grams) Air	SSD	Water	Specific Gravity (gm-cc) Actual	Maximum	Air Voids %	Unit (pcf)	Stability Load (lb)	Flow (.01 in)
1	5.0	2.621	1238.4	1238.9	702.6	2.309			144.09	4444	13
2	5.0	2.608	1243.8	1244.2	715.8	2.354			146.88	4529	13
3	5.0	2.585	1240.8	1241.5	713.0	2.346			146.41	3804	12
AVERAGE						2.336	2.478	5.9	145.80	4259	12.66
1	5.5	2.589	1243.7	1244.2	711.0	2.333			145.55	5522	14
2	5.5	2.587	1242.8	1243.4	710.1	2.330			145.42	3758	13
3	5.5	2.595	1244.8	1245.4	711.3	2.331			145.43	3838	
AVERAGE						2.331	2.452	4.7	145.0	4373	13.5
1	6.0	2.569	1242.1	1242.8	710.8	2.335			145.69		15
2	6.0	2.577	1242.3	1242.9	711.6	2.338			145.90	3986	12
3	6.0	2.601	1250.7	1251.2	715.7	2.336			145.74	3827	12
AVERAGE						2.336	2.414	3.2	145.8	3643	13
1	6.5	2.609	1257.8	1257.9	719.9	2.338			145.89	3912	17
2	6.5	2.569	1243.0	1243.1	713.4	2.347			146.43	3344	15
3	6.5	2.598	1254.9	1255.0	718.5	2.339			145.96		
AVERAGE						2.341	2.388	2.1	146.09	3628	16
1	7.0	2.605	1252.1	1252.1	717.5	2.342			146.15	3459	20
2	7.0	2.648	1252.2	1252.5	714.7	2.328			145.29	2523	24
3	7.0	2.599	1260.8	1261.1	720.4	2.332			145.50	3098	24
AVERAGE						2.334			145.65	3027	22.67

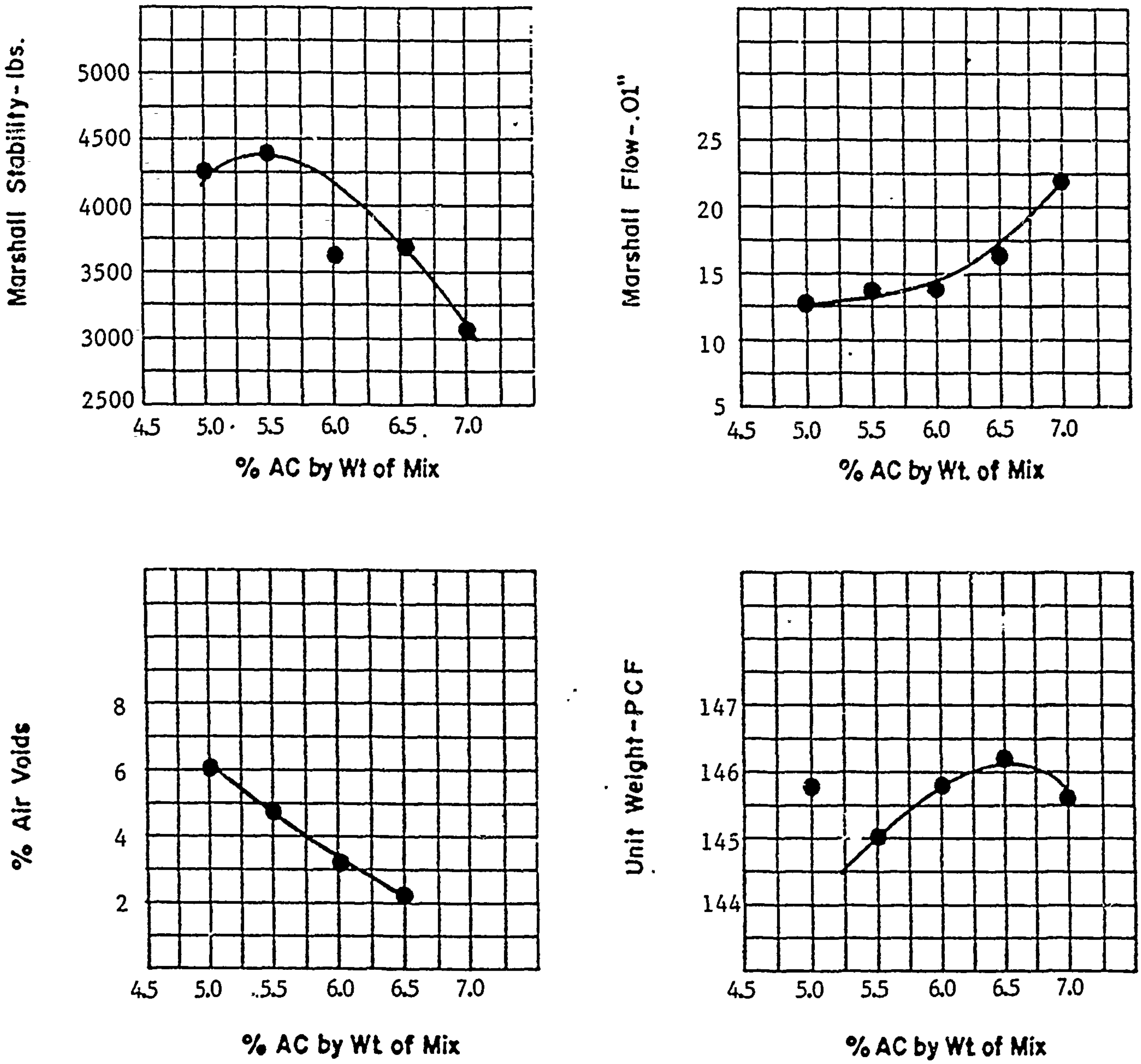

Figure C-16. Marshall Mix Design Curves for EVA.

8. MARSHALL MIX DESIGN DATA FOR FCB/AC-20

TABLE C-10. INFORMATION OF MARSHALL MIX DESIGN DATA, FCB/AC-20

No.	% A.C.	Specimen Ht. (in)	Weight (grams) Air	Weight (grams) SSD	Weight (grams) Water	Specific Gravity (gm-cc) Actual	Specific Gravity (gm-cc) Maximum	Air Voids %	Unit (pcf)	Stability Load (lb)	Stability Flow (.01 in)
1	4.5	2.601	1230.1	1231.8	689.2	2.267			141.44	4474	10
2	4.5	2.604	1230.0	1230.8	690.3	2.276			142.00	4234	11
3	4.5	2.607	1228.4	1230.4	687.2	2.261			141.11	4299	11
AVERAGE						2.268	2.506	9.5	141.52	4335	10.66
1	5.0	2.551	1234.4	1235.2	708.6	2.344			146.27	5037	8
2	5.0	2.587	1235.8	1236.9	687.0	2.247			140.23	5300	8
3	5.0	2.611	1226.5	1227.6	691.1	2.290			142.92	3829	6
AVERAGE						2.294	2.493	7.4	143.14	4722	7.33
1	5.5	2.576	1242.2	1243.5	709.3	2.325			145.10	4089	6
2	5.5	2.576	1238.1	1238.8	706.4	2.326			145.11	5786	6
3	5.5	2.582	1242.7	1243.4	710.3	2.331			145.46	5281	7
AVERAGE						2.327	2.479	6.1	145.22	5052	6.33
1	6.0	2.576	1246.6	1247.6	715.6	2.343			146.21	5009	7
2	6.0	2.578	1246.1	1246.6	713.1	2.336			145.75	5505	10
3	6.0	2.566	1245.1	1245.5	713.8	2.342			146.12	4334	13
AVERAGE							2.449	4.4	146.03	4950	10
1	6.5	2.555	1247.6	1247.8	720.8	2.366			147.67	3951	12
2	6.5	2.576	1253.5	1253.5	724.5	2.370			147.86	3769	9
3	6.5	2.593	1258.4	1258.6	722.0	2.345			146.33	3374	12
AVERAGE						2.360			147.29	3698	11
1	7.0	2.588	1266.8	1266.9	730.7	2.363			147.42	2868	16
2	7.0	2.580	1251.8	1251.8	719.8	2.353			146.83	3018	20
3	7.0	2.561	1256.8	1256.9	724.5	2.361			147.30	3542	16
AVERAGE						2.359			147.18	3143	17.33

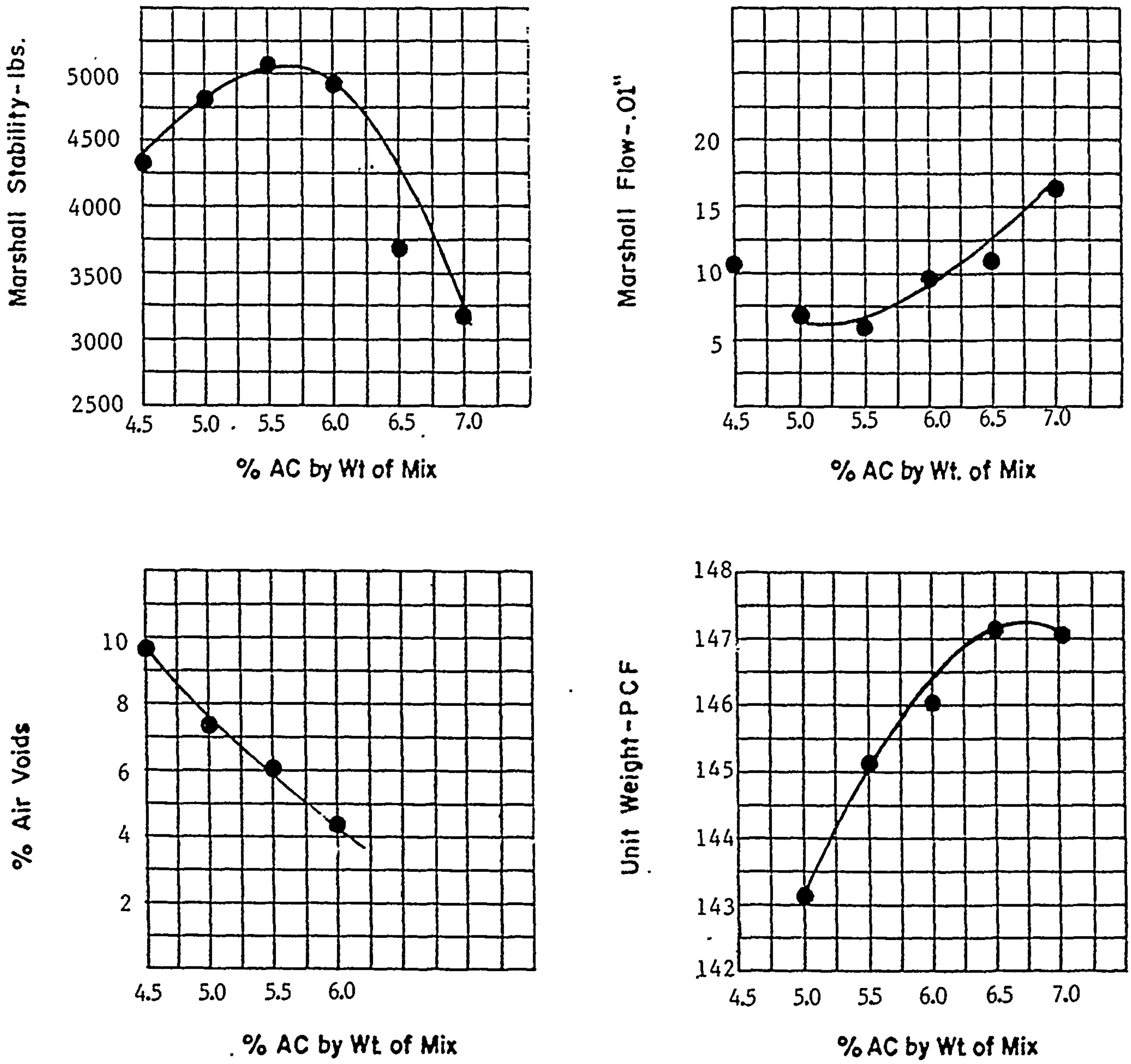

Figure C-17. Marshall Mix Design Curves for FCB/AC-20.

9. MARSHALL MIX DESIGN DATA FOR FCB/AC-10

TABLE C-11. INFORMATION OF MARSHALL MIX DESIGN DATA, FCB/AC-10

No.	% A.C.	Specimen Ht. (in)	Weight (grams) Air	SSD	Water	Specific Gravity (gm-cc) Actual	Maximum	Air Voids %	Unit (pcf)	Stability Load (lb)	Flow (.01 in)
1	5.0	2.598	1232.7	1233.0	696.3	2.287			143.32	5620	8
2	5.0	2.559	1234.7	1245.7	701.9	2.271			141.68	4531	12
3	5.0	2.574	1245.8	1246.6	699.9	2.279			142.19	3860	10
AVERAGE						2.282	2.456	7.1	142.40	4670	10
1	5.5	2.552	1237.0	1237.7	710.0	2.344			146.27	4709	10
2	5.5	2.553	1235.4	1236.3	702.4	2.314			144.39	4831	9
3	5.5	2.535	1234.2	1234.8	705.4	2.331			145.47	4502	7
AVERAGE						2.330	2.477	6.0	145.38	4681	8.67
1	6.0	2.596	1248.3	1248.8	710.1	2.317			144.60	4299	11
2	6.0	2.570	1249.1	1249.7	715.7	2.339			145.96	4108	9
3	6.0	2.551	1249.7	1250.5	717.4	2.344			146.28	4132	
AVERAGE						2.333	2.444	4.5	145.5	4179	10
1	6.5	2.548	1250.1	1250.5	719.1	2.352			146.73	3675	11
2	6.5	2.545	1214.0	1214.3	697.5	2.349			146.58	3970	11
3	6.5	2.560	1252.2	1252.7	720.1	2.351			146.71	3230	10
AVERAGE						2.351	2.440	3.6	146.67	3625	10.67
1	7.0	2.590	1253.6	1253.7	721.8	2.357			147.07	3524	15
2	7.0	2.584	1255.5	1256.1	718.9	2.337			146.02	2492	19
3	7.0	2.611	1261.5	1261.9	722.8	2.345			146.31	2242	15
AVERAGE						2.346				2753	16.33

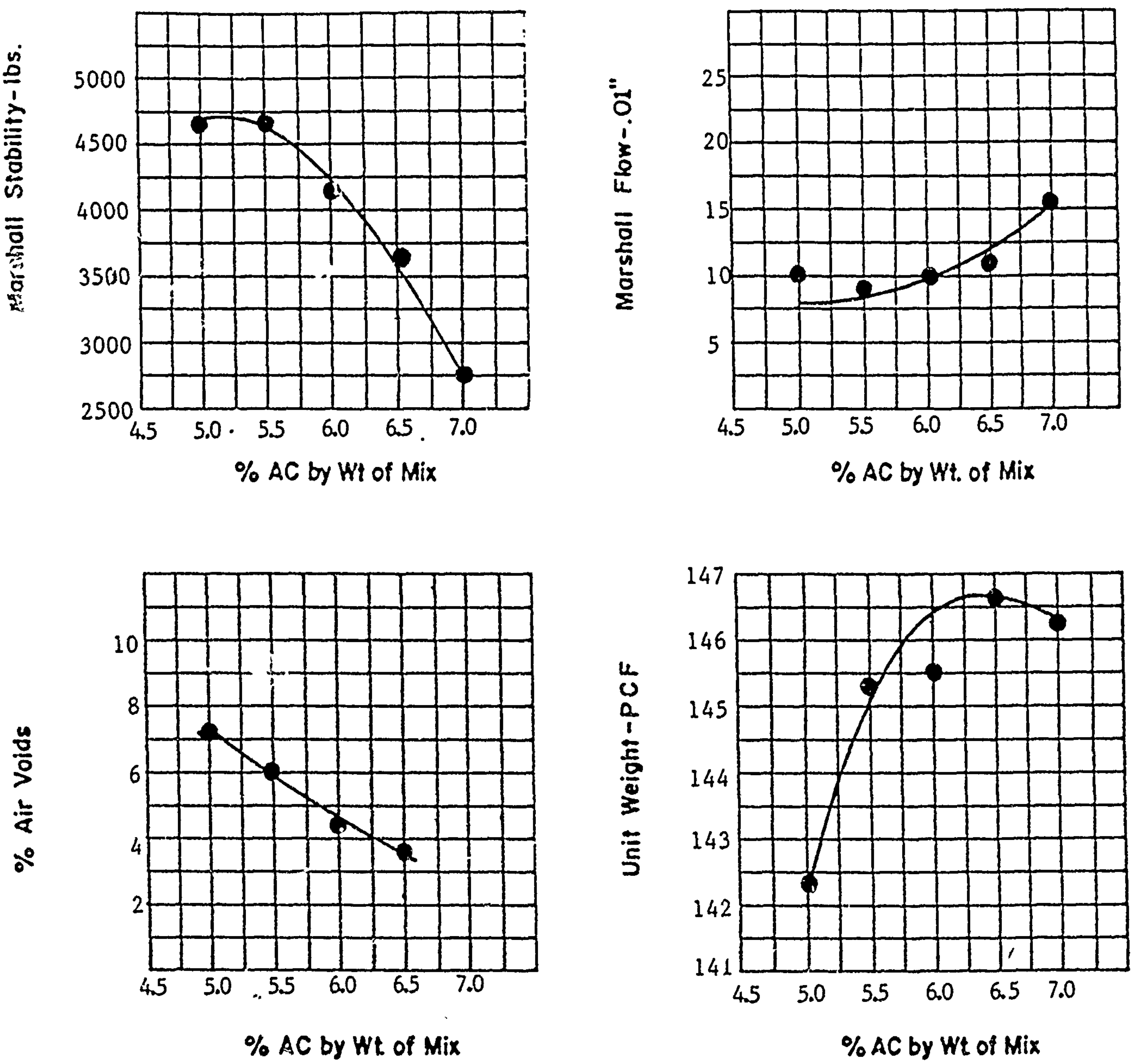

Figure C-18. Marshall Mix Design Curves for FCB/AC-10.

APPENDIX D

TEST RESULTS OF AGED SAMPLES

TABLE D-1. CREEP COMPLIANCE DATA AFTER AGING.

AC-20 AGED	HEIGHT (in)	LOAD (lbs)	STRESS (psi)	$J(t) \times 10^{-4}$ (psi^{-1})					
				1	3	10	30	100	1000
	2.00	188	15	0.045	0.060	0.075	0.120	0.157	0.293
	2.00	502	40	0.031	0.039	0.062	0.084	0.129	0.270
	2.00	1005	80	0.025	0.039	0.056	0.081	0.123	0.232
	2.00	2010	160	0.030	0.041	0.058	0.081	0.116	0.193

AC-10 AGED	HEIGHT (in)	LOAD (lbs)	STRESS (psi)	$J(t) \times 10^{-4}$ (psi^{-1})					
				1	3	10	30	100	1000
	2.00	188	15	0.060	0.101	0.142	0.191	0.296	0.439
	2.00	502	40	0.045	0.070	0.107	0.149	0.228	0.416
	2.00	1005	80	0.049	0.067	0.098	0.137	0.186	0.327
	2.00	2010	160	0.054	0.076	0.097	0.123	0.162	0.246

TABLE D-1. CREEP COMPLIANCE DATA AFTER AGING, (CONTINUED).

ESL AGED	HEIGHT (in)	LOAD (lbs)	STRESS (psi)	$J(t) \times 10^{-4}$					(psi^{-1})
				1	3	10	30	100	1000
	2.00	188	15	0.017	0.039	0.053	0.076	0.108	0.227
	2.00	502	40	0.026	0.034	0.054	0.077	0.115	0.259
	2.00	1005	80	0.031	0.041	0.061	0.085	0.122	0.253
	2.00	2010	160	0.031	0.045	0.069	0.088	0.125	0.214

SBS AGED	HEIGHT (in)	LOAD (lbs)	STRESS (psi)	$J(t) \times 10^{-4}$					(psi^{-1})
				1	3	10	30	100	1000
	2.00	188	15	0.034	0.056	0.090	0.123	0.180	0.334
	2.00	502	40	0.039	0.062	0.087	0.127	0.186	0.366
	2.00	1005	80	0.049	0.067	0.095	0.130	0.183	0.313
	2.00	2010	160	0.035	0.053	0.072	0.095	0.123	0.193

TABLE D-1. CREEP COMPLIANCE DATA AFTER AGING, (CONTINUED).

PP AGED	HEIGHT	LOAD	STRESS	$J(t) \times 10^{-4}$ (psi^{-1})					
	(in)	(lbs)	(psi)	1	3	10	30	100	1000
	2.00	188	15	0.021	0.028	0.039	0.053	0.067	0.120
	2.00	502	40	0.021	0.029	0.038	0.053	0.076	0.146
	2.00	1005	80	0.024	0.031	0.044	0.056	0.080	0.164
	2.00	2010	160	0.021	0.028	0.046	0.061	0.086	0.163

ER AGED	HEIGHT	LOAD	STRESS	$J(t) \times 10^{-4}$ (psi^{-1})					
	(in)	(lbs)	(psi)	1	3	10	30	100	1000
	2.00	188	15	0.030	0.041	0.056	0.075	0.094	0.159
	2.00	502	40	0.028	0.037	0.048	0.066	0.090	0.194
	2.00	1005	80	0.029	0.039	0.056	0.076	0.111	0.208
	2.00	2010	160	0.032	0.042	0.061	0.083	0.126	0.193

TABLE D-1. CREEP COMPLIANCE DATA AFTER AGING, (CONTINUED).

EVA AGED	HEIGHT (in)	LOAD (lbs)	STRESS (psi)	$J(t) \times 10^{-4}$ (psi^{-1})					
				1	3	10	30	100	1000
	2.00	188	15	0.021	0.031	0.049	0.069	0.100	0.198
	2.00	502	40	0.023	0.031	0.047	0.069	0.105	0.252
	2.00	1005	80	0.024	0.031	0.055	0.081	0.123	0.284
	2.00	2010	160	0.034	0.043	0.066	0.093	0.135	0.246

FCB/ AC-20 AGED	HEIGHT (in)	LOAD (lbs)	STRESS (psi)	$J(t) \times 10^{-4}$ (psi^{-1})					
				1	3	10	30	100	1000
	2.00	188	15	0.021	0.030	0.048	0.066	0.091	0.151
	2.00	502	40	0.019	0.032	0.049	0.067	0.097	0.180
	2.00	1005	80	0.023	0.038	0.059	0.108	0.108	0.182
	2.00	2010	160	0.032	0.050	0.065	0.095	0.095	0.150

TABLE D-1. CREEP COMPLIANCE DATA AFTER AGING, (CONCLUDED).

FCB/ AC-10 AGED	HEIGHT (in)	LOAD (lbs)	STRESS (psi)	$J(t) \times 10^{-4}$ (psi^{-1})					
				1	3	10	30	100	1000
	2.00	188	15	0.039	0.060	0.084	0.111	0.146	0.218
	2.00	502	40	0.040	0.060	0.078	0.111	0.143	0.250
	2.00	1005	80	0.044	0.068	0.090	0.121	0.159	0.245
	2.00	2010	160	0.040	0.059	0.080	0.100	0.125	0.183

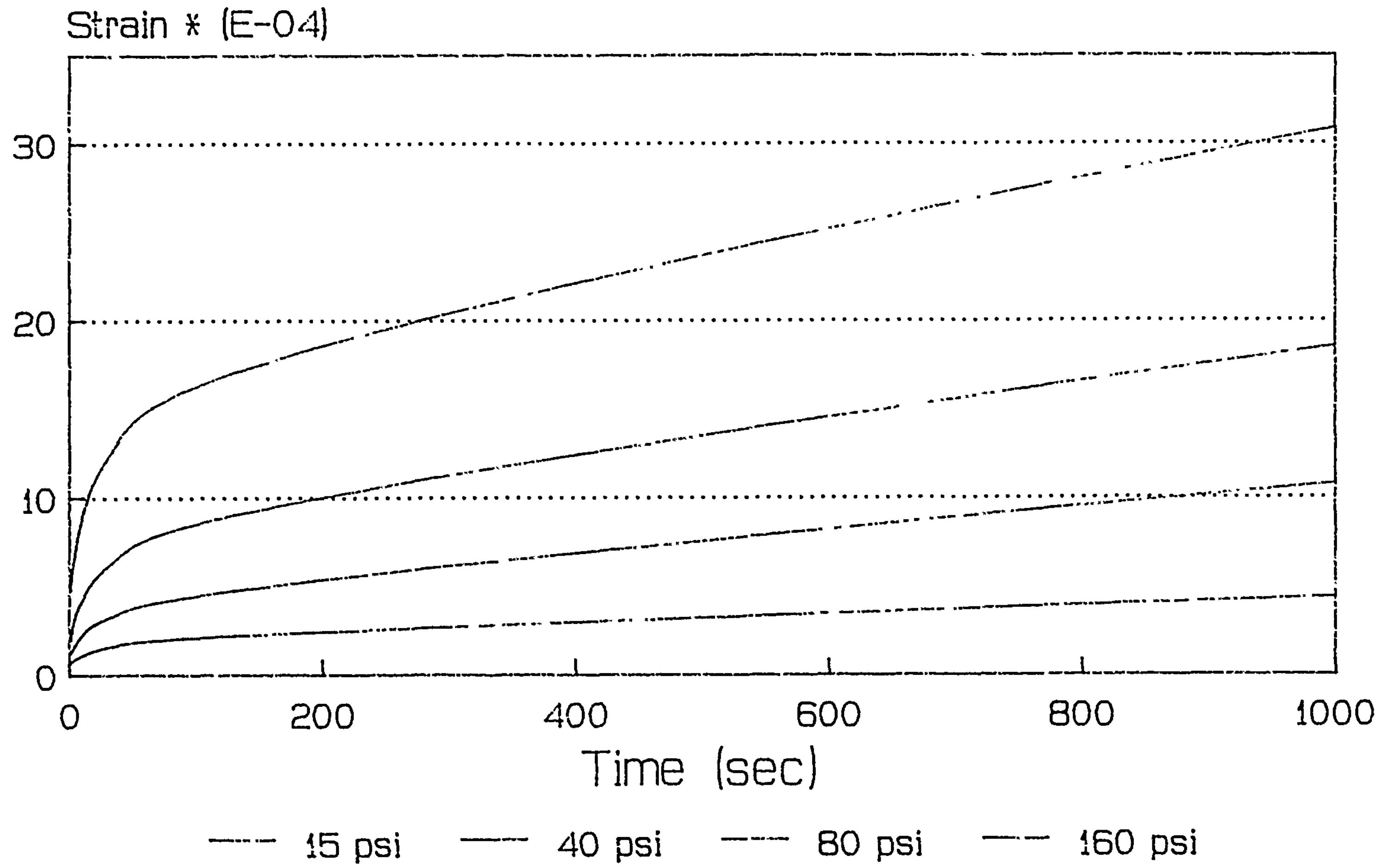

Figure D-1. Compression Rutting Creep for AC-20 Aged.

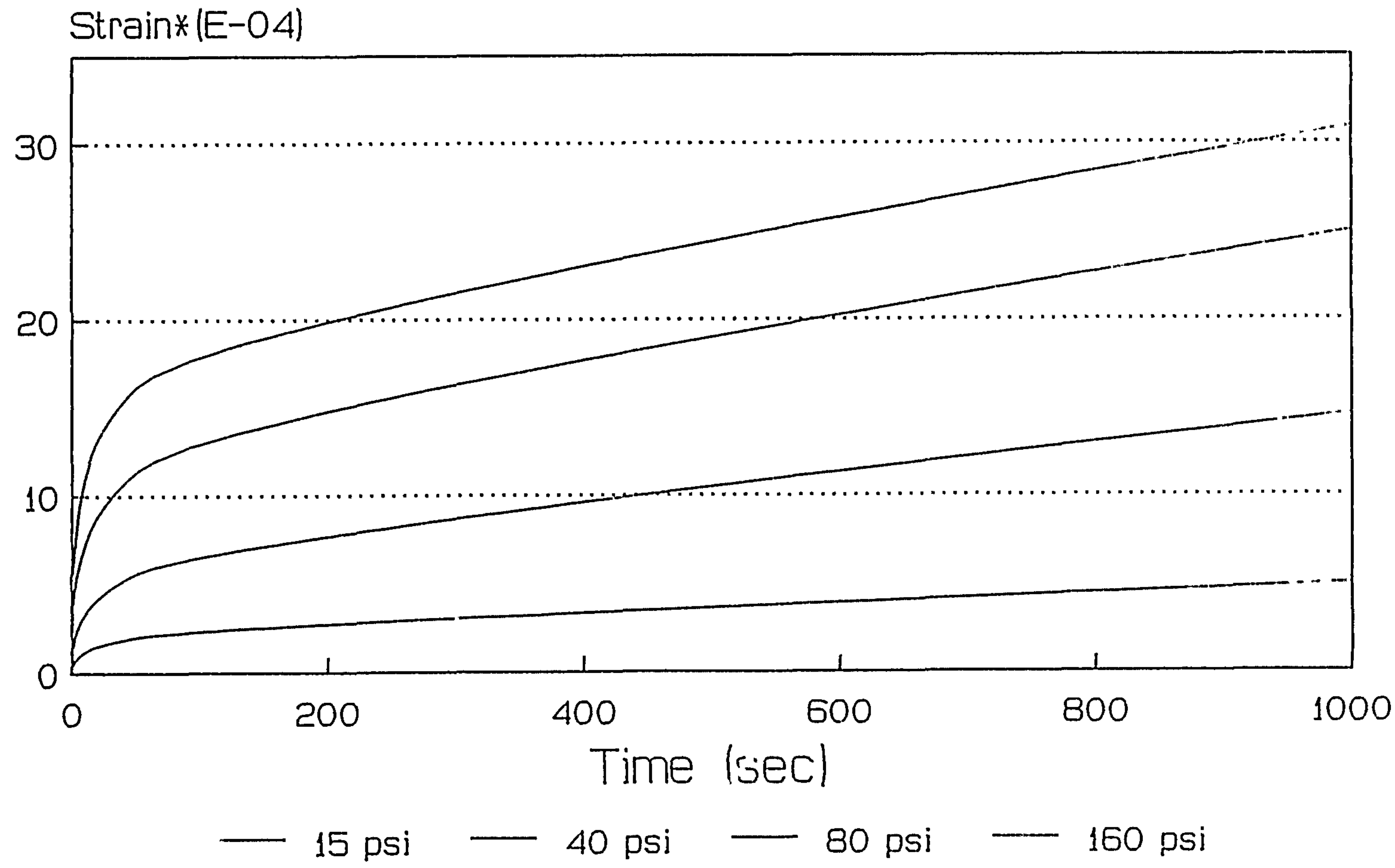

Figure D-2. Compression Rutting Creep for SBS Aged.

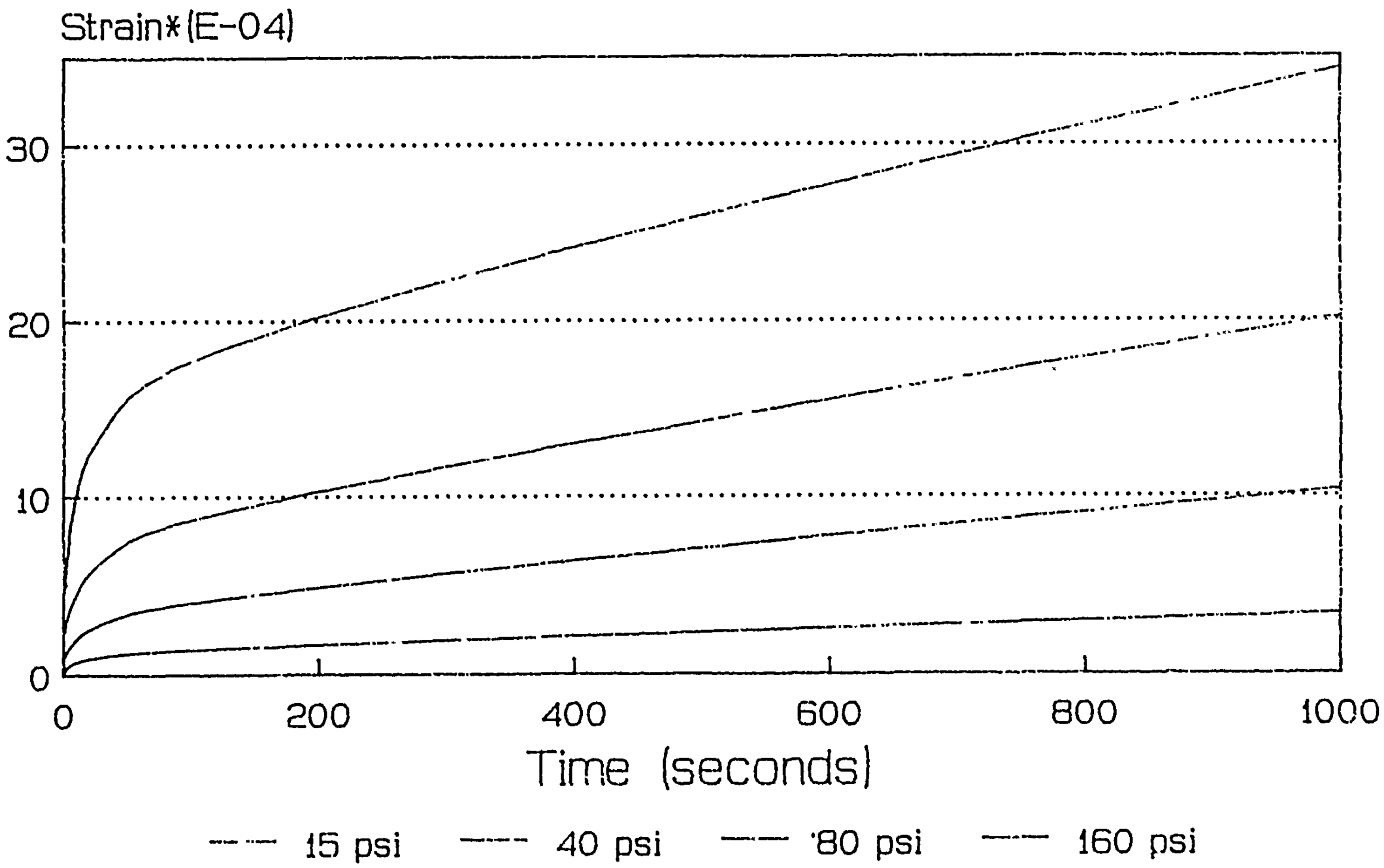

Figure D-3. Compression Rutting Creep for ESL Aged.

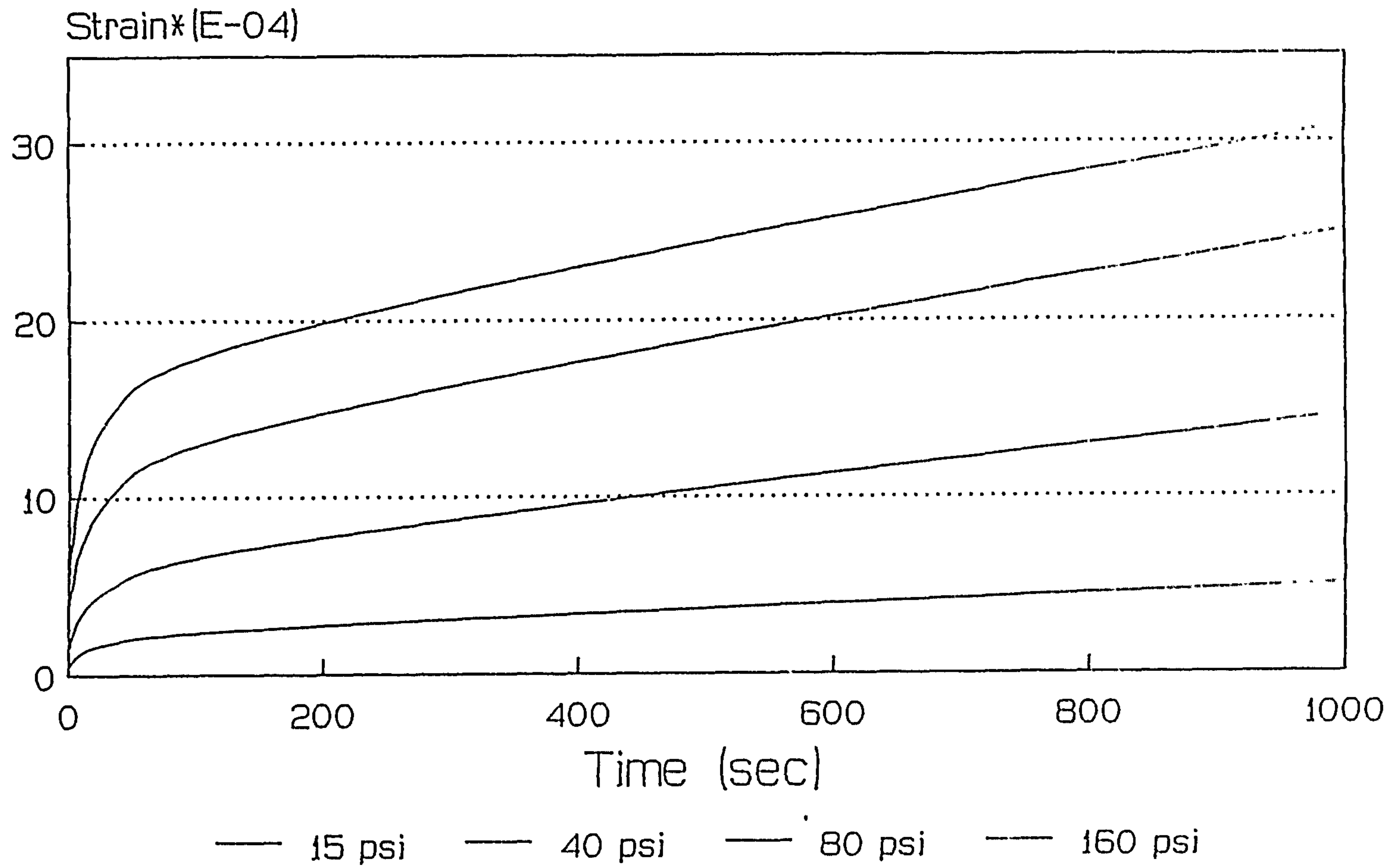

Figure D-4. Compression Rutting Creep for SBS Aged.

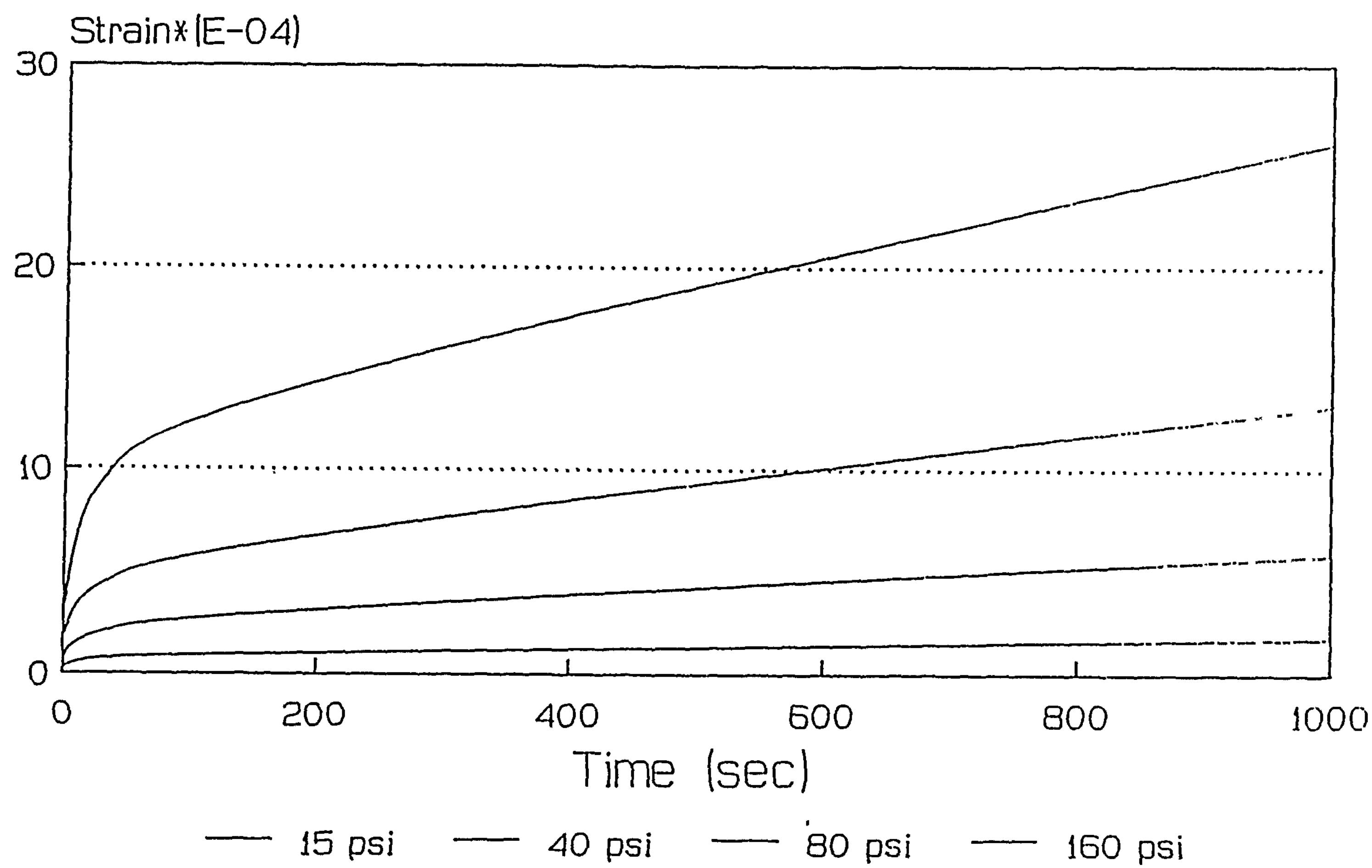

Figure D-5. Compression Rutting Creep for PP Aged.

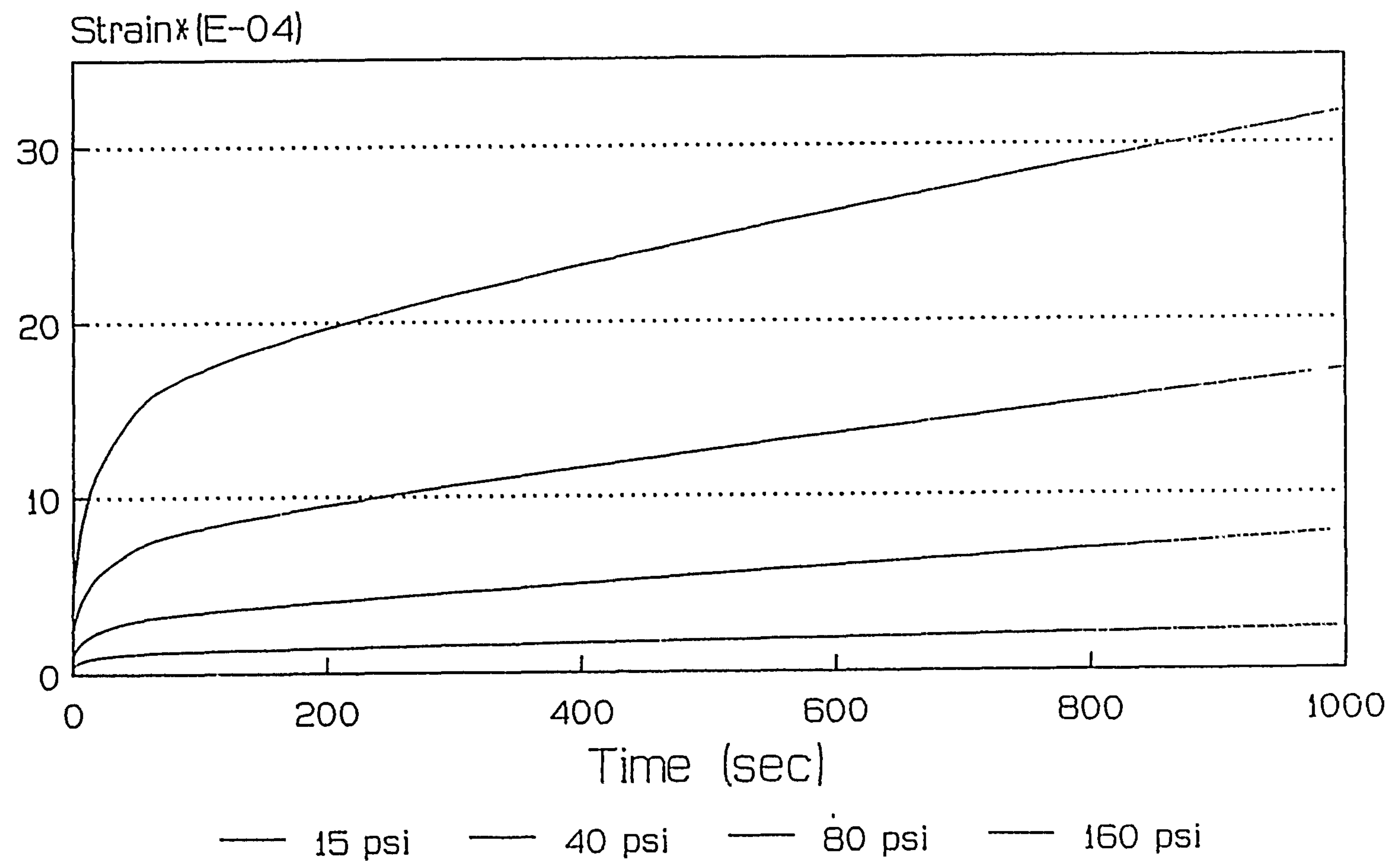

Figure D-6. Compression Rutting Creep for ER Aged.

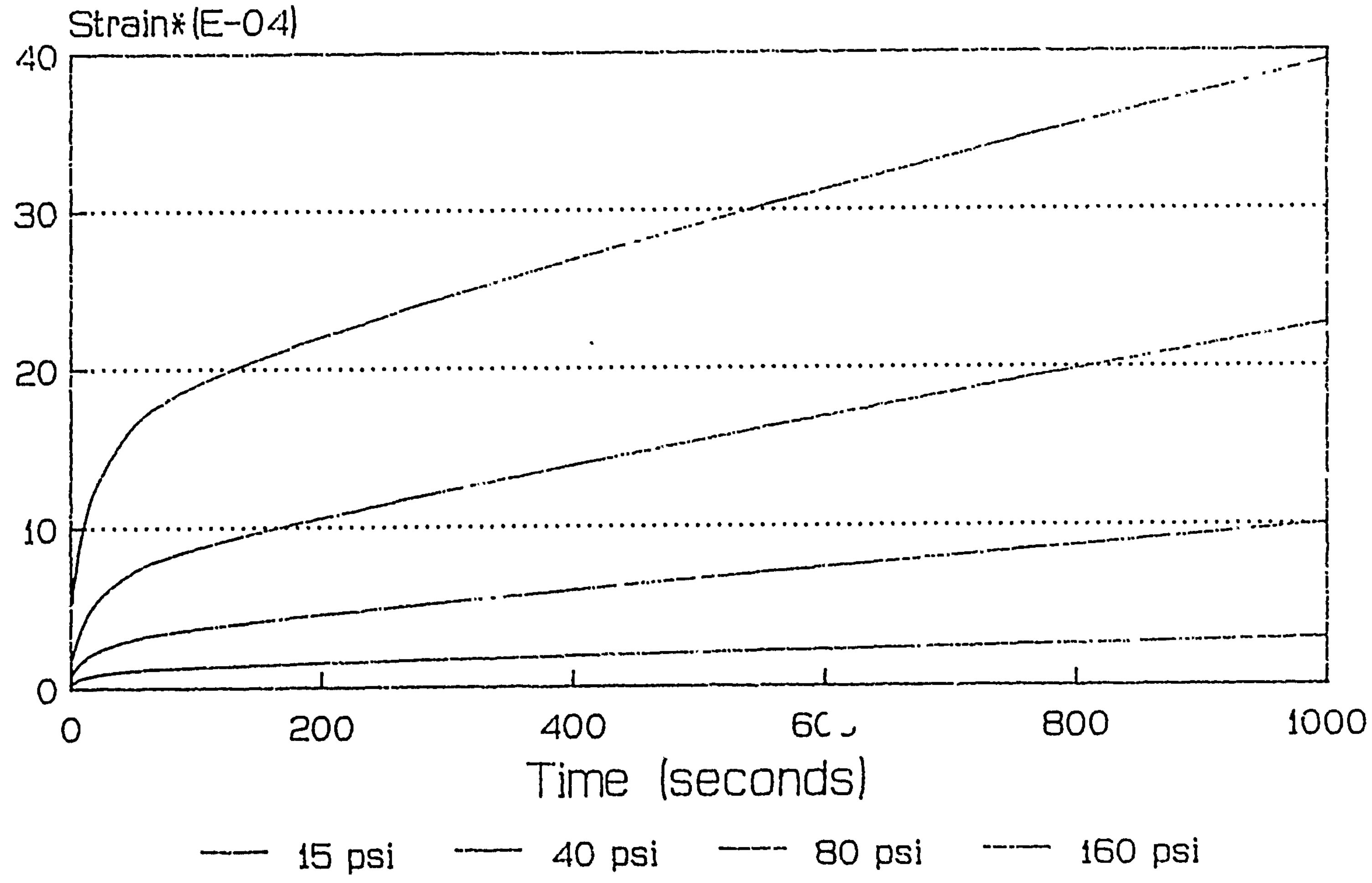

Figure D-7. Compression Rutting Creep for EVA Aged.

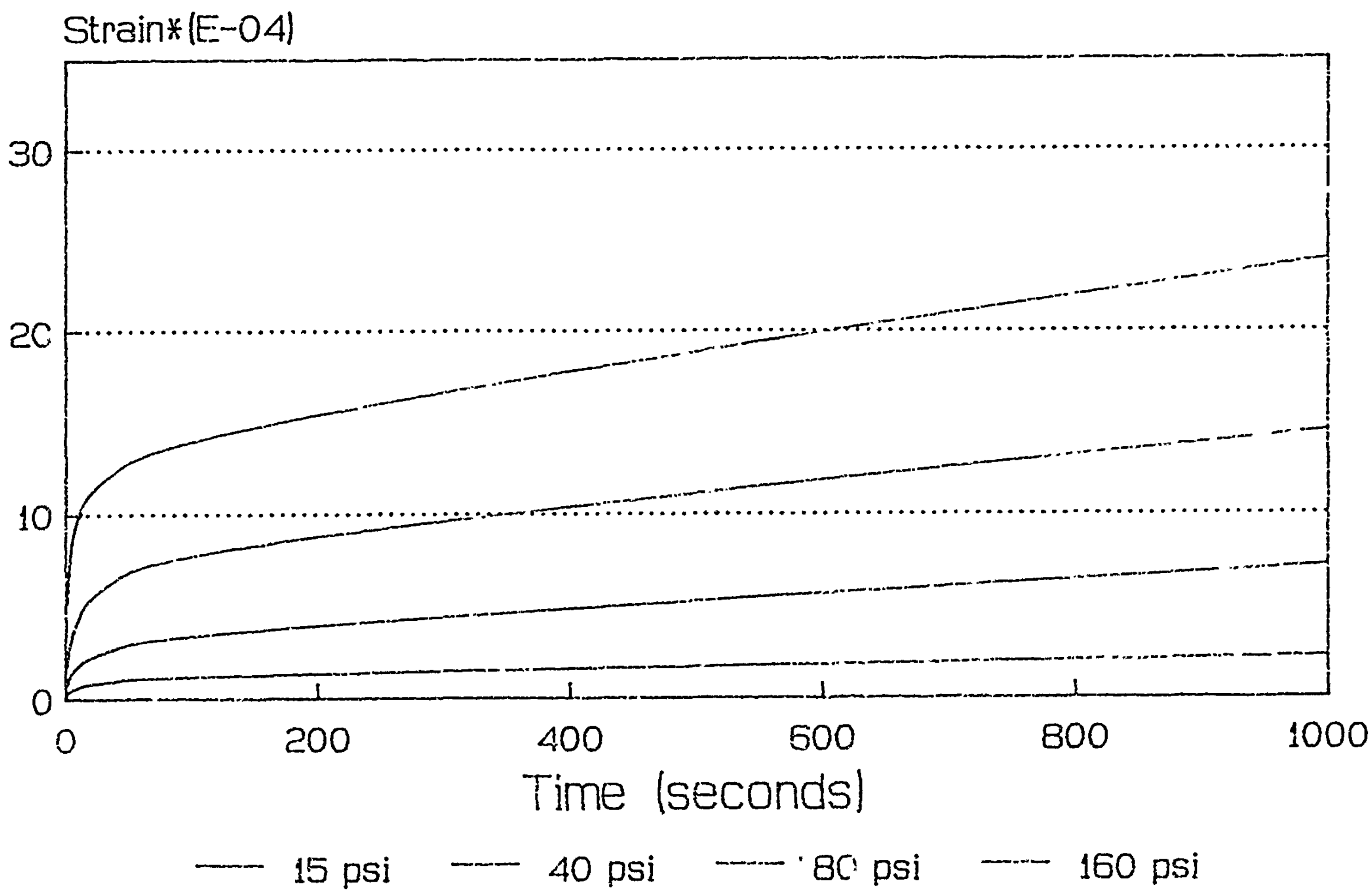

Figure D-8. Compression Rutting Creep for FCB/AC-20 Aged.

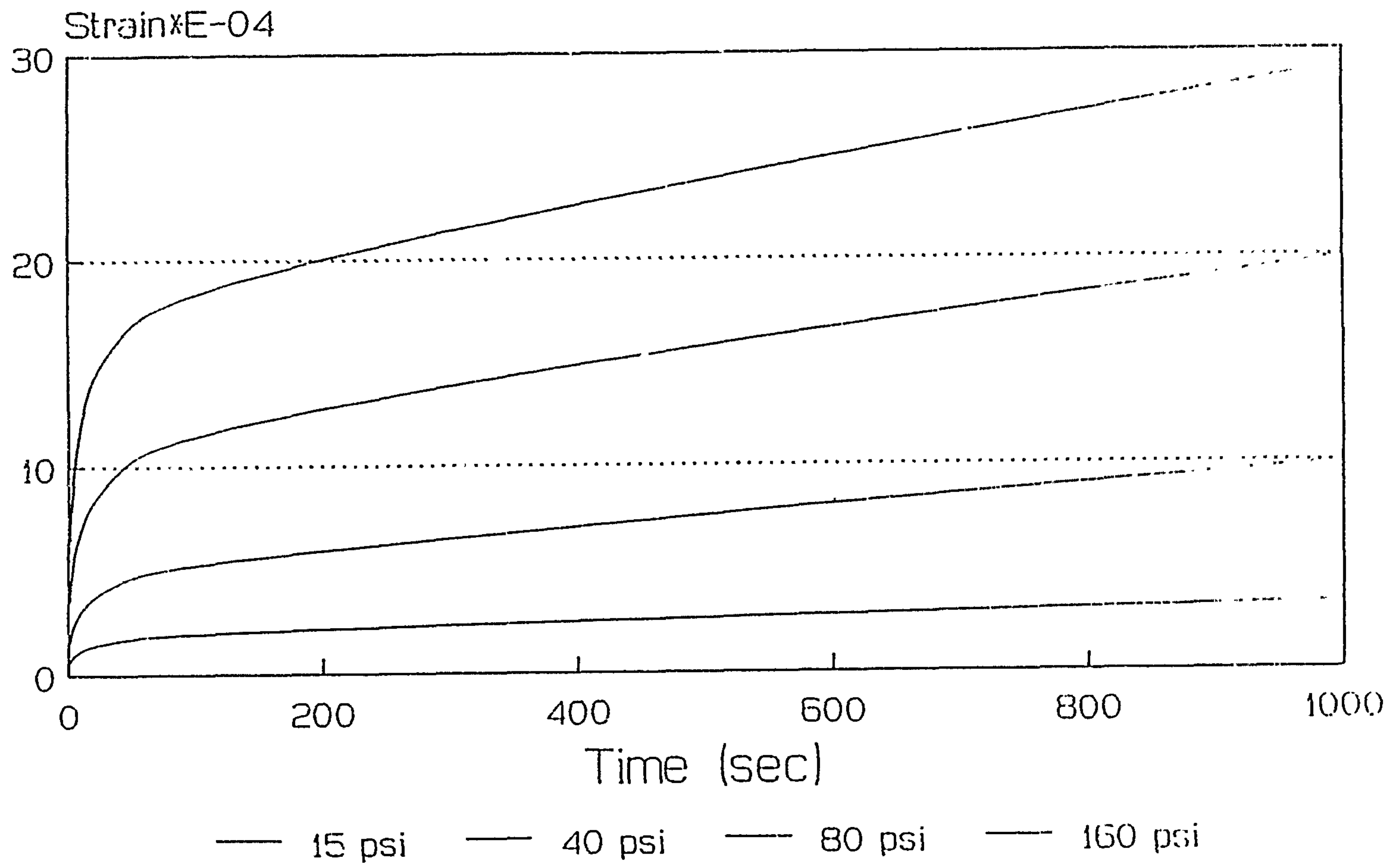

Figure D-9. Compression Rutting Creep for FCB/AC-10 Aged.

APPENDIX E

OPTIMUM ASPHALT CONTENT CALCULATIONS

1. OPTIMUM ASPHALT CONTENT CALCULATIONS, AC-20

	PERCENT
Asphalt Content at Maximum Unit Weight....................	6.00
Asphalt Content at 4% Air Voids..........................	5.40
Asphalt Content at Maximum Stability......................	5.50
Optimum Asphalt Content, Average	5.6

Marshall Design Data From the Above Optimum AC Content:

Marshall Stability	4040	lbs.
Unit Weight	147.3	pcf
Air Voids	3.0	%
Flow	13	

Remarks:

Marshall design data for AC-20 Mixture meets Air Force AFM 88-6 wearing course criteria.

2. OPTIMUM ASPHALT CONTENT CALCULATIONS, AC-10

	PERCENT
Asphalt Content at Maximum Unit Weight....................	5.7
Asphalt Content at 4% Air Voids...........................	5.2
Asphalt Content at Maximum Stability......................	5.3
Optimum Asphalt Content, Average	5.4

Marshall Design Data From the Above Optimum AC Content:

Marshall Stability	4200	lbs.
Unit Weight	147.7	pcf
Air Voids	3.7	%
Flow	16	

Remarks:

Marshall design data for AC-10 Mixture meets Air Force AFM 88-6 wearing course criteria.

3. OPTIMUM ASPHALT CONTENT CALCULATIONS, ESL

	PERCENT
Asphalt Content at Maximum Unit Weight....................	5.75
Asphalt Content at 4% Air Voids...........................	5.75
Asphalt Content at Maximum Stability......................	4.25
Optimum Asphalt Content, Average	5.3

Marshall Design Data From the Above Optimum AC Content:

Marshall Stability	3750	lbs.
Unit Weight	142.5	pcf
Air Voids	4.5 %	
Flow	11.5	

Remarks:

Marshall design data for ESL Mixture meets Air Force AFM 88-6 wearing course criteria.

4. OPTIMUM ASPHALT CONTENT CALCULATIONS, SBS

	PERCENT
Asphalt Content at Maximum Unit Weight....................	6.00
Asphalt Content at 4% Air Voids...........................	5.6
Asphalt Content at Maximum Stability......................	4.5
Optimum Asphalt Content, Average	5.4

Marshall Design Data From the Above Optimum AC Content:

Marshall Stability	2950 lbs.
Unit Weight	145.1 pcf
Air Voids	4.25%
Flow	13

Remarks:

Marshall design data for SBS Mixture meets Air Force AFM 88-6 wearing course criteria.

5. OPTIMUM ASPHALT CONTENT CALCULATIONS, PP

	PERCENT
Asphalt Content at Maximum Unit Weight....................	6.00
Asphalt Content at 4% Air Voids...........................	6.00
Asphalt Content at Maximum Stability......................	6.00
Optimum Asphalt Content, Average	6.0

Marshall Design Data From the Above Optimum AC Content:

Marshall Stability	4000	lbs.
Unit Weight	146.6	pcf
Air Voids	4.0	%
Flow	12	

Remarks:

Marshall design data for PP Mixture meets Air Force AFM 88-6 wearing course criteria.

6. OPTIMUM ASPHALT CONTENT CALCULATIONS, ER

	PERCENT
Asphalt Content at Maximum Unit Weight....................	5.70
Asphalt Content at 4% Air Voids...........................	5.8
Asphalt Content at Maximum Stability......................	5.2
Optimum Asphalt Content, Average	5.6

Marshall Design Data From the Above Optimum AC Content:

Marshall Stability	3250	lbs.
Unit Weight	145.5	pcf
Air Voids	4.5	%
Flow	11	

Remarks:

Marshall design data for ER Mixture meets Air Force AFM 88-6 wearing course criteria.

7. OPTIMUM ASPHALT CONTENT CALCULATIONS, EVA

	PERCENT
Asphalt Content at Maximum Unit Weight....................	6.5
Asphalt Content at 4% Air Voids...........................	5.75
Asphalt Content at Maximum Stability......................	5.50
Optimum Asphalt Content, Average	5.9

Marshall Design Data From the Above Optimum AC Content:

Marshall Stability	4200	lbs.
Unit Weight	145.7	pcf
Air Voids	3.7	%
Flow	13	

Remarks:

Marshall design data for EVA Mixture meets Air Force AFM 88-6 wearing course criteria.

8. OPTIMUM ASPHALT CONTENT CALCULATIONS, FCB/AC-20

	PERCENT
Asphalt Content at Maximum Unit Weight....................	6.75
Asphalt Content at 4% Air Voids...........................	6.10
Asphalt Content at Maximum Stability......................	5.50
Optimum Asphalt Content, Average	6.10

Marshall Design Data From the Above Optimum AC Content:

Marshall Stability	5000	lbs.
Unit Weight	146.5	pcf
Air Voids	4.0	%
Flow	10	

Remarks:

Marshall design data for FCB/AC-20 Mixture meets Air Force AFM 88-6 wearing course criteria.

9. OPTIMUM ASPHALT CONTENT CALCULATIONS, FCB/AC-10

	PERCENT
Asphalt Content at Maximum Unit Weight....................	6.50
Asphalt Content at 4% Air Voids...........................	6.25
Asphalt Content at Maximum Stability......................	5.25
Optimum Asphalt Content, Average	6.0

Marshall Design Data From the Above Optimum AC Content:

Marshall Stability	4150	lbs.
Unit Weight	146.4	pcf
Air Voids	4.2	%
Flow	10	

Remarks:

Marshall design data for FCB/AC-10 Mixture meets Air Force AFM 88-6 wearing course criteria.

(The reverse of this page is blank.)