EFFECT OF MIX INGREDIENTS ON PERFORMANCE OF RUBBER MODIFIED ASPHALT MIXTURES

Final Report

by

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16. Abstract

This research project consisted mainly of a laboratory study of mix properties as a function of variables, such as rubber gradation and content, void content, aggregate gradation, mix process, temperature, and asphalt content. Twenty different mix combinations were evaluated for diametral modulus and fatigue at two different temperatures (-6°C, + 10°C). Layered theory was used to evaluate the effects of mixture variations on pavement life. The information resulting from the study was used to develop guidelines for use of rubber asphalt mixes in Alaska.

The findings of this study indicate that the rubber gradation and content, aggregate gradation, and use of surcharge during sample preparation have considerable effect on modulus and fatigue life of the mix. Also, due to greater allowable tensile strain in rubber-modified mixtures, the thickness of the modified mixture can be reduced, using a layer equivalency of approximately 1.4 to 1.0. An economic comparison between rubber asphalt and conventional mixtures constructed in Alaska indicated that rubber mixes are slightly less cost effective. Other reported benefits of rubber-modified mixes, such as noise and ice control, were not included in the analysis.

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Implementation

This report summarizes the results of field performance surveys and laboratory testing programs aimed at identifying the critical factors in designing and constructing rubber-modified asphalt pavements using a content of 2 to 3% of coarse (¼ inch to #40 sieve) ground tire rubber. The benefits of adding rubber in this size range to asphalt paving mixes are those of increasing traction and reducing stopping distances.

A prior study by the Alaska Department of Transportation evaluated the ice-removal and stopping distance aspects and documented an average reduction of 25% in icy-road stopping distances from the addition of the rubber. Since that time, the use of such "rubberized" mixes has been encouraged for special situations where this benefit will offset the higher mix costs.

This study has indicated that benefits of extended fatigue life may also be expected, and that the addition of rubber may be practical in normal paving mixes not specifically gap-graded to provide a high percentage of coarse (+ ¼ inch) particles as has previously been done. Initially, implementation will take the form of field trials of such "dense-graded" rubber-modified mixes to evaluate their workability and field performance. The consequence of varying mixing temperatures, rubber gradations, and density levels were also evaluated. Pavement designers are encouraged to evaluate the results reported herein when proceeding to prepare specifications and trial mix designs for construction projects.

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1.0 INTRODUCTION

1.1 Problem Statement

The Alaska Department of Transportation and Public Facilities is presently evaluating the use of rubber-modified asphalt pavements in field trials (1,2,3). The potential advantages of using these mixtures include improved ice control and increased pavement life. Greatly needed is an evaluation of mix ingredients (rubber, asphalt, and aggregate) which will result in the discovery of optimum mix properties and greatest life for the least cost.

Rubber-modified asphalt paving mix is prepared by a process that typically uses 3% by weight of granulated coarse and fine rubber particles to replace some of the aggregate in the mixture. This concept was originated in the late 1960's by the Swedish companies Skega AB and AB Vaegfoerbaettringar (ABV) (4) and was patented under the trade name "Rubit". This product has been patented in the United States under the trade name Plusride*, and is marketed by All Seasons Surfacing Corporation of Bellevue, Washington (5).

The introduction of granulated recycled rubber into asphalt paving mixes has been attempted by various investigators in the past with varying success (5,6,7,8,9). Charles H. McDonald, considered to be the father of the asphalt-granulated rubber system developed in the United States, initiated work in 1963 which was based on concepts developed as early as the 1930's in the United States (9). These early experiments included the introduction of various forms of rubber (including raw unvulcanized rubber, rubber latex, and ground whole tire rubber from synthetic and/or natural tires) and various types and percentages of rubber to produce a "rubberized" asphalt for use in surface seal coating of deteriorated pavements (9). Because of its lower cost and promising performance in field experiments, the use of ground waste tire rubber was selected for extensive study in Arizona (8).

Since the work by McDonald, engineers and researchers have been adding rubber, or rubber-like, materials in one form or another to asphalt. The results have not always been successful, but the benefits of flexibility and durability have long been recognized (9). The durability and fatigue resistance of the rubber asphalt mixture is achieved, in part, by the physical

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*Plusride is a trademark for a rubber-modified asphalt mix.

swelling action of rubber at elevated temperature and the rubber's reaction with the asphalt. There also appears to be a partial molecular bond between the two hydrocarbons which yields an increased fatigue resistance in the pavement structure (5).

In addition to the above advantages, use of waste rubber in asphalt mixtures provides many other advantages including:

1) Environmental: Discarded tires provide the source for the rubber granules used in rubber asphalt. It is estimated that the annual amount of rubber available from discarded tires is 1.9 million tons, an amount sufficient to modify the pavements on 40,000 miles of two-lane highway (10). The use of these discarded tires helps to solve the environmental problem of disposing of them in other ways.

2) De-icing: Rubber asphalt pavements have been reported to keep themselves de-iced. The patent holder claims de-icing occurs by compression of protruding rubber granules which sufficiently deform the pavement under the weight of traffic. This causes fracture of the ice layer formation. Following this, wind created by passing vehicles clears the ice from the roadway (10).

3) Noise Reduction: Reductions of up to 10 dB (A) in noise level in comparison with noise levels of conventional pavement surfaces have been reported (5).

4) Skid Resistance: The surface texture and protruding rubber granules are reported to give the pavement improved skid resistance during dry, wet, and icy conditions. Measurements have shown a reduction in stopping distance averaging 25% under icy road conditions (2).

5) Hydroplaning and Water Spray: The high content of coarse aggregate in this product results in a coarse surface texture with good surface drainage, which reportedly eliminates hydroplaning and reduces water spray (10).

6) Sanding and Salting: With improved skid resistance and de-icing characteristics, the need for sanding and salting would be greatly reduced. This would result in a reduction of maintenance costs and corrosive damage to vehicles.

A major disadvantage of rubber-modified asphalt over conventional asphalt is increase in cost. However, if it can be shown that the increased cost is offset by improved performance, the greater expense will be justified.

1.2 Project Objectives

The purpose of this study is to optimize mix ingredients for rubber-modified asphalt pavement in terms of critical mix properties. Specifically, the objectives are to:

1) develop mix design recommendations for rubber-modified asphalt mixes for use in Alaska, and
2) formulate guidelines indicating how these mixes can best be utilized in the Alaska State roadway system.
3) Analyze the economic alternatives of various rubber-modified mixes as compared to conventional mixes.

To accomplish these tasks, a laboratory study was set up to evaluate the effects of:

1) amount and gradation of rubber on mix properties and pavement life,
2) aggregate gradation on mix properties and pavement life,
3) void content on mix properties and pavement life, and
4) mixing temperature, cure time, and surcharge on mix properties and pavement life.

The results of the laboratory study will be used to develop guidelines for selecting mix properties and for determining how rubber-modified asphalt mixes can best be utilized in a state roadway system.

1.3 Scope of Report

The approach used in the conduct of this study is shown in Figure 1.1. A general literature review of the effect of rubber particle shape, type, and gradation upon the properties of the asphalt rubber mix is presented in Chapter 2. The criteria for designing rubber-modified pavements using the Marshall and Hveem procedure are also described. In addition, an evaluation of mix properties (modulus and fatigue) on submitted cores tested by Alaska DOT and All Seasons Surfacing Corporation are included. Finally, a summary of the answers to a questionnaire submitted to various agencies that have used rubber-modified asphalt is presented.

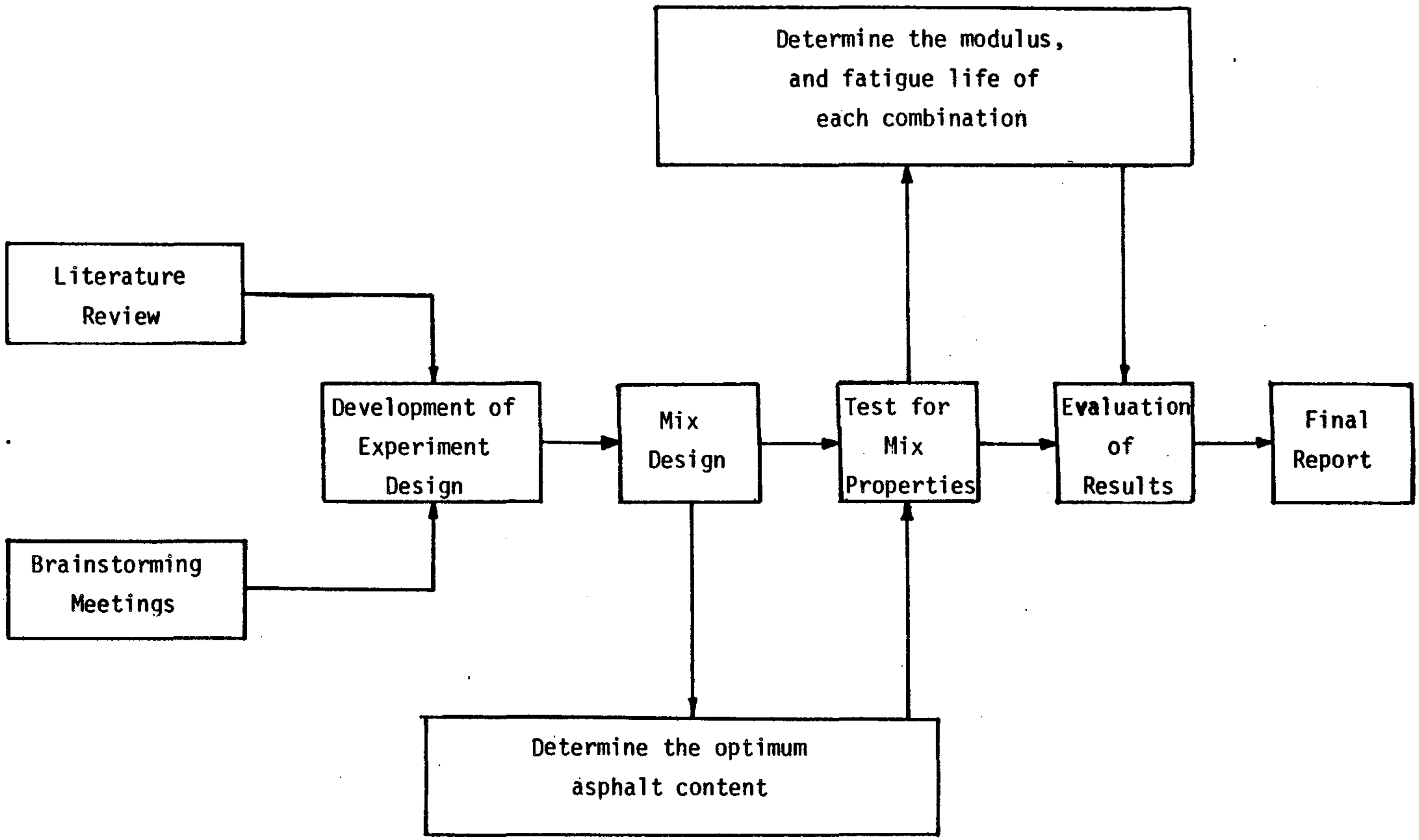


Fig. 1.1. Study Approach

Chapter 3 presents the laboratory experiment design for the study. In particular, it describes the mix variables studied, the materials used, specimen preparation techniques, and the types of tests and test procedures.

Twenty different mix combinations of rubber asphalt mixtures are evaluated for mix design, resilient modulus, and fatigue life. These results are presented in Chapter 4. Also, in Chapter 4, is analysis of data to evaluate the effect of each variable on mix properties.

Chapter 5 presents layered elastic analysis of data to evaluate the effect on pavement life, and an economic analysis of rubber asphalt versus conventional mixtures. Chapter 5 also includes guidelines indicating how rubber modified mixes may best be utilized.

Chapter 6 presents conclusions, along with recommendations for future use of rubber-modified asphalt mixes in the state of Alaska and recommendations for additional research.

2.0 LITERATURE REVIEW

Discarded tires are the source of the rubber granules used in rubber-modified asphalt mixes. It is estimated that the amount of rubber available annually from discarded tires is 1.9 million tons. While a limited number of these 1.9 million tons of tires are used for resource and energy recovery, the vast majority go to landfills or are disposed of in an environmentally unacceptable manner (12). Table 2.1 shows the use of discarded tires in the United States.

This chapter presents the results of a search of the literature related to the following aspects of rubber-modified asphalt:

1) examination of the effects of rubber particle shape, type, and gradation upon the properties of rubber-modified mixes,
2) evaluation of current mix design procedures and guidelines for rubber-modified mixes,
3) evaluation of the effects of varying the rubber content, rubber source, rubber and aggregate gradations, and mixing temperature on mix properties (resilient modulus and fatigue life), and
4) evaluation of the performance of selected field projects placed in the United States.

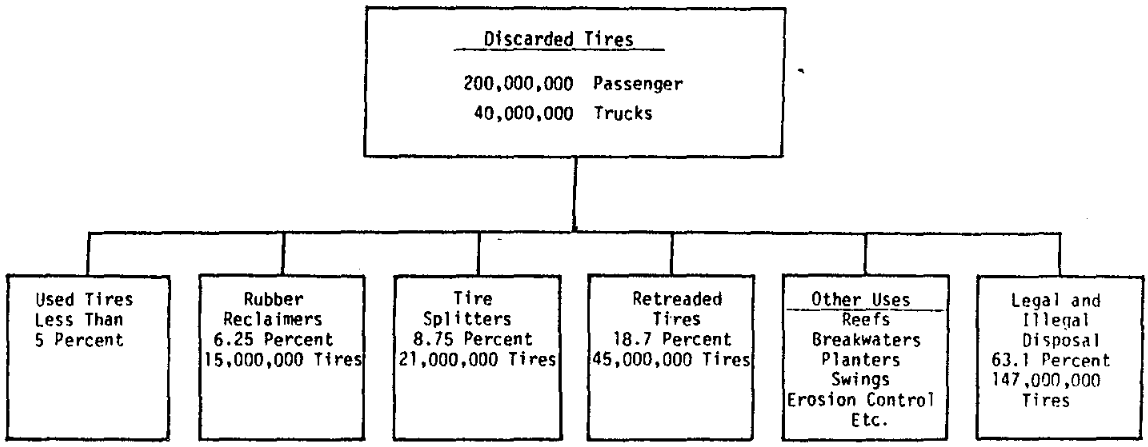
2.1 Use of Rubber in Asphalt Mixtures

Recommendations for use of rubber to improve asphalt pavements date back for more than a century (9). This section briefly reviews the history of the rubber industry, important properties of rubber, asphalt-rubber interaction theories, and existing patents which deal with various aspects of utilizing rubber in asphalts for road construction and maintenance.

2.1.1 History of the Rubber Industry

Rubber was one of the first substances to impress the early European explorers of the New World. They had never encountered anything like the resilient balls that were used by the natives of Central and South America for playing games. The balls were made from a dried milky liquid which could be obtained by cutting the bark of certain trees. Samples of this curious gum

Table 2.1. Uses of Discarded Tires in the United States (12).



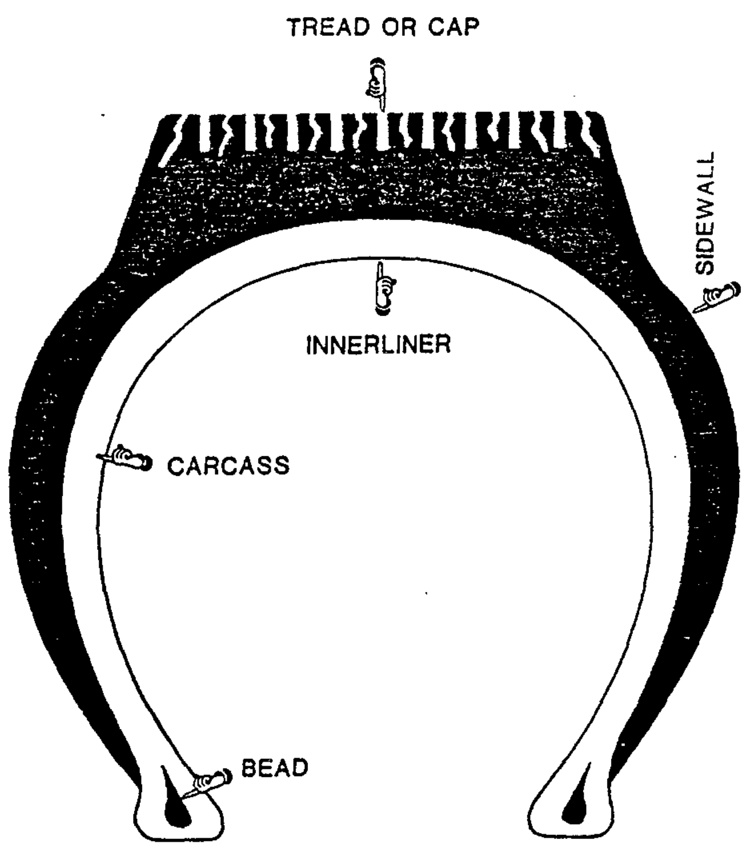


Figure 2.1. Cross Section of a Passenger Tire (13)

were taken back to Europe by the Spaniards and Portuguese. However, their discovery had no impact on civilization at that time (13).

In 1770, Joseph Priestly discovered that the material could be used to rub out pencil marks and coined the name "rubber". Rubber was not widely used on a commercial basis until Charles Goodyear, in 1839, discovered how to "vulcanize" it with sulfur. Vulcanization with sulfur reduced the temperature susceptibility of the rubber and with further compound development, made possible the production of items, such as the pneumatic tire, which today consumes more than half of all rubber used worldwide. The rubber tire accelerated the development of the automobile and this, in turn, created the necessity for an improved highway system (13).

During World War II, due to problems encountered in maintaining an adequate supply of natural rubber, a government-sponsored organization was set up to pool all available technology in an effort to develop a substitute for natural rubber (13). This group was successful in producing several grades of GRS (Government Rubber-Styrene) rubber. The government later sold the synthetic rubber plants to industry and this move led to the rapid development of numerous specialty polymers. There are presently over 20 major types of synthetic rubber produced in this country with over 700 individual specialty grades (13). For the past several years, synthetic rubber has constituted approximately 78% of the new rubber used in this country (13).

2.1.2 Tire Construction and Compounding

Rubber has unique characteristics that permit it to be milled into a soft putty-like material that can be extruded, shaped, or molded with ease, but it becomes very tough, nontacky, and resistant to deformation when vulcanized with crosslinking agents (13). It is this tougher material that is used to produce tires for the automobile industry.

A cross-sectional view of a typical passenger tire is shown in Figure 2.1. Definitions of terms which are often used in tire construction and compounding are:

1) Automobile Tires. Tires with an outside diameter less than 26 inches (66 cm) used by automobiles or light trucks and pick-ups.

2) Truck Tires. Tires with an outside diameter greater than 26 inches (66 cm) and less than 60 inches (152 cm) used by commercial trucks and buses.

3) Whole Tire Rubber. Rubber that includes tread and sidewalls in proportions that approximate the respective weights in an average tire. This is approximately 1/5 tread and 4/5 sidewall by total weight.

4) Tread. The tread section of a passenger tire is normally compounded using styrene butadiene rubber (SBR) with some polybutadiene rubber added for improved wear. Tread has approximately 33% of a very fine, high structure carbon black to give the best possible abrasion resistance.

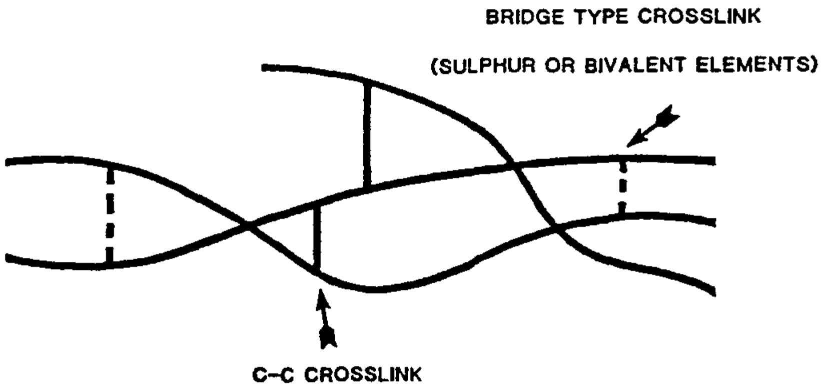
5) Sidewall Rubber. Tire rubber that is usually composed of synthetic rubbers.

6) Vulcanized Rubber (or Recycled Rubber). Scrap vulcanized rubber (tire rubber) that has been ground to pass a given screen. It retains all the properties of the original vulcanized scrap. This chemical mechanism of recycled rubber is shown in Figure 2.2a.

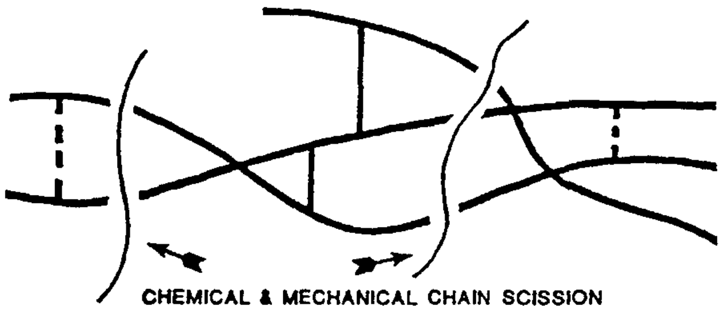
7) Devulcanized Rubber (or Reclaimed Rubber). Scrap vulcanized rubber (tire rubber) that has been subjected to treatment by heat, pressure or the addition of softening agents to alter the chemical composition of the material. In this process, sulphur crosslinks are broken as illustrated in Figure 2.2b.

2.1.3 Important Properties of Recycled Rubber

The important characteristics of recycled rubber affecting the various properties of asphalt rubber mixes include particle shape, rubber type, and rubber gradation. Studies conducted by Oliver (14) indicate that particle structure is the most important factor affecting the elastic properties of the mix. Tests performed for Environment Canada also indicate rubber particle size is an important factor in resistance to crack growth at low temperatures (15). The chemical constituents of bitumen and rubber also display a vital role in asphalt rubber properties (14,15).



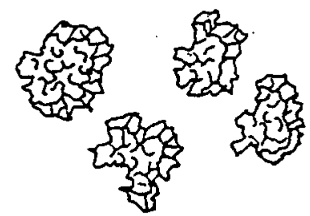
a) Vulcanized Rubber



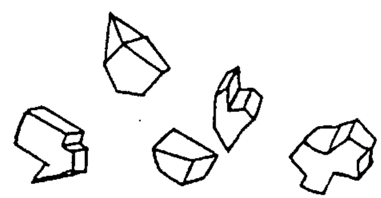
b) Devulcanized Rubber

Figure 2.2. Chemical Mechanism of Vulcanization and Devulcanization (13).

a) Buffings - hair-like or stranded materials, elastic recovery 21%



b) Ambiently Ground-rubber with torn edges, elastic recovery 35%



c) Cryogenically Ground-rubber with sharp angular edges, elastic recovery 6%

Figure 2.3. Effect of Rubber Processing Method (55).

2.1.3.1 Particle Shape. Various processing methods result in different morphology (structure) of the rubber particles. Figure 2.3 illustrates the shape of particles produced by various processes. Hair-like or stranded materials are buffings from the recapping industry and do not represent a whole tire product. Rubber with torn edges is produced by the most common method of ambient grinding in which the tires are literally torn apart. Rubber with sharp angular edges is produced by the cryogenic grinding process in which the tires are frozen and broken like glass.

Oliver (14) found surface particles, similar to those in Fig. 2.3b, produced a bitumen/rubber blend with highest elastic recovery. The large surface area of these particles offered a reactive surface to the bitumen. Cryogenically produced particles (Fig. 2.3c) with less surface area produced lowest elastic recovery.

2.1.3.2 Rubber Types. Interest in the past has been directed toward the addition of specially prepared rubbers to bitumen. The cost of these additives has been high in relation to the bitumen cost; to keep costs low, relatively small amounts (less than 5% by weight of bitumen) have been used. The major types of additives are outlined below (18):

1) Natural Rubber. Chemically a polyisoprene, natural rubber is extracted from rubber trees. It is available as the natural latex, as a powder, or as a solution in kerosene.
2) Styrene Butadiene (SBR). A random copolymer of styrene and butadiene, SBR is marketed depending on the degree of polymerization, ratio of styrene to butadiene, and the presence of additives.
3) Styrene Butadiene Styrene (SBS). This is a block copolymer which behaves as a liner polymer at high temperatures but reverts to vulcanized rubber form at ambient temperatures. Rubbers of this type are known as thermoplastic rubbers.
4) Neophrene. This was the first synthetic substitute for natural rubber and is chemically a polychloroprene. Neophrene is noted for its resistance to oil absorption.

In recent times, attention has centered on the use of recycled rubber in asphalt rubber mixes. The main sources of this rubber are used motor vehicle tires and rubber buffings from tire retreaders. However, it should be noted that the treads of truck tires normally have a high natural rubber content, while passenger and light truck tire treads are usually composed of synthetic rubber. The sidewalls of most vehicle tires are composed of synthetic rubbers (Table 2.2).

2.1.3.3 Rubber Gradation. The improvement of pavement properties via the effect of rubber gradation depends on the pavement application. Plusride recommends the coarse and fine rubber gradation shown in Table 2.3. The fine rubber particles (- #10 sieve) are added in addition to coarse particles because they tend to swell and disperse within the binder, reportedly producing a mix with increased viscosity. This thickening results in good stability at low surface temperatures. Oliver (14) found the elastic recovery of the rubber/bitumen blend improved as rubber particle size decreased. He suggested that the improvement could be due to a difference in particle shape; the larger particles had smooth faces, while the smaller particles were rougher and more porous.

Coarse rubber particles act as an elastic aggregate in the mix. Studies done in Canada suggest that larger rubber particles are more effective than small particles for increasing crack resistance and toughness (15). Also, the repeated flexing of protruding large rubber particles due to traffic loading, has been suggested as causing breakdown of surface ice deposits (16).

Rubber gradation also affects the optimum asphalt content of the mix. A fine rubber gradation (100% passing #10 sieve) requires less asphalt because the rubber disperses better throughout the mix (17).

Table 2.2. Typical Composition of Recycled Rubber Used in Asphalt Rubber (16).

	Auto Tires (Whole)	Truck Tires (Whole)	Auto Tread	Truck Tread	Devulcanized Whole Tire
Acetone Extractables, %	19.0	12.5	21.0	16.0	20.0
Ash, %	5.0	5.0	5.0	4.0	20.0
Carbon Black, %	31.0	28.5	32.0	30.0	20.0
Total Rubber Hydrocarbon	46.0	54.0	42.0	50.0	40.0
Synthetic Rubber, %	26.0	21.0	37.0	23.0	22.0
Natural Rubber, %	20.0	33.0	5.0	27.0	18.0

Table 2.3. Rubber Gradation for Plusride (4).

	Percent Passing		
Sieve Size	Coarse Rubber	Fine Rubber	80/20 Rubber Blend*
1/4"	100		100
#4	70-90		76-92
#10	10-20	100	28-36
#20	0-5	50-100	10-24

*Note: The "80/20" is 80% coarse and 20% fine rubber in combination.

Table 2.4. Common Test Methods for Ground Rubber.

Property	Method	Purpose
Specific Gravity	ASTM D-1817 Baker Rubber Method U.S. Rubber Method	Intended to determine the density of solid materials.
% Natural/ Synthetic	ASTM D-297 Baker Rubber Method U.S. Rubber Method	To find the specific rubber polymers present in a rubber product.
% Carbon Black & % Ash	ASTM D-297 Baker Rubber Method U.S. Rubber Method	Intended to determine the percentage of carbon black and ash contained in a rubber product.
% Acetone Extract	ASTM D-297 Baker Rubber Method U.S. Rubber Method	Indicates the quality of the rubber present.
Gradation	ASTM D-1511 Baker Rubber Method U.S. Rubber Method	Indicates the gradation of the ground rubber particles.

2.1.4 Survey of Rubber Suppliers

In October 1983, a survey of the following recycled rubber suppliers was conducted:

1) Baker Rubber
   P.O. Box 2438
   South Bend, IN 46680

2) Genstar Conservation Division
   3733 West Willis Road
   Chandler, AZ 85224

3) Atlos Rubber
   1522 Fishburn Ave.
   Los Angeles, CA 90063

4) U.S. Rubber and Reclaiming Co., Inc.
   P.O. Box 54
   Vicksburg, MS 39180

5) Rubber Granulators, Inc.
   12701 Mukiltee Speedway
   Everett, WA

The purpose of the survey was to collect information on the type and portion of tire used, the method of processing, and test methods used to evaluate the rubber.

The results of the survey indicated that all of the suppliers processed the tires at ambient temperature. The majority ground the whole tire using fabric-type automobile or light truck tires, producing a heterogeneous mixture of synthetic rubbers.

Common tests run by the suppliers are summarized in Table 2.4. It should be noted that Baker Rubber and U.S. Rubber have developed many of their own test methods.

2.1.5 Asphalt-Rubber Interaction

This section briefly examines the effect of rubber type on the asphalt rubber blend. Most research conducted in this area has been oriented toward the use of rubber additives rather than recycled rubbers. Since recycled rubber is generally composed of a mixture of natural, SBR, and SBS rubbers, this information should provide insight on recycled rubber-asphalt interactions.

2.1.5.1 Theories. In a rubber/bitumen system, the rubber can be dispersed as an integral part of the binder (true solution), as microscopic particles, or as visible discrete particles. The degree of dispersion depends on the time and temperature of heating, the composition of the rubber and the asphalt, and the degree of mixing (18). It is not clear at this time what degree of dispersion is needed to produce optimum mix properties.

Rostler (19) provided an explanation of the rubber-bitumen interaction as follows. Bitumen is composed of a bodying agent (asphaltenes) dissolved in a solvent (the chemically active portion of the maltenes), and a gelling agent (paraffins). Rubber in true solution with asphalt is incorporated as part of the solvent or the asphaltene portion. Rubber soluble in n-pentane will become part of the solvent, while rubber insoluble in n-pentane will modify the asphaltene fraction. Natural and SBR rubbers, soluble in n-pentane, will primarily act to increase the viscosity of the maltene fraction. Insoluble in n-pentane, SBS rubbers increase the viscosity of the asphaltene portion. As with any solution, surplus will be precipitated out when supersaturated.

Work done by Huff (20) suggests that asphalts having less than 30% second acidaffins (part of the solvent portion) do not produce the adhesive properties required with rubber. Those asphalts that contain more than 40% second acidaffins become soft at summer pavement temperatures.

2.1.5.2 Results of Lab Studies. Van Beem and Brasser (21) investigated the properties of an SBS block copolymer and bitumen blends. They discovered the degree of dispersion of rubber in the mix depended on the bitumen type and particularly the aromaticity of the bitumen. In low aromaticity bitumens, the dispersion of the rubber was visible to the naked eye and only marginally affected the bitumen properties. Blends with an intermediate aromaticity were found to exhibit much improved flow and deformation characteristics, with the rubber present as microscopically fine filaments. Very high aromaticity blends did not show improved bitumen properties; the rubber was visible as a "single phase" system under a microscope.

Studies conducted by Patrick indicate the addition of Samrubba™, another thermoplastic rubber, decreases the penetration of the blend at low temperatures (18). The addition of natural rubber produced no significant effect on penetration at low temperatures (18).

Oliver found that natural rubber blends exhibited superior elastic properties as compared to those of SBR blends (14). However, synthetic rubbers were found to be more thermally stable than natural rubbers, as shown by Figures 2.4 and 2.5. Both natural and SBR rubbers behave satisfactorily under normal digestion conditions, but if overheating should occur, the properties of natural rubber would degrade at a faster rate than those of synthetics.

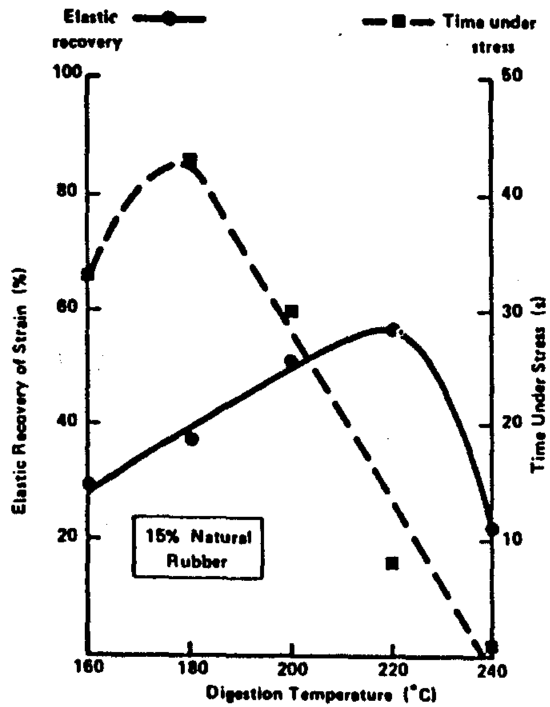


Figure 2.4. Effect of Digestion Temperature on Properties of an Asphalt Natural Rubber (14).

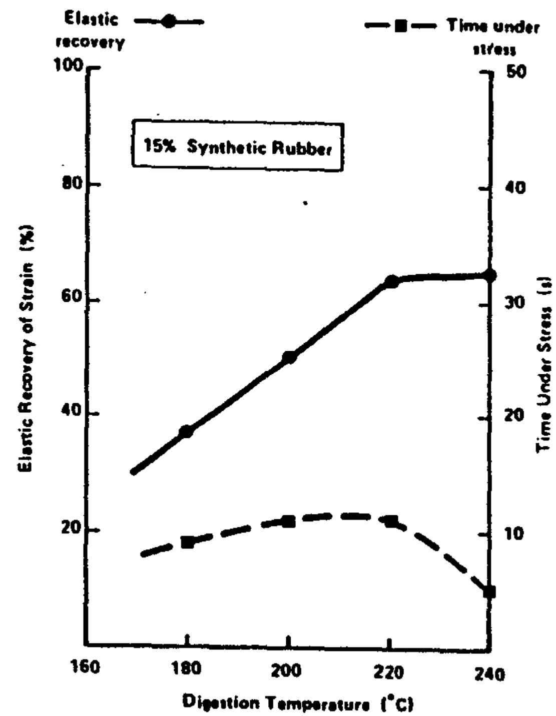


Figure 2.5. Effect of Digestion Temperature on Properties of an Asphalt Synthetic Rubber (14).

2.1.6 Patents

Many patents currently exist which deal with various aspects of utilizing recycled rubber in asphalts for road construction and maintenance. A summary of patents are presented in this section.

2.1.6.1 Patent Types. Two major types of patents were reviewed in this study. U.S. Patent Numbers 3,844,668, 3,919,148, 4,068,023, 4,069,182, and 3,891,585 deal with the use of asphalt rubber for chip seals, stress absorbing membranes, waterproofing membranes, and crack fillers. U.S. Patent Numbers 4,166,049 and 4,086,291 describe processes in which the asphalt rubber is used as a binder in asphaltic mixtures.

2.1.6.2 Asphalt Concrete Patents. The process described in U.S. Patent Number 4,166,049, which is held by U.S. Rubber Reclaiming Company, provides a rubberized asphalt using devulcanized reclaimed and scrap crumb rubber produced from whole tires. The asphalt composition is quite specific, as shown in Table 2.5. Asphalt and rubber (75% to 95% and 5% to 25% by weight, respectively) are cooked at about 177°C to 232°C (350°F to 450°F) for 30 minutes to 2 hours, producing a blend with a viscosity of 800 centipoises at 204°C (400°F). This material is then incorporated as a binder in an asphaltic concrete using conventional equipment. The mix produced is claimed to have improved strength and flexibility, and stripping, cracking, rutting, bleeding, and skid resistance (20).

The primary objective of U.S. Patent Number 4,086,291, held by All Seasons Surfacing Corporation, is stated "to render possible the production of a paving mass which can contain a substantially greater amount of well-bound macadam than heretofore possible" (22). The patent holder claims the increased amount of macadam improves the "wear resistance" of the pavement, while the addition of rubber in the asphalt provides increased flexibility, and skid, and stripping resistance (22). In general, the process involves the following steps:

1) Heating the aggregates to a temperature of 160°C to 170°C (320°F to 338°F).

Table 2.5. Asphalt and Rubber Composition Claimed for U.S. Patent No. 4,166,049 (20).

a) Asphalt Composition

Percent by Weight	Component
20-30	Asphaltenes
5-15	Nitrogen Bases
10-20	First Acidaffins
30-40	Second Acidaffins
10-20	Paraffins

b) Typical Rubber Composition

Rubber Compounding Materials	15-20% by weight
Carbon Black	10-35% by weight
Ash	10-20% by weight
Rubber Hydrocarbon	35-45% by weight

2) Adding vulcanized rubber particles (1 to 8 mm measured in the greatest dimension) to the heated rock, and mixing together for a time sufficient to cause the rubber to adhere to the rock.

3) Adding fine (less than 1 mm measured in the greatest dimension) vulcanized rubber particles to the above mixture.

4) Mixing the above mass with a filling material and an asphalt.

The amount of materials being as follows:

1) Aggregates - at least 65% by weight (defined as particles larger than 8 mm).

2) Coarse rubber (1 to 8 mm in the greatest dimension) - 1.35% by weight.

3) Fine rubber (less than 1 mm in the greatest dimension) - 1.65% by weight.

4) Asphalt - 8.5% by weight.

5) Filling material (which may include lime) - 6% to 10% by weight.

2.2 Mix Design Considerations

Mix designs for rubber-modified asphalt mixtures are normally made using the Marshall or Hveem method; however, the criteria (at least for Plusride) for selecting the asphalt content are different for conventional hot mix asphaltic concrete and rubber-modified asphalt. Most engineers use stability, flow, cohesion, air voids, and density as criteria for designing conventional hot mix asphaltic concrete pavements. However, stability values for rubber asphalt mixes which are currently on the market are lower than values obtained for typical asphalt mix. The flow values for rubber-modified mixes are generally greater than the maximum allowable in asphalt mix design criteria (23). Consequently, stability and flow values for rubber-modified mixes may give guidance only in terms of their relative position on design curves. Prior experience has shown that the critical factor for successful rubber-modified asphalt installations has been a low percentage of voids of the total mix (23). For example, pavements placed in Alaska which have low void contents (approximately 4.6%) and satisfactory performance had stabilities as low as 350 pounds and flows up to 0.19 inch (23). In general, the laboratory air voids are recommended to range from 0% to 4% maximum depending on the traffic level of the facility being designed (23):

1) Low traffic - 0% to 2%.
2) Medium traffic - 3% max.
3) High traffic - 4% max.

This required void content is achieved by increasing both the mineral filler and the asphalt cement content until the target value is reached (23).

2.2.1 Guidelines for Mix Design - Marshall Method

Results of mix designs with the Marshall method have indicated that the added rubber greatly changes the mix properties, and the optimum asphalt content is generally increased by 1.5% to 2% compared with conventional mixtures. The aggregates, heated to a temperature between 163°C (325°F) and 177°C (350°F), should be placed in the mixing bowl and then the rubber granules are added and thoroughly mixed before adding the liquid asphalt. The compaction mold, as well as the hammer and bottom plate, should be lightly greased to break any bond between the mold and mixture. Filter papers stick to the specimens and should not be used unless some method is available for removal (e.g., a knife and/or temperature flame). Alternatives to filter paper are release paper or a greased composition paper.

The compaction mold assembly and the compaction hammer should be preheated to 141°C to 149°C (285°F to 300°F). The compaction temperature shall be over 116°C (240°F). At lower compaction temperatures, the mixture may get stiff and proper compaction is not possible. After compaction and during cooling, wood plugs should be used to provide a surcharge of at least 5 pounds during cooling. This helps prevent the specimen from expanding or decompacting. The standard 50-blow Marshall procedure is recommended by Plusride to select the asphalt content for low to medium traffic (4).

2.2.2 Guidelines for Mix Design - Hveem Procedure

The Hveem method of designing paving mixtures was developed by Francis N. Hveem, formerly Materials and Research Engineer with the California Division of Highways (33). This test involves determining an approximate asphalt content by the centrifuge kerosene equivalent test and then subjecting the specimen at that asphalt content, and at higher and lower asphalt contents, to a stability test after compaction by a particular method of kneading compaction (33). A swell test on a specimen exposed to water is also made.

The purpose of the Hveem method is to determine the optimum asphalt content for a particular blend of aggregate and/or rubber. It also provides information about the properties of the resulting asphalt mix. Currently, there are no specifications existing for a Hveem procedure on rubber-modified mixes.

The Federal Highway Administration (WDFD) has performed a mix design for rubber-modified asphalt mixtures using the standard Hveem procedure (11). After blending, the aggregate was heated to 160°C (320°F). Rubber at ambient temperature was added to the heated aggregate and dry mixed for 15 seconds. After adding the required asphalt, the sample was mixed for an additional 3 minutes. Each sample was then returned to the 160°C (320°F) oven for a 1-hour curing period. After curing, the samples were compacted using 50 compactor foot applications at 250 psi, followed by a 40,000-pound leveling load. The forming mold part of the compaction mold was lubricated using standard multipurpose grease and a release paper disk was used to prevent the mix sticking to the base. Finally, a 5-pound surcharge was placed on each sample until it cooled to room temperature.

2.3 Evaluation of Mix Properties

Only limited mix properties (e.g., modulus and fatigue) are available for Plusride asphalt mixtures. Most of this data was developed by Oregon State University and Alaska Department of Transportation and Public Facilities (24,25). The results of resilient modulus and fatigue tests on laboratory-prepared samples from two rubber asphalt projects in the State of Alaska and on laboratory-prepared samples prepared by All Seasons Surfacing Corporation are presented in this section.

2.3.1 Alaska DOTPF Study (25)

This section describes the results of resilient modulus and fatigue on rubberized asphalt mix performed by Alaska DOTPF. Two projects were evaluated:

1) Peger Road, and
2) Upper Huffman.

All tests were performed in the Central Region Laboratory (ADOTPF) using aggregates secured from the Anchorage area.

The purpose of this study was to evaluate the effect of varying:

1) aggregate gradation (coarse, medium, fine),
2) rubber content, and
3) proportion of fine rubber.

2.3.1.1 Test Procedures. Standard Marshall mix designs were made for the two projects. For Peger Road, the variables considered included:

1) rubber content - 2.5%, 3%, and 3.5% by weight of total mix. In all cases an 80 to 20 blend of coarse and fine rubber was used.
2) proportion of fine rubber - one set had an added 2% fine rubber, and
3) mix temperatures - 190°C (375°F) and 204°C (400°F).

The compaction temperature in all cases was 121°C (250°F) while the asphalt content was held constant at 8.0%, AC-2.5.

For Huffman Road, the variables considered were:

1) aggregate gradation - coarse, medium, and fine,
2) proportion of fine rubber - one set had 2% additional fine rubber, and
3) mix temperatures - 190°C (375°F) and 204°C (400°F).

The compaction temperature in all cases was 121°C (250°F).

The asphalt and rubber content were calculated by weight of dry aggregate. The optimum asphalt content (based on 2% air voids) for Peger Road varied with rubber content as follows:

Rubber Content, %	Optimum Asphalt Content, %
2.5	7.5
3	8
3.5	8.5

Figures 2.6 and 2.7 show the effect of rubber content on Marshall stability and voids.

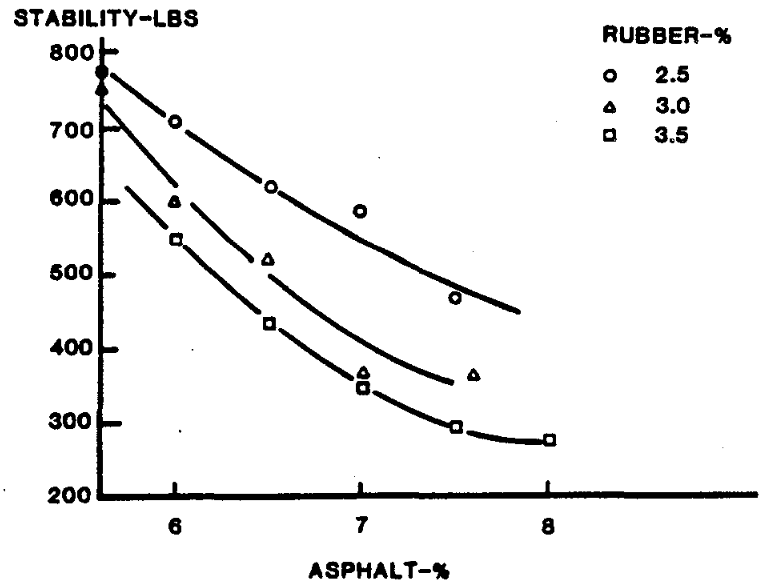


Figure 2.6. Effect of Rubber Content on Stability - Peger Road (Normal 80:20 Rubber Grading) (25).

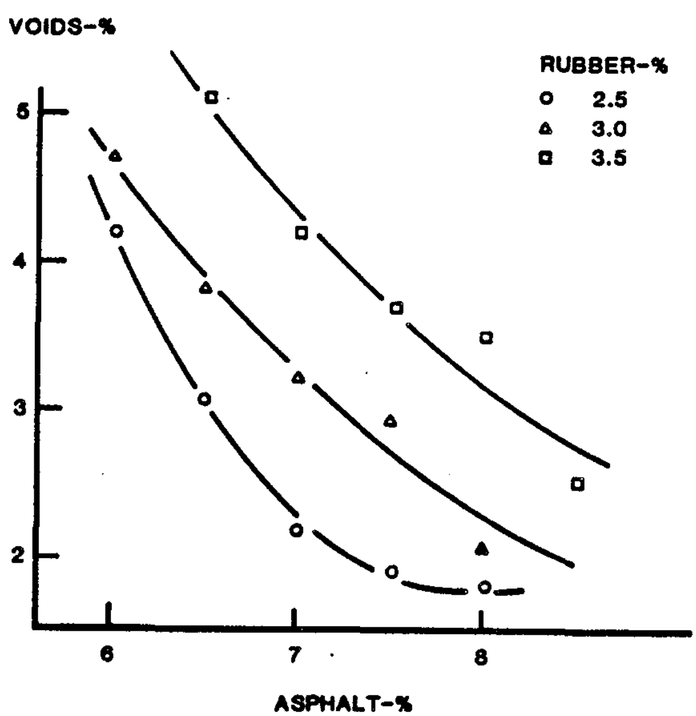


Figure 2.7. Effect of Rubber Content on Air Voids - Peger Road (Normal 80:20 Rubber Grading) (25).

For Huffman Road, the optimum asphalt content (based on 2% air voids) varied with aggregate gradation as follows:

Aggregate Gradation	Optimum Asphalt Content, %	Recommended for Test Program
Coarse - A	10.5%	9.7
Medium - C	8.7%	8.0
Fine - B	7.5%	7.0

Figure 2.8 shows the aggregate grading employed. Mixes A, B, and C are those discussed above, while Mix D is dense grading. The effects of aggregate gradation on voids, Marshall stability, and flow is shown in Figures 2.9, 2.10, and 2.11.

2.3.1.2 Modulus and Fatigue Data. Eighteen samples from each project were tested for diametral modulus and fatigue at 50°F (10°C). All tests were conducted using a load duration of 0.1s at a frequency of 1 Hz.

Tables 2.6 and 2.7 summarize the results of modulus tests for each project. As indicated in Table 2.6, the effect of rubber content is slight; however, the effect of added fine rubber and mixing temperature increases the modulus from 22% to 61%. In Table 2.7, the effects of aggregate gradation, fine rubber content, asphalt content, and mixing procedure on the modulus are shown. The highest modulus values resulted with the finer aggregate gradations. Figure 2.12 summarizes all modulus data for both projects.

Table 2.8 and Figure 2.13 summarize the results of the diametral fatigue tests. Only the medium gradation results are given for Huffman Road. As indicated, the rubber content (Peger Road) and fine rubber percentage both increased the fatigue life.

2.3.1.3 Discussion of Results. The results of these tests generally indicate:

1) The effects of aggregate gradation (Huffman Road) are dramatic, affecting the asphalt content by 3%. As the asphalt content increases, the modulus decreases. When the aggregate gradation approaches the fine end of the band, 2% voids can be

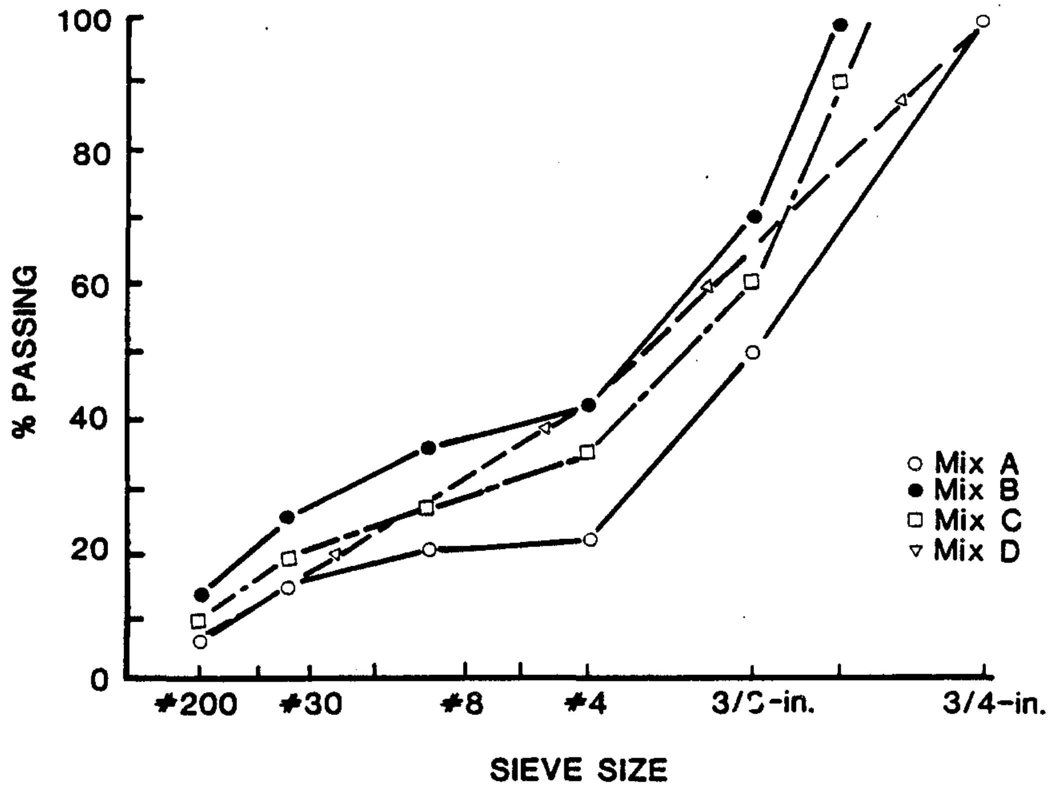


Figure 2.8. Aggregate Gradation Used - Huffman Road (25).

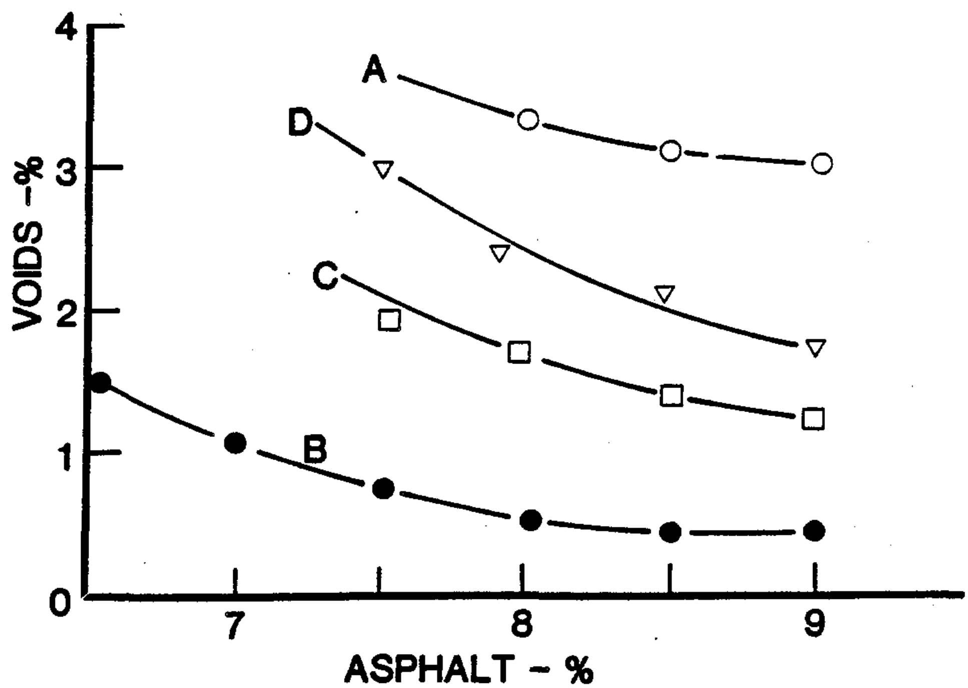


Figure 2.9. Effect of Aggregate Gradation in Air Voids - Huffman Road (25).

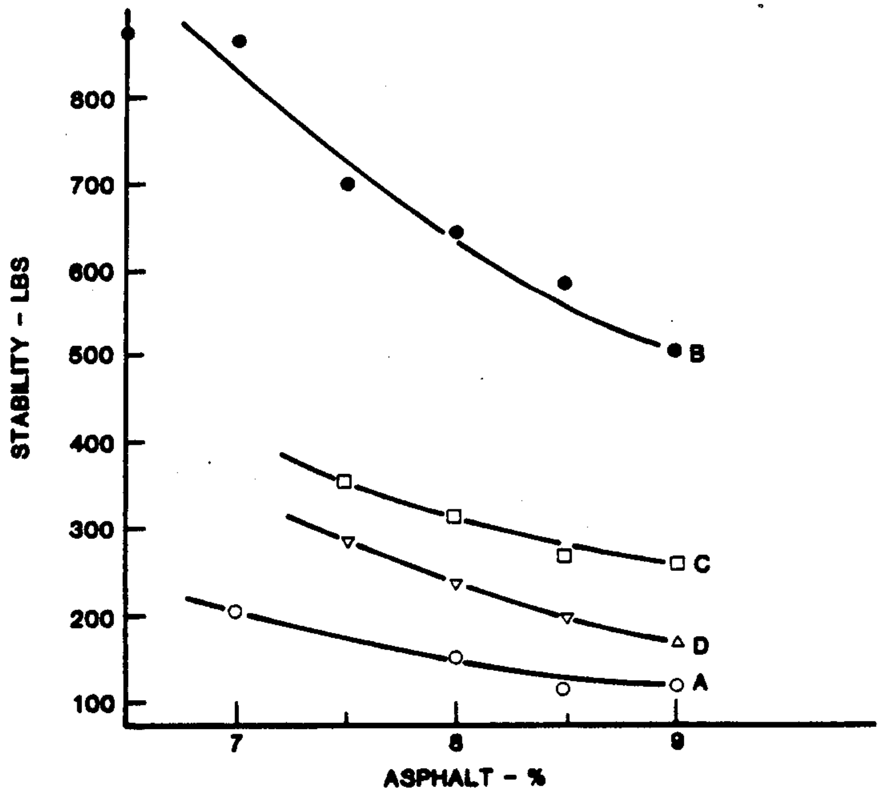


Figure 2.10. Effect of Aggregate Gradation on Stability (25).

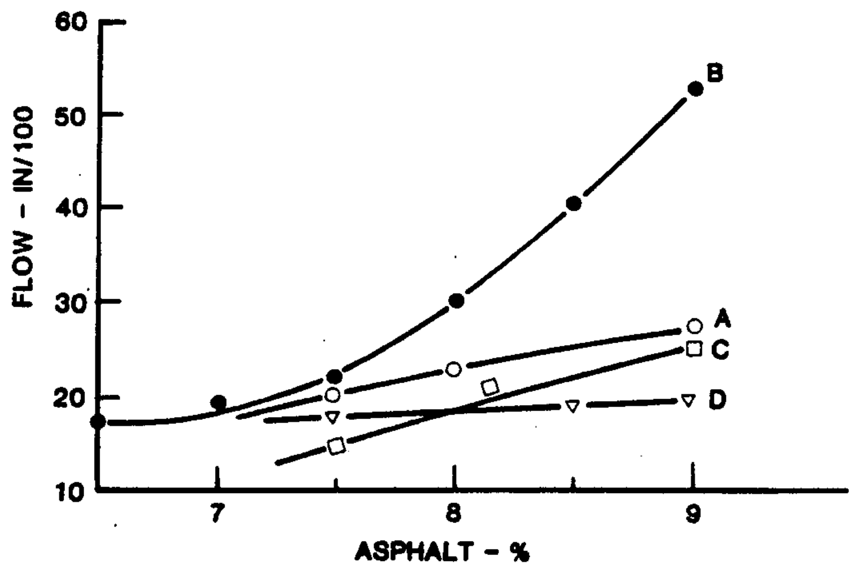


Figure 2.11. Effect of Aggregate Gradation on Flow (25).

Table 2.6. Summary of Modulus Data - Peger Road.

(Test Temperature 10°C (50°F), Strain Level 200 Mictrostrain)

a) 8.0% AC-5, 2.5% Rubber (80-20)

Standard Mix (1)			Modified Mix (2)			% Increase in Ave. Modulus
Sample Number	Modulus, ksi Ind	Avg	Sample Number	Modulus, ksi Ind	Avg	
1	149		10	188		
2	130	154	11	223	190	+23.3
3	180		12	158		

b) 8.0% AC-5, 3% Rubber (80-20)

Standard Mix (1)			Modified Mix (2)			% Increase in Ave. Modulus
Sample Number	Modulus, ksi Ind	Avg	Sample Number	Modulus, ksi Ind	Avg	
4	134		13	153		
5	151	133	14	76	163	+22.6
6	113		15	173		

c) 8.0% AC-5, 3.5% Rubber (80-20)

Standard Mix (1)			Modified Mix (2)			% Increase in Ave. Modulus
Sample Number	Modulus, ksi Ind	Avg	Sample Number	Modulus, ksi Ind	Avg	
7	115		16	204		
8	115	127	17	193	205	+ 61.4
9	152		18	217		

Notes: 1) Cores 1-9, standard mix and compaction procedures.
2) Cores 10-18, 2% fine rubber in addition to blend. Mixed and cured @ 204°C (400°F) for 45 minutes. Standard compaction.

Table 2.7. Summary of Modulus Data - Huffman Road.

(Test Temperature 10°C (50°F), Strain Level 200 Microstrain)

a) 9.7% AC-5, Coarse Aggregate Gradation

Standard Mix (1)			Modified Mix (2)			% Increase in Ave. Modulus
Sample Number	Modulus, ksi Ind	Avg	Sample Number	Modulus, ksi Ind	Avg	
1	135		10	74		
2	80	92	11	125	97	+ 5.4
3	61		12	93		

b) 7.0% AC-5, Fine Aggregate Gradation

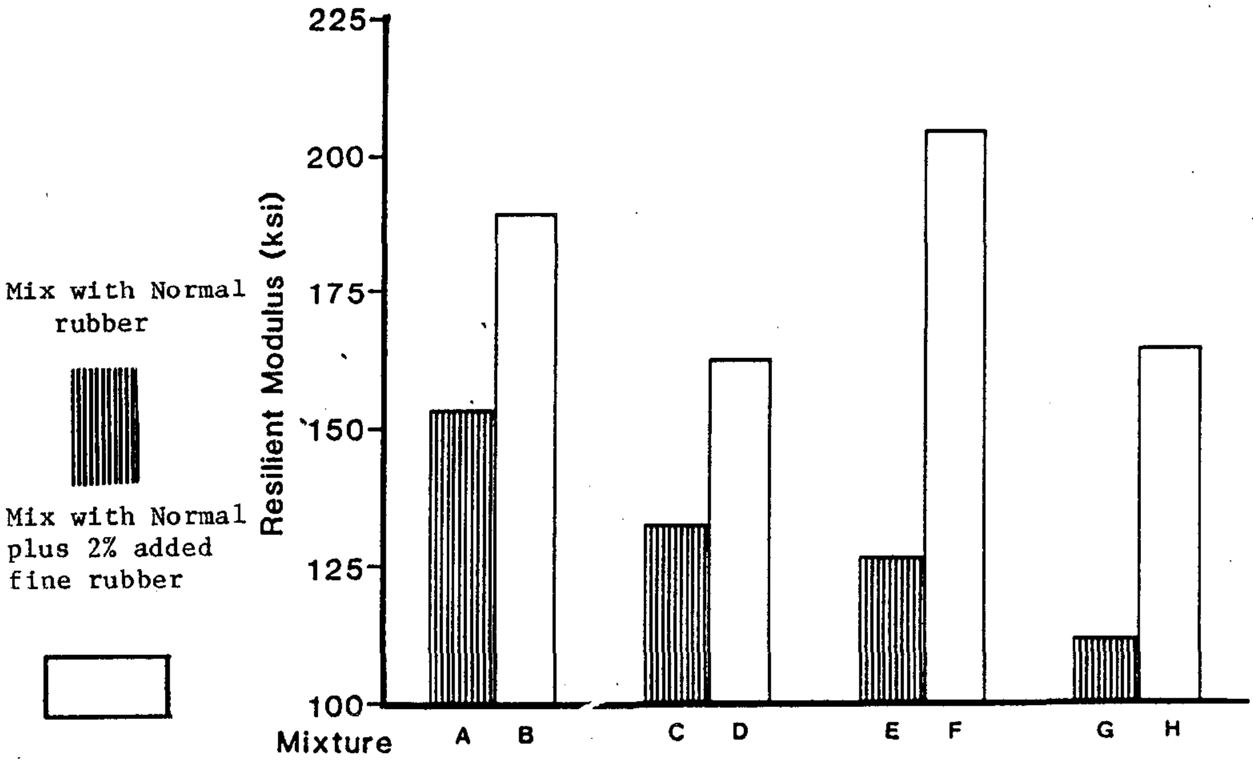
Standard Mix (1)			Modified Mix (2)			% Increase in Ave. Modulus
Sample Number	Modulus, ksi Ind	Avg	Sample Number	Modulus, ksi Ind	Avg	
4	204		13	326		
5	200	206	14	314	329	+59.7
6	213		15	347		

c) 8% AC-5, Middle Aggregate Gradation

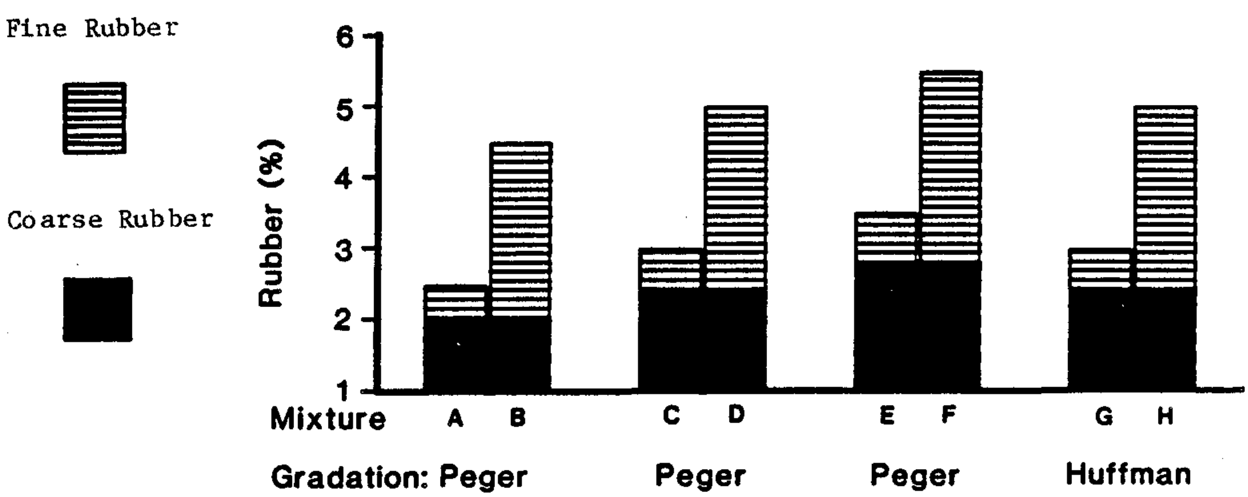
Standard Mix (1)			Modified Mix (2)			% Increase in Ave. Modulus
Sample Number	Modulus, ksi Ind	Avg	Sample Number	Modulus, ksi Ind	Avg	
7	126		16	134		
8	91	112	17	193	177	+58.0
9	118		18	205		

Notes: 1) Cores 1-9 have 3% rubber (80-20) with standard mix and compaction procedures.

2) Cores 10-18 have 3% rubber (80-20) plus 2% fine rubber. Mixed and cured @ 204°C (400°F) for 45 minutes. Standard compaction.



a) Resilient modulus for mixes with rubber contents shown on plot below



b) Rubber content

Figure 2.12. Modulus vs. Amounts of Coarse and Fine (-30) Rubber in Mix (3).

Table 2.8. Summary of Fatigue Tests - 10°C (50°F).

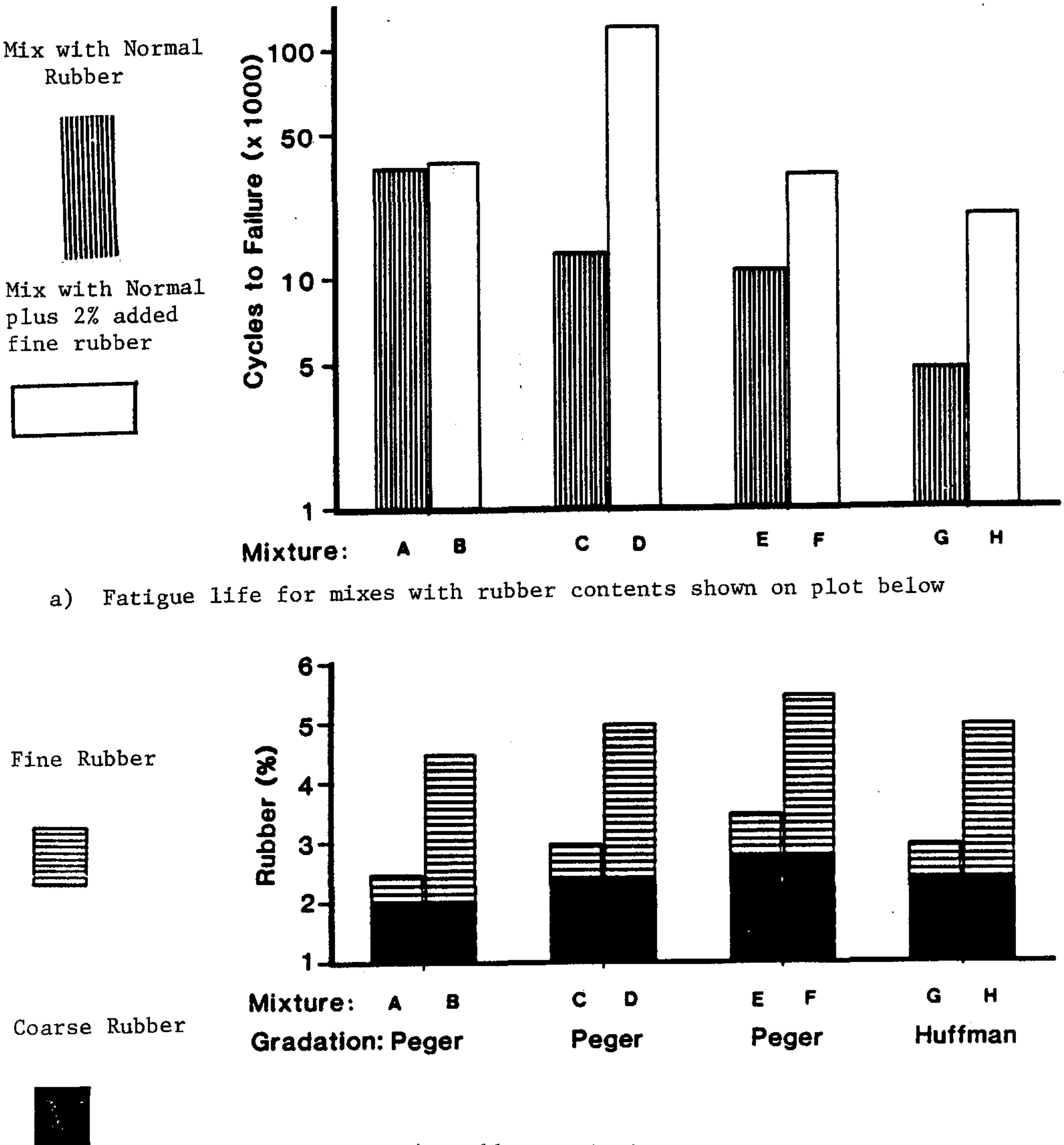
a) Peger Road

Sample No.*	Tensile Strain, 10^{-6} m/m	Fatigue Life Ind Result	Fatigue Life Average
2	200	31,360	
4	200	13,180	
7	200	6,686	11,095
8	200	15,504	
10	200	33,463	
14	200	134,000	131,726
15	200	129,452	
18	200	29,239	

b) Upper Huffman Road

Sample No.**	Tensile Strain, 10^{6}	Fatigue Life
2	200	9,349
5	200	5,914
8	200	4,069
11	200	17,161
13	200	227,000
17	200	19,242

*See Table 2.6 for sample identification.
**See Table 2.7 for sample identification.



a) Fatigue life for mixes with rubber contents shown on plot below

b) Rubber content

Figure 2.13. Fatigue Life for Mixes with Fine and Coarse Rubber (3).

obtained only at low asphalt contents, which results in a high modulus. The effect of aggregate gradation on fatigue was not evaluated.

2) The effect of rubber content (Peger Road) on modulus was slight (Figure 2.12). However, the maximum fatigue life was achieved at 3% rubber (standard 80 to 20 blend). Fatigue life decreased as the rubber content increased to 3.5% as shown in Figure 2.13.

3) Added fine rubber proportions increased the modulus and fatigue values in all cases. The maximum fatigue life was obtained with 5% total rubber (2.4% coarse and 2.6% fine).

2.3.2 All Seasons Surfacing Corporation Study

This section describes the results of preliminary tests on rubberized asphalt mix performed by Oregon State University on prepared samples submitted by All Seasons Surfacing Corporation (24). The evaluation consisted of:

1) varying the types of filler, amount of filler, amount of fine rubber, and supplier of rubber asphalt mixes,
2) visual observation of the mixture consistency (or appearance) and determination of mix void content, and
3) resilient modulus and fatigue tests of the briquettes.

2.3.2.1 Test Procedures. To reduce result variations due to lab procedures, the following standards were used for each mixture:

1) All mixes were made with Plusride 12 aggregate gradation and 3% rubber by weight of the total mix.
2) The aggregates and rubber granules were heated to 171°C (340°F), and the specimens were compacted using a Marshall hammer (50 blows) at 149°C (300°F) to 154°C (310°F).
3) All briquettes were surcharged with a 5-pound weight and allowed to cool down to about 49°C (120°F) before removal from the mold.
4) Voids were determined using Rice's specific gravity (AASHTO T-209).
5) Samples were tested for diametral modulus and fatigue.

Items 1 to 4 above were determined by All Seasons, while item 5 was determined by Oregon State University.

2.3.2.2 Modulus and Fatigue Data. Sixteen samples were tested for diametral modulus and fatigue at room temperature (22°C ± 2°C). All tests were conducted using a load duration of 0.1 s at a frequency of 1 Hz.

Tables 2.9 and 2.10 summarize the results of tests for modulus at 75 and 100 microstrain, respectively. As indicated in Tables 2.9 and 2.10, the effect of strain level is slight. The higher strain level generally shows lower resilient modulus. As indicated, the filler type, filler percentage, rubber content, and rubber source all affect the resilient modulus.

Table 2.11 summarizes the results of the diametral fatigue tests. The effect of type of filler shows the greatest change in fatigue life, with amount of filler, amount of rubber, and source of rubber still having considerable effect. Unfortunately, the resilient modulus and fatigue were obtained by testing only one specimen. For each variable, therefore, the results shown may not be extremely reliable.

2.3.2.3 Discussion of Results. Preparation of the various mixtures in this experiment yielded a broader knowledge of the various factors that affect the behavior of rubber asphalt mixtures. The following are the most significant findings:

1) The materials used for mineral filler play an important part in the mix characteristics and asphalt demand.
2) Increasing the filler (minus No. 200) actually increases the workability of the mixture. This indicates that the fillers act as an asphalt extender (24).
3) Filler type greatly affects the resilient modulus. The mixture with bag house filler had the highest modulus, while fly ash had the lowest modulus for rubber asphalt mixtures (Tables 2.9 and 2.10). The effect of filler type on fatigue life of mixtures is also significant. The mixture with fly ash endures about 85,000 repetitions, while the mixture with portland cement fails after 1364 repetitions.

Table 2.9. Summary of Modulus Data.*

(Test Temperature 22 ± 2°C, Strain Level 75 Microstrain).

a) 7.5% AC-20, 3% Rubber (Rubber Granulators), 8% Filler

Filler Type	Modulus, ksi Ind.	Avg.
Bag House Fines	317	
Fly Ash	160	
Volcanic Ash	191	210
Limestone Dust	178	
Portland Cement	205	

b) 7.5% AC-20, 3% Rubber (Rubber Granulators), Bag House Fine

Amount of Filler	Modulus, ksi Ind.	Avg.
0%	120	
4%	167	148
12%	157	

c) 7.5% AC-20, 3% Rubber, Bag House Fine, 8% Filler

Amount of Fine Rubber	Modulus, ksi Ind.	Avg.
0%	176	
10%	287	224
24%	207	

d) 7.5% AC-20, 3% Rubber, Bag House Fine, 8% Filler

Variable, Rubber Granules Source	Modulus, ksi Ind.	Avg.
U.S. Rubber & Reclaiming (Vicksburg)	149	
Rubber Granulators (Everett)	221	
Cumberland (Rhode Island)	157	192
Genstar (Phoenix)	193	
Baker Rubber (South Bend)	238	

*Moduli were obtained by testing only one specimen.

Table 2.10. Summary of Modulus Data.*

(Test Temperature 22 ± 2°C, Strain Level 100 Microstrain)

a) 7.5% AC-20, 3% Rubber (Rubber Granulators), 8% Filler

Filler Type	Modulus ksi Ind.	Modulus ksi Avg.
Bag House Fines	309	
Fly Ash	147	
Volcanic Ash	182	203
Limestone Dust	179	
Portland Cement	197	

b) 7.5% AC-20, 3% Rubber (Rubber Granulators), Bag House Fine

Amount of Filler	Modulus ksi Ind.	Modulus ksi Avg.
0%	124	
4%	166	152
12%	167	

c) 7.5% AC-20, 3% Rubber, Bag House Fine, 8% Filler

Amount of Fine Rubber	Modulus ksi Ind.	Modulus ksi Avg.
0%	177	
10%	-	190
24%	203	

d) 7.5% AC-20, 3% Rubber, Bag House Fine, 8% Filler

Rubber Granules Source	Modulus ksi Ind.	Modulus ksi Avg.
U.S. Rubber & Reclaiming (Vicksburg)	192	
Rubber Granulators (Everett)	220	
Cumberland (Rhode Island)	178	205
Genstar (Phoenix)	199	
Baker Rubber (South Bend)	238	

*Moduli were obtained by testing only one specimen.

Table 2.11. Summary of Fatigue Tests.

(Test Temperature 22 ± 1°C, Strain Level 200 Microstrain).

a) 7.5% AC, 3% Rubber (Rubber Granulators), 8% Filler

Filler Type	Modulus,* ksi	Fatigue Life*
Bag House Fines	222	12,968
Fly Ash	129	85,267
Volcanic Ash	175	44,766
Limestone Dust	118	15,774
Portland Cement	254	1,364

b) 7.5% AC, 3% Rubber (Rubber Granulators), Bag House Fine

Amount of Filler	Modulus,* ksi	Fatigue Life*
0%	116	5,824
4%	136	7,500
12%	160	19,968

c) 7.5% AC, 3% Rubber, Bag House Fine, 8% Filler

Amount of Fine Rubber	Modulus,* ksi	Fatigue Life*
0%	149	11,254
10%	166	17,850
24%	151	5,518

d) 7.5% AC, 3% Rubber, Bag House Fine, 8% Filler

Rubber Granules Source	Modulus,* ksi	Fatigue Life*
U.S. Rubber & Reclaiming (Vicksburg)	136	14,309
Rubber Granulators (Everett)	139	36,821
Cumberland (Rhode Island)	160	30,160
Genstar (Phoenix)	140	11,209
Baker Rubber (South Bend)	218	6,743

*Moduli and fatigue life were obtained by testing only one specimen.

4) The effect of filler and rubber content on resilient modulus and fatigue life is interesting. The mixtures with 12% filler and with 10% fine rubber exhibited the highest fatigue life.

5) The effect of rubber source on resilient modulus and fatigue life is also significant. The Baker Rubber source resulted in the highest modulus of both the 75 and 100 microstrain levels, while the Rubber Granulator source has the highest fatigue life. Due to the number of specimens tested in the study, it is impossible to make any statement regarding the effect of type and amount of rubber or filler on mix properties.

2.4 Evaluation of Field Projects

This section presents a summary of the results of initial and follow-up questionnaire surveys. The initial survey was sent to various transportation agencies that have used Plusride mixes. The initial questionnaire requested specific details concerning the mix design, construction, mix performance, and reasons for use. Also included in the summary are the results of an Australian Road Research Board (ARRB) experiment on a rubber-modified asphalt project conducted in 1977 (26), and the results from five test projects conducted between 1979 and 1983 (23,27) by the Alaska Department of Transportation and Public Facilities (ADOTPF). The follow-up questionnaire was sent in July of 1984 to the same agencies originally surveyed. The follow-up questionnaire was used to further define the present condition of the Plusride mixes.

2.4.1 Questionnaire Survey

The results of both surveys are summarized in Appendix A and include information on:

1) Project location and agency in charge.
2) General data, including tons mixed and thickness of paving.
3) Rubber and asphalt content.
4) Construction data and problems encountered.
5) Overall performance and any problems noted.
6) Reasons for using rubberized asphalt.
7) Present condition (1984).

Some agencies enclosed a copy of their preliminary performance evaluation report with their questionnaire, which allowed a more complete understanding of the rubber asphalt mix performance (23,26,27,29,31).

2.4.2 Discussion of Survey Results

From the summaries of the replies obtained from the various agencies queried, certain general trends were established. These are shown in Table 2.12.

The aggregate gradation used by those agencies which reported a gradation different from that specified is shown in Figure 2.14, along with the gradation envelope recommended by All Seasons Surfacing Corporation for Plusride (12).

The results of the follow-up questionnaire are summarized in Table 2.13. This table shows that only one agency visually observed and reported de-icing behavior on their rubber-modified asphalt project. Each of the projects is evaluated in the discussion that follows.

Bellevue, Washington. Of the agencies which did not include a preliminary evaluation report with their reply, only the City of Bellevue reported no problems with the mix used. The existing pavement was PCC with transverse cracks every 10 to 12 feet, along with random cracks and moving slabs. As reported in Table A.1, the main reason for use was based on a comparison between rubber-modified asphalt and geotextile-reinforced pavement for the control of reflective cracking. To date, after two years, the rubber-modified asphalt remains virtually unchanged; however, the fabric-reinforced pavement is beginning to show the transverse cracks.

Washington State Department of Transportation. As of 1984, WSDOT had used rubber-modified asphalt in three projects. Of these three, the questionnaire received concerned only the Union Gap Project (Table A.10). This project consisted of resurfacing of four lanes which were divided into two sections. The first consisted of 2-1/2 inches of Class B asphalt base and 1-1/4 inches of Class B wearing course. The second section received 2-1/4 inches of the same base and 1-1/2 inches of Plusride (23) as the wearing course. The area, Eastern Washington, experiences below freezing temperatures in the winter and summer temperatures exceeding 100°F. Preliminary data indicates some problems with rutting and bleeding. The asphalt content was 8% with an air void content of 3.5%.

Table 2.12 Summary of Initial Questionnaire Survey.

	Average	Range
Asphalt Content, %	7.7	5.0-9.5
Rubber Content, %	3.0	2.5-4.0
Mix Temperature, ^oF	330	285-360
Total Mix Time, Sec.	30	15-45
Compaction Temperature, ^oF	320	200-330
Voids in Mix, %	4.8	0.5-12.0

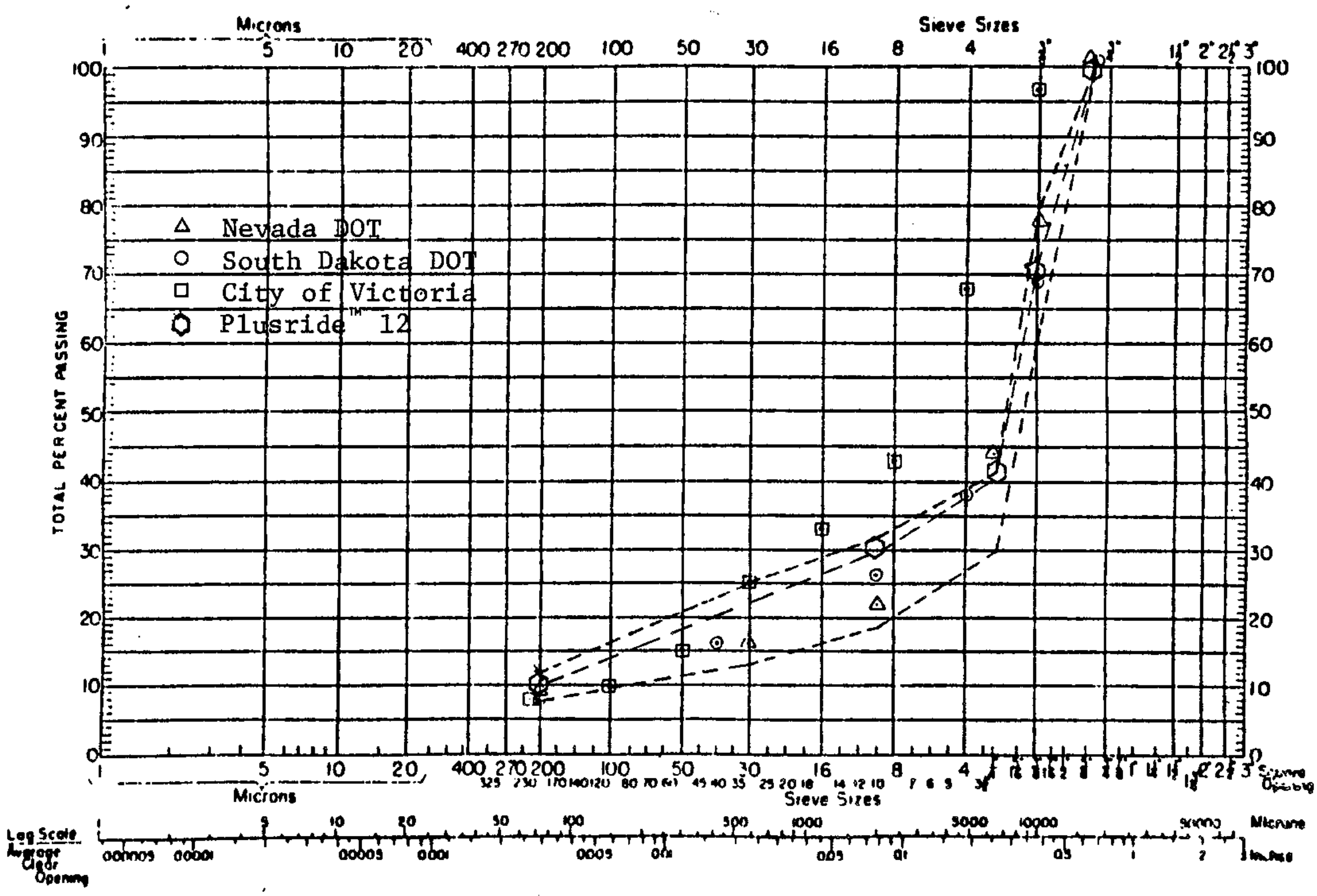


Figure 2.14. Aggregate Gradation Used on Selected Rubber Asphalt Projects.

Table 2.13 Summary of Follow-up Questionnaire Survey (1984).

a) Present Condition of Rubber-Modified Asphalt Mixes from 8 Agencies

Pavement Condition	Severe	Moderate	None
Raveling	1	1	6
Bleeding	0	2	6
Potholing	0	3	5
Wheel Track Rutting	0	0	8
Cracking	0	0	8

b) Other Pavement Performance Observations from 8 Agencies

Pavement Performance	Noted	Not Noted	Not Evaluated
Ice Control	1	6	2
Noise Control	4	4	0
Reflective Crack Control	4	1	3
Skid Resistance	3	2	3
Fatigue Resistance	3	3	2

Data was limited on the other two projects in Washington (28). The first of these was an overlay on Interstate 82 at the Yakima River Bridge. This consisted of 3/4 of an inch of Plusride (28). The climatic conditions are similar to those reported above. The expected ADT is 14,000 with 13% trucks. The final application was on a circular interchange 25 miles south of Seattle at Auburn. The overlay thickness varied from 1-1/4 to 1-1/2 inches.

Oklahoma DOT. The Oklahoma project included comparisons of four dense-graded pavement products: Chem-Crete asphalt, Arm-r-Shield asphalt-rubber, Over-Flex asphalt-rubber, and Plusride rubber-modified asphalt concrete (28). The existing pavement was overlaid with 2 inches of each product for a distance of one mile. Unfortunately, the response contained only comments concerning the Plusride product.

This pavement was placed to evaluate reflective crack control compared to conventional mix. To date (1984), after two years, the rubber-modified asphalt remains virtually unchanged, except for a moderate amount of potholes. The pavement performance (noise control, reflective crack control, skid resistance, and fatigue resistance) was promising. Rubberized asphalt has not demonstrated de-icing characteristics. The Oklahoma DOT reported potholing occurred at the beginning of construction. The 0.2-mile potholed area was totally removed and patched.

South Dakota DOT. This project consisted of paving a two-lane street and its I-90 interchange ramps. One lane and two ramps were overlaid with 1-1/2 inches of Class G asphalt concrete (control) with the remaining lane and ramps receiving 1-1/2 inches of Plusride (Table A.2).

The mix contained 8.4% P200 and air voids of 3%. In 1982, Dynaflect testing was conducted on both the Class G and the rubber-modified asphalt. The Class G averaged 1.24, whereas the Plusride mean was 1.14. Testing for skid resistance was performed shortly after completion of paving. The Class G skid number at 32.2 and Plusride at 31.8. Both numbers were relatively low, probably due to the asphalt coating of aggregate at the surface. This was expected to wear off under traffic. South Dakota DOT reported moderate to severe raveling and potholing in localized areas. The poor performance has been tentatively attributed to an asphalt content being too low (6.5 to 6.8%).

City of Victoria. This project involved overlaying 1.3 km of downtown streets in Victoria, B.C. The mixture had 7% asphalt and approximately 3% air voids. The rubber-modified asphalt was placed over severely cracked existing pavement to determine, among other things, the mixture's ability to control reflective cracking (Table A.7).

Some raveling problems were reported from the first 150 tons of the 1200 tons placed (6). The raveled strips were confined to one-half the width of the paving machine. Numerous possibilities have been suggested as the cause of this problem. There was an asphalt deficiency of 1% in these batches and the aggregate used was flaky. It was also reported that half the screed was not vibrating properly, indicating the initial compaction provided by the paving machine may be important in the ultimate compaction of the mixture. In a report submitted by the City of Victoria by West-Tech Inspection Service, Limited, a minimum Marshall stability value of 500 and maximum air voids of 2% are suggested as laboratory mix design criteria for a stable, durable product (30).

ARRB. The report received from the Australian Road Research Board (AARB) summarized the results of three rubber-modified asphalt overlay projects conducted in 1977 using a similar process called Rubit (26). The projects were small-scale, in high-density traffic areas. The first project, Kingsway Site, failed completely within ten weeks of placement. Severe rutting and separation from the underlying asphalt occurred with a moist layer of uncoated sand and fines present at the interface. The air void content was 9.2%. The reported cause of failure was the penetration of rainwater into the surfacing prior to complete sealing by traffic which apparently caused stripping of the pavement (Table A.8). The second overlay project, Mordialloc Road, also failed completely within one year, after the bond at the interface broke. The layer of fines was not present at the interface, indicating stripping did not occur as at the Kingsway Site (Table A.9). The third project, also at Kingsway Site, involved the replacement of the original rubber asphalt mix with new material. This new mix contained hydrated lime to prevent stripping and had a much lower air void content of 2.9%. After seven months, the experimental section showed no signs of distress (Table A.9).

FHWA - EDFD. This experimental section was placed in Tellico Plaines, Tennessee in November, 1981. Although mixed at 325°F, compaction occurred at 235°F. The percent passing No. 200 sieve was reported to be 3.5%. The average air void content was 5.5%. This pavement was placed to evaluate reflective crack control and skid resistance compared to conventional mixes (Table A.8). The follow-up questionnaire was not received from this agency.

Nevada DOT. The project included resurfacing a 1-mile section of eastbound Interstate 80 from the California border. The expected traffic volume is 17,775 with 22% trucks (Table A.7). Within one month, the Plusride asphalt began showing signs of raveling and potholing. According to the preliminary evaluation received with the questionnaire, the distress was caused by hydraulic action from the traffic loading (31). This resulted in the washing of the asphalt from the aggregate. Visual inspection of other areas revealed a "brittle appearance which resembled age hardened asphalt." Nevada DOT suspects that the heated rubber and asphalt react in a way which may affect the quality of the asphalt. Their laboratories, however, were unable to determine if, in fact, this was the cause of the brittle asphalt.

All Seasons Surfacing Corporation (56) offered a different explanation for the observed distress. They reported that excessive voids (10 to 12%), instead of the 3 to 5% target air voids, was the main cause of the pavement distress. The excess air voids in the mix was caused by deficient P-200 material in the contractor's aggregate. As a result, the pavement had excessive voids that permitted water intrusion. This, together with heavy traffic created excess hydrostatic pressures resulting in early pavement failure.

In the follow-up questionnaire, Nevada DOT reported extensive raveling and bleeding in the Plusride section and the mix was subsequently removed. The main reason for use of Plusride was ice control. This reported characteristic of rubber modified asphalt was not noted in this project.

Alaska DOT - Carnation Curve and Fairhill Access Road (23). The first test project in North America utilizing rubber-modified asphalt consisted of two test sections constructed in Fairbanks in 1979. These sections were chosen due to the hazardous icing conditions which frequently existed at both locations.

The first section, Carnation Curve, was placed with a tracked paver to a depth of 2 inches over existing asphalt concrete paving which had been tacked with RC-800. The final air void, as determined by coring, was 4.6% (Table A.5).

The second section, Fairhill Access Road, was placed using a motor patrol after end dumping onto the existing asphalt concrete paving. This procedure was utilized to determine if rubber asphalt could also be used in maintenance-type situations. The mixture proved too sticky to handle well and excessive blading caused the mixture to cool quickly, resulting in the final air voids being 9%. Both sections are still serviceable. The second site raveled slightly, but was reported to be still functional after 5 years.

Alaska DOT: Old Seward Highway (23). This project was undertaken to determine the influence of various rubber contents on mix performance. The work included 5.7 miles of badly cracked and rutted asphalt which was prepared using a 1-inch conventional asphalt concrete overlay to the ruts. Rubber contents of 3%, 3.5%, and 4% by weight of total mix were placed on the prepared surface. The mixtures were produced in a batch-type plant with a discharge temperature of 285°F and were placed at 260°F or less. The 4% section was placed considerably below 260°F due to traffic control delays. Cores of the various test sections indicated air voids in the 4% rubber section averaging up to 12%, and 7.5% in the other two sections (Table A.6). The 4% section raveled almost immediately and the other sections within 2 to 3 months. Subsequent testing revealed that most samples were out of gradation specifications and lacked mineral filler. All sections have been replaced with conventional mix.

Alaska DOT: Peger - Van Horn Intersection (23). Because ADOTPF believed the failure of the 4% test section of the Old Seward Highway Project was due, in part, to the heavy truck turning movements, this intersection was chosen to further investigate performance under similar conditions. This mixture, produced in a batch plant, was discharged at 310°F and placed over an untreated aggregate base to a thickness of 1-1/2 inches. The initial asphalt content of 8%* at 310°F was raised by 8.2%* at 330°F and finally increased to 8.5%* at 345°F with no resultant placement problems. Compaction was achieved with a single static 10-ton steel-wheeled roller breaking down at 295°F and continuing for 10-15 passes until the temperature was below 140°F. Due to the restrictive confines of this test section, only one roller was necessary for compaction. The final air voids averaged 4.2% (Table A.7). This section demonstrated de-icing characteristics of Plusride during the winters, of 1981 through 1983, as measured by Tapley meter stopping distance tests.

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*Asphalt contents by weight of dry aggregate.

Alaska DOT: Upper Huffman Road (23). This site in Anchorage was chosen to determine the effectiveness of rubber-modified asphalt on very steep (average grade 10%) roads in alleviating icing problems. The test section consisted of 1.01 miles of unconstructed surface with 1-1/2 inches of conventional mix overlaid with 3/4-inch Plusride. This mix contained 9.5%* AC-5 asphalt which was discharged from a batch plant at 360°F. The apparent air void content was 10%, but this value may be in error due to the thin overlay (Table A.5). To date, the section is performing well with no raveling or surface failures apparent.

Alaska DOT: Lemon Road (27). This project undertaken by Alaska DOT includes the placement of 2,462 tons of rubberized asphalt pavement to determine the mix effectiveness in reducing ice deposits, improving skid resistance and increasing pavement life through improved fatigue failure resistance. The recommended asphalt content was 8.6%*, with a mix temperature of 275°F (Table A.4). To date, after one year, the rubber-modified asphalt remains virtually unchanged.

Montana DOH (53). In September 1983, the Montana Department of Highways constructed an experimental rubber-modified section to determine the de-icing capabilities of Plusride 12. The mix was placed 1-1/2 inches thick at an asphalt content of 8.75%. The mixture was produced in a batch-type plant at 377°F. Breakdown compaction commenced at 250°F and was continued until the mix reached a temperature of approximately 203°F. The average air void content was 2% (Table A.3). To date, after one year, the rubber-modified asphalt remains virtually unchanged. Montana DOH reported that pavement performed well against noise and reflective crack, but pavement performance against ice, fatigue, and skid resistance was not noticed.

CALTRANS (54). The California Department of Transportation has begun compiling test data on a 9-mile test section. This section was designed to compare, among others, Plusride and ARCO rubberized binder, of various thickness, with and without rubberized stress absorbing membrane interlayers (SAMI's). Also included in the test section is 2.5 miles of rubberized chip seal (Table A.3). To date, after one year, the rubber-modified asphalt is performing well with no raveling or surface failures apparent. CALTRANS reported, "The 0.15' and 0.2' thick conventional AC control sections on the project have begun to crack heavily in places, whereas the rubberized AC, including the Plusride shows no sign of distress."

FHWA - WDFD (11). This experimental section was placed in the Gifford Pinchot National Forest as part of the Volcanic Activity Disaster Relief (VADR) project in August 1983. It consisted of 1.11 miles of rubber-modified asphalt overlay (Plusride) of various thicknesses placed to determine the de-icing effect and the fatigue life of Plusride (Table A-4).

This test section was expected to receive heavy log truck traffic as the timber blowdown during the Mt. St. Helens eruption was removed. This traffic was to have helped define the fatigue life of Plusride within three years, however, delays prevented construction until after the majority of timber had been removed.

Testing and monitoring of the section is continuing. At present, the Plusride section is performing as well as the control.

2.5 Summary

The results of this chapter indicate that

1) Asphalt-rubber is a viable material that provides an attractive alternative for construction, rehabilitation, and maintenance of roadway networks if properly constructed. Reported advantages include increased skid resistance, increased life, and reduced thicknesses of asphalt pavement sections. In addition, the material is attractive from an energy and resource recovery point of view.

2) Rubber particle shape, as determined by the method used in processing recycled rubber, is an important factor in determining the elastic properties of an asphalt rubber mix. Particles with a low bulk density give blends with a desirable high elastic recovery. Those particles with a high bulk density, as produced by cryogenic processing, give products with poor elastic properties (14).

3) The effect of rubber gradation on asphalt rubber pavement material is not well known at this time. Based on past experience, Plusride recommends a rubber gradation to provide pavement with increased skid resistance and improved durability characteristics (4). Continued research in this area is needed to ascertain the advantages or disadvantages of various rubber gradations.

4) Rubber type is known to affect the properties of the asphalt-rubber mix. The addition of natural rubber produces improved elastic properties of the binder. However, recycled rubber includes both natural and synthetic rubbers of which the exact percentages of each are rarely known. The effect of recycled rubber on asphalt mix properties is dependent on such variables as rubber source, recycle processing, and recycled tire type.

5) The mixtures may be compacted using the Marshall or Hveem procedure. The optimum asphalt content is generally determined by the voids in the total mix. The air voids in place should range from 0% to 4% maximum depending on the traffic level of the facility being designed. Tests for stability and flow are not currently used as criteria for optimum asphalt content, as these conventional asphalt tests have been found to be inappropriate for rubber-modified mixes due to their resiliency.

6) The results of modulus and fatigue tests on laboratory-prepared samples from two projects in Alaska and samples prepared by All Seasons Surfacing Corporation indicated the following factors affect these properties:

   a) rubber content and gradation,

   b) aggregate filler type and content, and

   c) rubber source.

7) A total of 19 experimental projects constructed between 1976 and 1983 were evaluated using a questionnaire survey. Almost all of the projects encountered some difficulties in the construction and/or performance of the mix. Many of the performance problems appeared to be related, at least indirectly, to the construction methods used. In a few cases construction was hampered by "sticky" mixes which can be attributed to the added rubber. The stickiness appeared to make joint construction difficult. This may have led to high voids and contributed to early mix raveling. Other possible causes of performance problems included: 1) incomplete mixing, 2) excess or insufficient asphalt, 3) high voids, and 4) low P200 content.

The patent holder, All Seasons Surface Corporation, claims that the cause of pavement performance problems prior to 1983, was due to technology transfer. In the spring of 1983, the first guide specification was developed and this reportedly has solved most of the construction related performance problems.

8) The de-icing characteristics expected of a rubber-modified asphalt have not been observed in most of the surveyed projects. However, Tapley stopping distance tests by the Alaska DOT Research Section showed an average reduction in icy-road stopping distances of 25% on rubber-modified pavements for 23 test-days over a 3-year period. On nearly all of these days no difference in surface ice was apparent by the visual windshield survey method. This demonstrates that test measurements are needed for other sites before conclusions can be reached on ice-control benefits.

3.0 LABORATORY PROGRAM

This chapter describes the test program used to evaluate the effect of mix variations on properties of rubber-asphalt mixes. In particular, it describes the following:

1) variables considered,
2) materials used and their preparation,
3) the types of tests and test procedures, and
4) specimen preparation techniques.

The project materials selected for evaluation for this study were from the Lemon Road project in Juneau, Alaska. A description of the project, together with related field test data, is given in Appendix B.

3.1 Variables Considered

To evaluate the effect of mix variations on the behavior of rubber-asphalt mixture, it was necessary to first establish a list of variables to be considered. Each variable was selected based on discussions with ADOTPF and on a critical review of the literature. The test variables considered for this study are given in Table 3.1.

Variations in void content were selected to see if one could produce acceptable mixes at higher void contents. Two percent (normally recommended) and 2-10% (normally obtained in the field) were selected for study. Rubber contents of 2% and 3% were also selected to determine their effects on optimum asphalt content, resilient modulus, and fatigue life. The existing rubber gradation employed is a mixture of 20% fine (- #40) and 80% coarse rubber (#40 x 1/4 in.). Increasing the amount of fine rubber to 40% and 100% of total rubber may increase the potential for improving some of the mix properties, such as fatigue. Mix temperatures of 190°C (375°F) and 218°C (425°F) were considered. By increasing the mix temperature there is increased potential for dissolving some of the finer rubber into the asphalt. This interaction may improve resilient modulus or fatigue life. The high mixing temperature and lowered compaction temperature simulates the effects of cooling during a long haul and placement. One compaction temperature 129°C (265°F) was selected. However, to obtain 4% void content in the mix, the compaction temperature, as well as compaction effort (normally 50 blows), were lowered to

Table 3.1. Variables and Levels of Treatment Considered for Laboratory Experiment.

Variables	Level of Treatment
Air Voids, %	2, 4,
Rubber Content, %	2, 3
Rubber Gradation (Coarse/Fine)	Coarse (80/20), Medium (60/40), Fine (0/100)
Mix/Compaction Treatment, °F	375/265, 425/265
Mix Curing at 375°F and 425°F	0, 2 hrs
Aggregate Gradation	gap-graded, dense-graded
Surcharge	0, 5 lb

Table 3.2. Aggregate Gradation Used and Corresponding Specification.

Sieve Size	Gap-Graded	Alaska Type II Dense-Graded	All Seasons Specification (Plusride™ 12)
3/4 inch	-	100	-
5/8 inch	100	-	100
3/8 inch	70	76	60-80
1/4 inch	37	-	30-42
No. 4	-	55	-
No. 10	26	36	19-32
No. 30	18	-	13-25
No. 40	-	22	-
No. 200	10	7	8-12

Table 3.3. Aggregate Properties for Lemon Creek Project*

Property	Test Value
Specific Gravity (APP) (T-85)	2.76
Liquid Limit (T-83)	NA (25 max)
Plastic Limit (T-89)	NP (6 max)
LA Abrasion, % (T-35)	33
Sodium Sulfate Soundness, % (T-104)	1
AASHTO Classification	A-1-a
Average Percent of Fractured Faces on the Coarse Aggregate	94

*Performed by State of Alaska Department of Highways.

99°C (210°F) and 10 blows, respectively. Two mix curing periods (0 and 2 hours) were also selected for study to determine whether increased curing or "reaction time" can impart any beneficial effects. Two aggregate gradations were used to perform the tests. These are the recommended aggregate gradation by Plusride (gap-graded) and the mid-band gradation used for conventional asphalt mixes (see Table 3.2).

3.2 Description of Materials

3.2.1 Aggregate

The aggregates were obtained from the actual source used for the Lemon Road project in Juneau, Alaska. Aggregate processing operations were started by drying the aggregate to a constant weight. Then the aggregates were sieved in the following sizes: 3/4"x5/8", 5/8"x3/8", 3/8"x1/4", 1/4"x4, 4x8, 8x16, 16x30, 30x50, 50x100, and -100. The different size fractions of the aggregates were stored in separate containers. Tables 3.2 and 3.3 include the gradations and properties of aggregate which were used in making the laboratory samples of rubber asphalt mixtures.

3.2.2 Asphalt

The paving grade asphalt generally used in the project area was selected. For this study, an AC-5 produced by Chevron USA's Richmond Beach Refinery was used. Its physical properties are given in Table 3.4.

Also, Rostler-Sternberg composition data for that AC-5 were determined based on former ASTM procedure D2006, which is described in reference (47,48,50). The procedure entails the removal of asphaltenes with reagent grade n-pentane and stepwise precipitation of the components (nitrogen bases, first and second acidiffins, and paraffins) from the maltenes with sulfuric acid. The test results for the Rostler-Sternberg analyses are presented in Table 3.5. This table shows the amount of individual chemical components. This is important for identification purposes, but relatively unimportant in determining behavior of asphalts. Of importance is the combined effect of these components and their interrelationship. One such relationship is the ratio of the two more reactive components to the two less reactive components expressed by the Rostler parameter $(N+A_1)/(P+A_2)$. In previous studies, this parameter has been shown to be a decisive factor in identifying embrittlement

Table 3.4. Asphalt Cement (AC-5) Characteristics - Anchorage, Alaska.

	Actual Values	Specifications*
Viscosity, 140°F, Poises	509	500 ± 100
Viscosity, 275°F, CS (Minimum)	142	110
Penetration, 77°F, 100 g, 5 sec (Minimum)	137	120
Flush Point, COC, °F (Minimum)	547	350
Solubility in trichloroethylene, % (Minimum)	99.84	99
Tests on Residue From Thin-Film Oven Test:		
Viscosity, 140°F, Poises (Maximum)	1055	2000
Ductility, 77°F, 5 cm/min, m (Minimum)	-	100
Spot Test (When and As Specified) With:		
Standard Naptha Solvent	-	Negative
Naptha-Xylene-Solvent, % Xylene	-	Negative
Heptane-Xylene-Solvent, % Xylene	-	Negative

*Table 1, AASHTOM 266

Table 3.5. Chemical Analysis by Rostler Method.*

Composition	Percentages
Asphaltenes	14.8
Nitrogen bases (N)	31.6
First acidaffins (A1)	10.1
Second acidaffins (A2)	29.4
Paraffins (P)	14.1
Refractive Index of Paraffins, N_D^{2S}	1.4825
**Rostler Parameter	0.96

*Tested by Matrecon, Inc., Oakland CA.

**Rostler Parameter = $\frac{N + A1}{A2 + P}$

of asphalts in aging, as measured by the Pellet abrasion test and also shown to relate to field performance (50,51,52).

The purpose of the behavior parameters is to determine that two asphalts can be expected to perform alike in service. In this regard, they need not be chemically identical as long as the Rostler parameter is the same. Asphalts which are identical should behave alike. Others, which differ in one or more identity characteristics but have the same Rostler parameter, should also perform the same (50).

3.2.3 Rubber

Recycled rubber was obtained from Rubber Granulators in Everett, Washington for use in the study. The samples were sieved using 1 to 2% talcum powder to reduce tackiness on the following sizes: 1/4"x4, 4x10, 10x20, 20x40, 40x50, and -50. The talcum powder was removed by sieving the fine rubber (-50) through a No. 200 sieve. The different size fractions of the rubbers were stored in separate containers. The rubber properties and gradations are given in Tables 3.6.a and 3.6.b.

3.3 Laboratory Test Procedures and Equipment

The two general types of tests used in this study were:

1) mix design tests, and
2) mix properties tests.

Each of these different types of tests are summarized in Table 3.7. The following sections describe the procedures and equipment used in performing each of these tests.

3.3.1 Mix Design Tests

The Marshall mix design procedure was used as part of this study. The samples were prepared using the standard Alaska DOTPF procedure (T-17). This method is the 50-blow Marshall procedure. The aggregates were sieved to different sizes and stored in separate containers. To ensure hot and dry mix, the aggregates were placed in an oven at a temperature of 190°C (375°F) for at least 12 hours. The aggregates were weighed into separate pans for each test specimen and then blended by the appropriate fractional size to a 1100-gram sample. The asphalt was heated to 135°C (275°F) prior to mixing. Previously

Table 3.6. Rubber Properties*.

a) Gradation

Sieve Size	Coarse	Fine	80/20	60/40	0/100	All Seasons 80/20 Rubber (4) Specifications
1/4 inch	100		100	100		100
No. 4	97		97.6	98.2		76-100
No. 10	15	100	32	49	100	28-36
No. 20	4	86	20.4	36.8	86	16-24
No. 40	3	30	8.4	13.8	30	-
No. 50	2.9	20	6.3	9.7	20	-

b) Other Physical Properties*

Natural Rubber (%)	20
Synthetic Rubber (%)	80
Specific Gravity (lb/ft^3)	30
<u>Mixture</u>	
Carbon black (%)	30
Acetone (%)	15
Hydrocarbon (%)	45
Fiber (%)	10

*Rubber Data Source: Rubber Granulators, Everett, WA (42).

Table 3.7. Tests Performed on Rubber Asphalt Mixtures*.

Type of Tests	Mix Properties
Mix Design Tests	• Stability
	• Flow
	• Voids*
Mix Property Tests	• Diametral Modulus
@ +10°C, -6°C	• Diametral Fatigue

*Based on Rice's theoretical maximum specific gravity (AASHTO T-209).

heated and overheated asphalts were avoided by careful temperature control. The rubber was mixed with the hot aggregate and cured in a 135°C (275°F) oven for 3 minutes. The mixture of hot aggregate and rubber was placed in the mixing bowl, mixed for two minutes, then the proper amount of asphalt cement added (Figure 3.1). The mixing was accomplished using a Cox mixer (Figure 3.2). About three minutes of mixing time was required to fully coat the aggregate with asphalt. The entire batch was placed in the preheated, greased mold and base with greased filter paper. The compaction was performed according to ADOTPF procedures. The mixture was spaded vigorously with a heated spatula. Each of the 2 faces was then compacted with a 50-blow Marshall hammer assembly at 179°C (265°F) (see Figure 3.3). After compaction, the base plate was removed and the specimen was allowed to cool in the air until the specimen temperature reached room temperature (approximately 5 hours). The specimens were removed from the mold with an extrusion jack. The equipment is shown in Figure 3.4.

Sixty-six samples were prepared for this part of the study. All of these samples were tested for flow, stability, void content, and diametral modulus. The tests for flow and stability were conducted using an MTS machine with a rate of loading of 2 in./min as shown in Figure 3.5. The tests for diametral modulus were conducted using a load duration of 0.1 s, a load frequency of 1 Hz and at a temperature of 22 ± 2°C. The equipment is shown in Figure 3.6.

The major mix material variables used in the mix design study were as follows

1) rubber content - 2% and 3%,
2) rubber gradation - coarse, medium, and fine, and
3) aggregate gradation - gap and dense-graded.

The 2% void content was used as criteria to select the optimum asphalt content for each combination. A summary of the steps involved in the mix design process are given in Table 3.8.

3.3.2 Mix Property Tests

Once the optimum asphalt contents were determined for the different mix combinations, other tests were used to evaluate their mix properties. For all dynamic tests, samples were subjected to a constant load, applied at 60 cycles

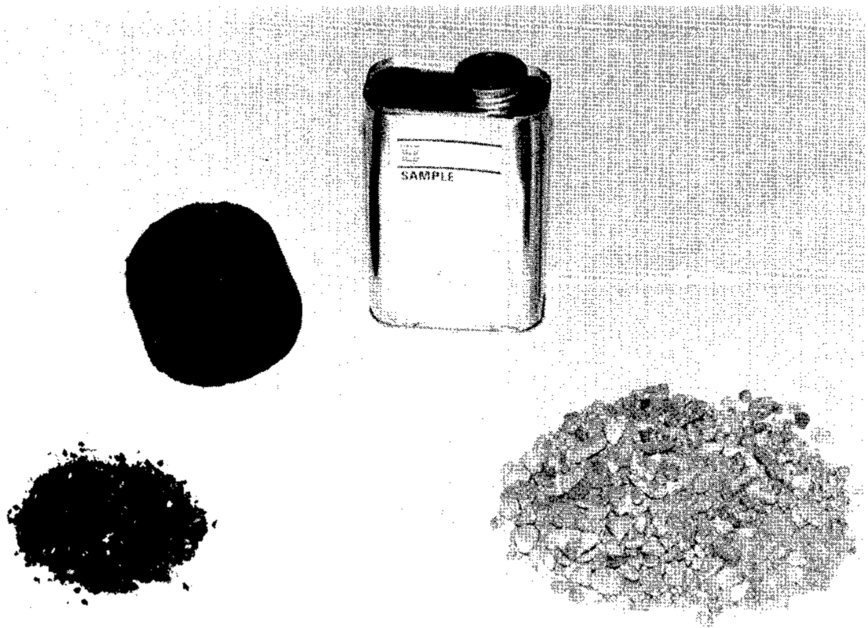


Figure 3.1. Material Components for Specimen Preparation.

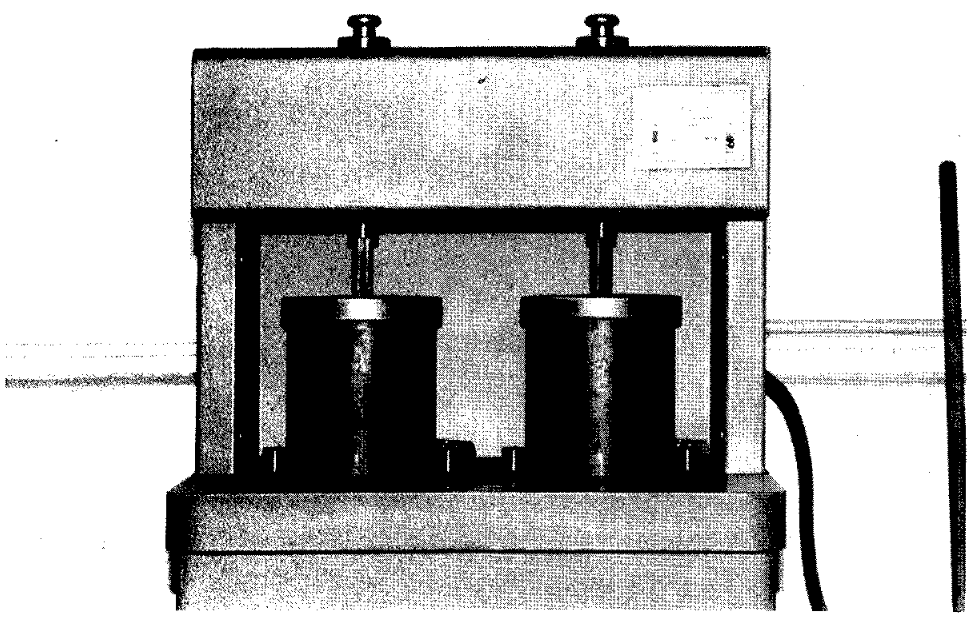


Figure 3.2. Cox Mixer.

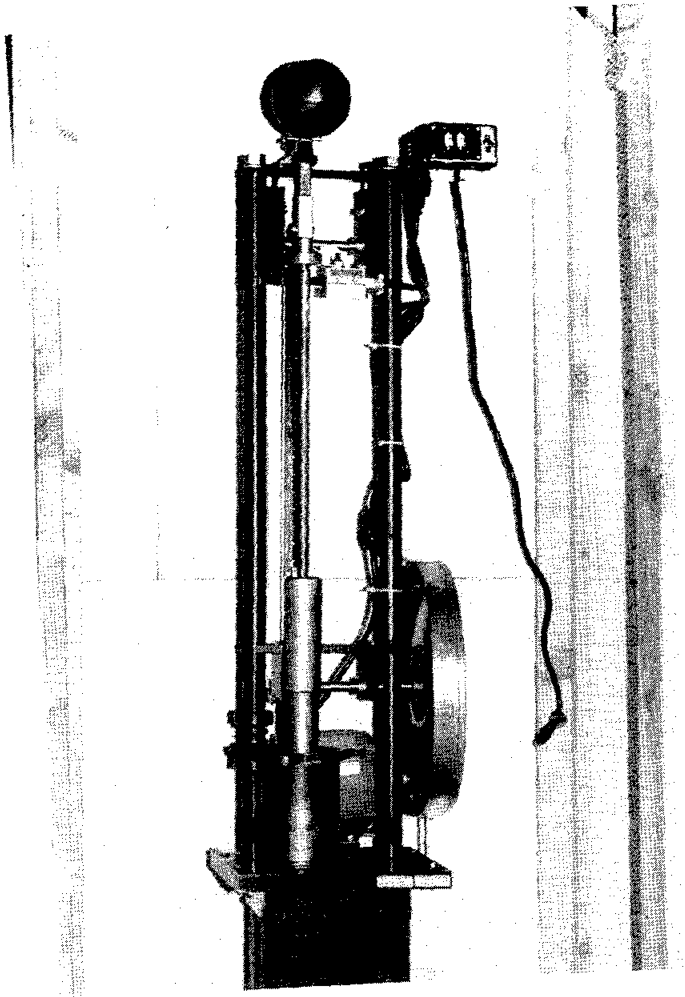


Figure 3.3. Marshall Assembly.

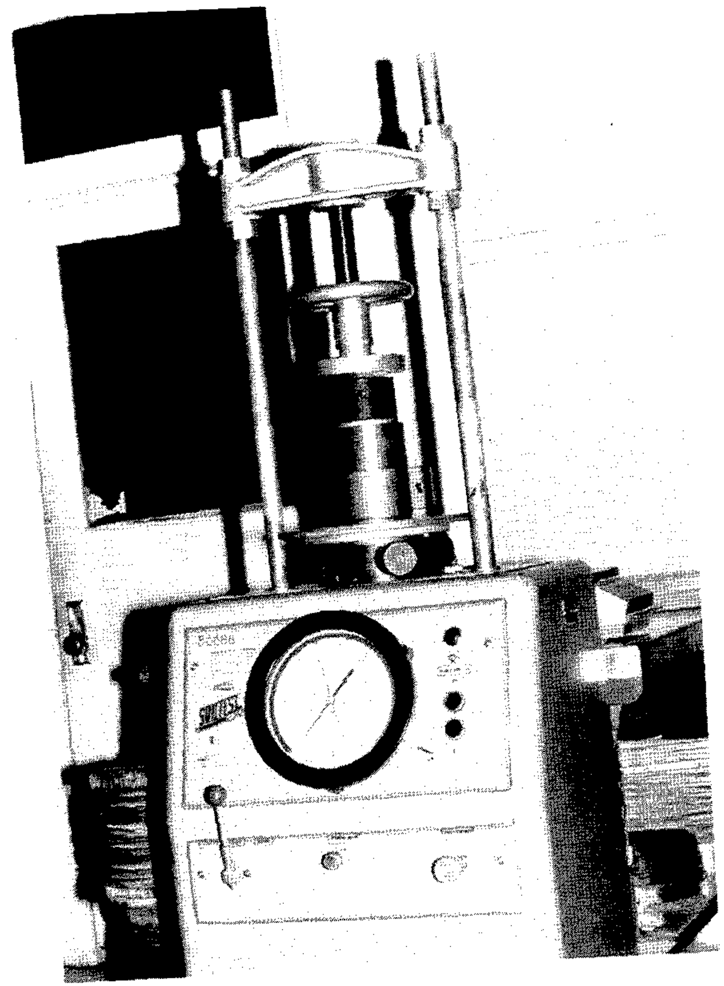


Figure 3.4. Sample Extrusion Assembly.

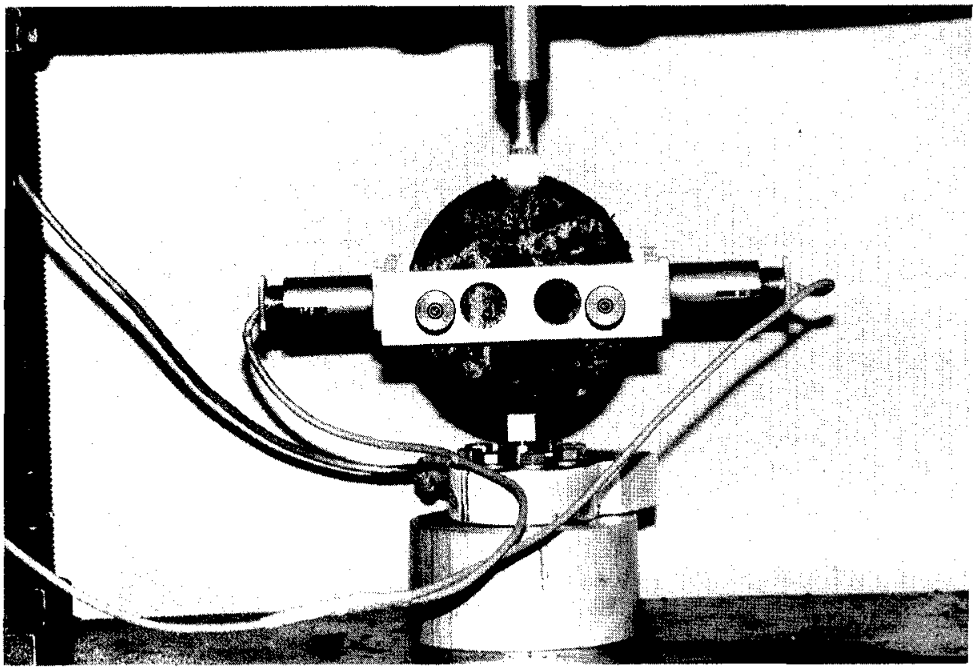
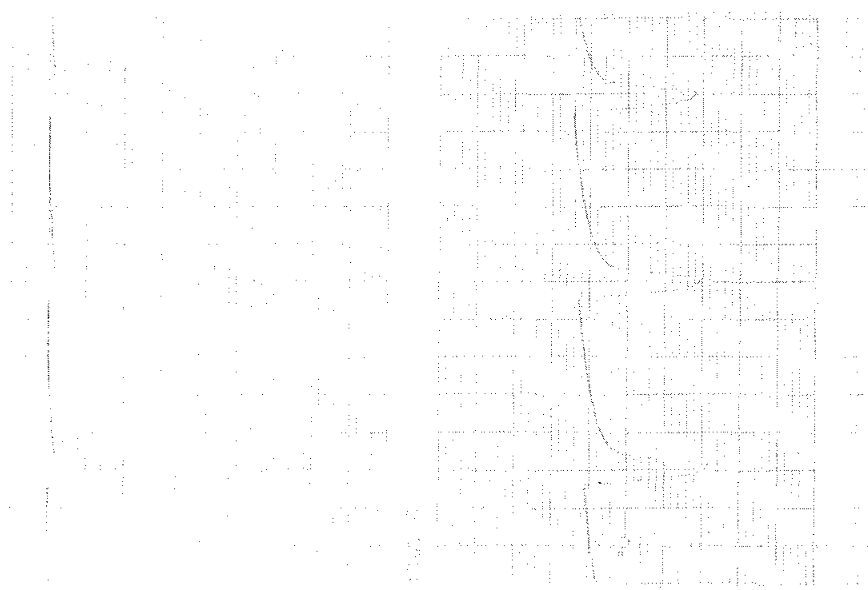


Figure 3.8. Resilient Modulus Setup.



a) Load

b) Deformation

Figure 3.9. Example of HP Recorder Output for Diametral Test.

Table 3.10. Summary of Compaction Study.

Sample Number	Material Combination	Mix/Compaction Temp. (°F)	Number of Blows	Bulk Specific Gravity	Maximum Specific Gravity	Air Voids
1	AC = 9.3%	375/265	30	2.307	2.354	2.00
2	Rubber Content = 3%	375/265	20	2.295	2.342	2.01
3	Rubber Gradation = 80/20	375/265	10	2.302	2.351	2.08
4	Aggregate Gradation = Gap	375/265	5	2.301	2.362	2.57
5		375/240	10	2.278	2.369	3.85
6		375/185	10	2.262	2.359	4.11
7	AC = 6.5%	375/265	10	2.317	2.394	3.21
8	Rubber Content = 3%	375/240	10	2.254	2.394	5.85
	Rubber Gradation = 40/60					
	Aggregate Gradation = Gap					
9	AC = 7.5%	375/265	10	2.268	2.363	4.02
10	Rubber Content = 3%	375/240	10	2.259	2.363	4.40
	Rubber Gradation = 100/0					
	Aggregate Gradation = Gap					

Table 3.8. Mix Property Program.

(Test Temperatures for all Combinations are +10°C, -6°C)

Rubber Content, % of Dry Aggregate			2			3		
Rubber Gradation			C	M	F	C	M	F
Aggregate Gradation	Gap	Air Voids % 2	X	X	X	X(a,b,c)	X	X
		Air Voids % 4				X(a)		
	Dense	Air Voids % 2				X(a,b,c)		
		Air Voids % 4				X		

NOTES:
(a) Mix/compaction temperature: 375°F/265°F and 425°F/265°F.
(b) Cure time: 0, 2 hours.
(c) Surcharge: 0, 5 pounds.

Twelve samples were made for each combination of variables.

Table 3.9. Steps for Mix Design*.

1) Prepare 1100 grams of aggregate according to the mix proportion,
2) Place the aggregate pans in 190°C (375°F) oven for 12 hrs,
3) Heat asphalt to 135°C (275°F),
4) Blend aggregate with rubber and cure for 3 min in 135°C (275°F) oven,
5) Add proper amount of asphalt cement to the mixture of aggregate and rubber and mix for 3 min,
6) Grease the mold with vacuum silicone grease and place in 191°C (375°F) oven,
7) Place the mixture in the mold,
8) Compact at 129°C (265°F), apply 50 blows per side with Marshall hammer assembly,
9) Allow to air cool approximately 5 hrs,
10) Extrude with extrusion jack and measure resilient modulus, specific gravity, flow and stability,
11) Determine maximum specific gravity (Rice method),
12) Determine void content
13) Develop void content vs. asphalt content curve, and
14) Select optimum asphalt content at 2% air void.

*Modified after All Seasons Surfacing Corporation recommendations.

per minute, with a load duration of 0.1 s. Samples were tested at temperatures of +10°C, and -6°C, in the as-compacted condition.

A number of samples were initially tested at what was thought to be +10°C. However, because of substantial variations in modulus and fatigue life, the test program was halted. It was determined that the temperature of the specimens varied considerably. Therefore, three linear response thermistors (Model No. YSI 44004) were used and each was connected to a probe (probes A, B, and C). To obtain a better indication of the actual specimen temperature, probe A was inserted in a drilled hole in a dummy specimen of the same size and shape as the test specimens. Probe B was attached by molding clay (1-inch thick) on the side of a dummy specimen. Probe C was hung in the controlled-temperature chamber. All subsequent specimens tested were conditioned in the testing chamber, along with the dummy specimens, to the desired temperature (+10°C, -6°C). Equilibrium was reached between the three probes after about 4 hours which indicated that the test specimens were ready for testing (see Figure 3.7).

Twenty different combinations were considered for this phase of the study. For each combination, a minimum of 12 samples were prepared and tested for resilient modulus and fatigue at two different temperatures (+10°C, and -6°C). Fatigue curves for five combinations were developed at +10°C. Fatigue curves were also developed for four mix combinations at -6°C.

The mix variables considered for this phase of the study are summarized in Table 3.9. This includes two rubber contents (2% and 3% by weight of dry aggregate), two aggregate gradations (gap and dense), three rubber gradations (fine, medium, and coarse), two void contents (2% and 4%), and two mixing temperatures (190°C (375°F) and 218°C (425°F)), with 5 pounds surcharge and without surcharge.

A series of supplementary tests were carried out to characterize materials and simulate their behavior in field conditions. These tests evaluated effects of compaction temperature and compaction effort on void content and the effects of aging and temperature on the resilient modulus of the samples. These tests are discussed in the following sections.

3.3.2.1 Fabrication of Samples for Modulus and Fatigue Tests. The following steps were used to prepare the rubber asphalt specimen mixtures:

1) The aggregate fractions for the selected gradation and desired quantity were combined. The aggregates were weighed into separate pans for each test specimen and blended with the amount of each size fraction required to produce 1100 grams. To ensure hot and dry mix, the aggregates were placed in an oven at the selected temperature (375°F or 425°F) for at least 12 hours. The asphalt was heated to 135°C (275°F) prior to mixing. Overheated asphalts were avoided.
2) The rubber fractions were combined to desired gradation and weight (i.e., 33 grams for a 1100-gram specimen).
3) The heated aggregate was mixed with the rubber granules and cured in the oven 375°F or 425°F for approximately 3 minutes.
4) The asphalt required was added to the mixture of aggregate and rubber and mixed for at least 3 minutes as quickly and thoroughly as possible to yield a mixture having a uniform distribution of asphalt throughout.
5) Standard Marshall molds, 4 inches in diameter, 2-1/2 inches high, were heated in an oven to 135°C (275°F). The forming mold part of the compaction mold was lubricated with silicone grease for ease of removing the specimen from the mold. The standard filter papers were not used because of the tendency of rubber-modified asphalt to stick to the paper. Alternatives to filter paper were release paper or a greased composition paper, both of which were used. The entire batch was placed in the mold. The mixture was spaded vigorously with a heated spatula. Prior to compaction, some of the samples were cured in the molds open to air at 190°C (375°F) or 218°C (425°F) ovens for 2 hours to evaluate the effect of cure time on mix properties of the samples.
6) The mix was cooled at room temperature until it reached the desired compaction temperature (i.e., 265°F). Fifty blows were applied to each side with a Marshall hammer assembly. For the 4% void content in the samples, the compaction temper-

ature and compaction effort was lowered to 210°F and 10 blows, respectively.

7) The specimens were removed from the mold by means of an extrusion jack and then placed on a smooth, level surface until ready for testing. In some cases, to evaluate the effect of surcharge on the mix property, a 5-pound surcharge was applied immediately after compaction. The surcharge was removed after a 24-hour period, and the specimen was then extruded from the mold.

8) The bulk specific gravity and height of each compacted test specimen were measured immediately after extrusion from the mold (AASHTO T-166).

3.3.2.2 Effect of Compaction Effort and Compaction Temperature. Ten samples with three different mix formulas were prepared using three different compaction temperatures (265°F, 240°F, and 185°F) and three different compaction efforts (30, 10, and 5 blows per side). All of the samples were tested for bulk specific gravity and maximum specific gravity. The air void content based on Rice's theoretical maximum specific gravity (AASHTO T-209) was calculated for all samples. The results are shown in Table 3.10.

3.3.2.3 Resilient Modulus Test Method. The diametral modulus test (ASTM D-4123) was used to evaluate the effects of mix variables at the different temperatures and strain levels. Horizontal deformation was measured with two horizontal transducers attached to the specimen. Repeated loads were measured with a load cell under the specimen (Figure 3.8). Load and deformation were recorded with a two-channel oscillographic recorder (Figure 3.9). The duration of pulse loading was 0.1 s, which corresponds to a 30 mph actual tire speed (35). The load is applied at a frequency of 60 cycles per minute. A seating load of about 10% of the required dynamic load at specified strain level was used to hold the specimen in place. The modulus was calculated by the equation below (35):

$$M_R = \frac{f\ (\mu + 0.2734)}{t\ (\Delta h)} \tag{3.1}$$

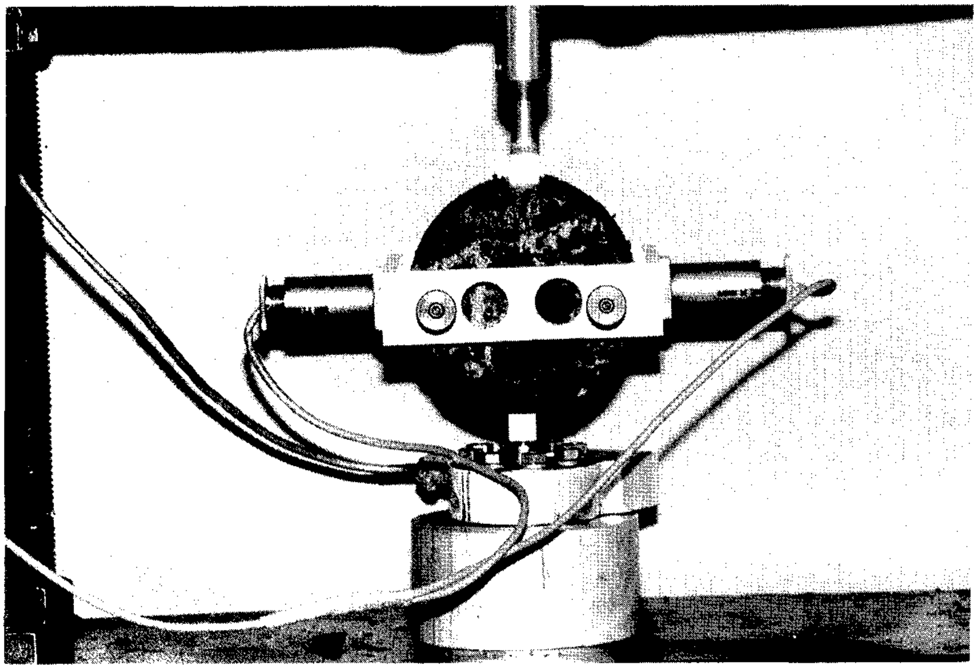
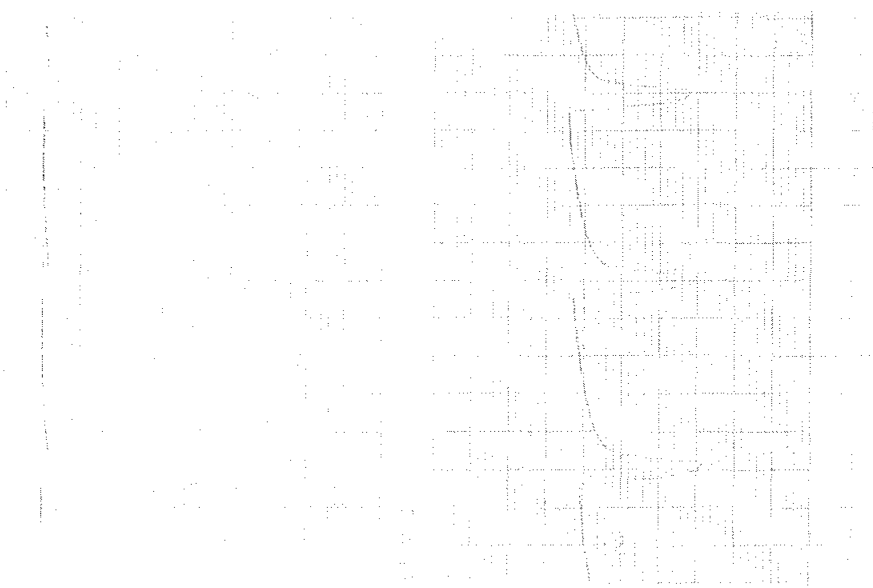


Figure 3.8. Resilient Modulus Setup.



a) Load b) Deformation

Figure 3.9. Example of HP Recorder Output for Diametral Test.

Table 3.10. Summary of Compaction Study.

Sample Number	Material Combination	Mix/Compaction Temp. (^{o}F)	Number of Blows	Bulk Specific Gravity	Maximum Specific Gravity	Air Voids
1	AC = 9.3%	375/265	30	2.307	2.354	2.00
2	Rubber Content = 3%	375/265	20	2.295	2.342	2.01
3	Rubber Gradation = 80/20	375/265	10	2.302	2.351	2.08
4	Aggregate Gradation = Gap	375/265	5	2.301	2.362	2.57
5		375/240	10	2.278	2.369	3.85
6		375/185	10	2.262	2.359	4.11
7	AC = 6.5%	375/265	10	2.317	2.394	3.21
8	Rubber Content = 3%	375/240	10	2.254	2.394	5.85
	Rubber Gradation = 40/60					
	Aggregate Gradation = Gap					
9	AC = 7.5%	375/265	10	2.268	2.363	4.02
10	Rubber Content = 3%	375/240	10	2.259	2.363	4.40
	Rubber Gradation = 100/0					
	Aggregate Gradation = Gap					

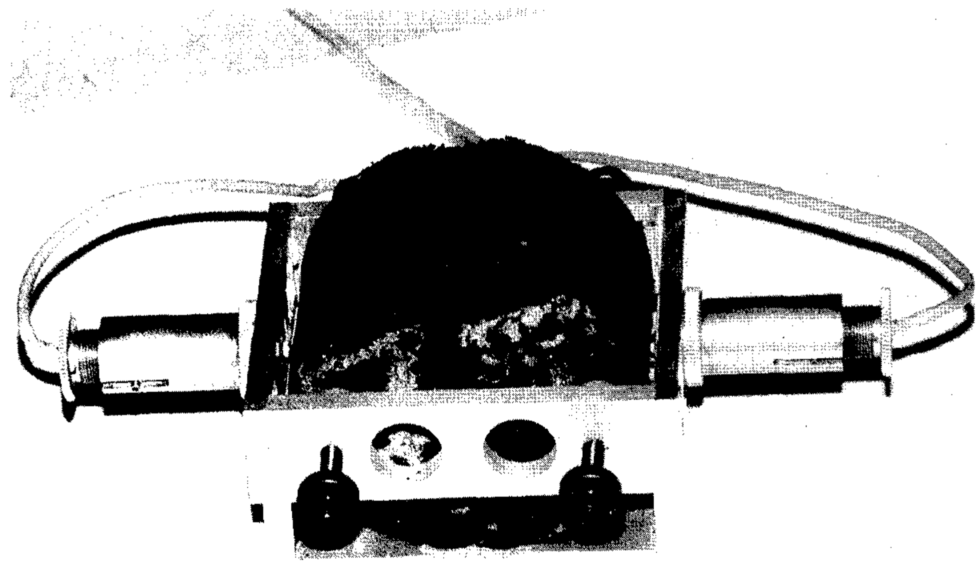


Figure 3.12. Sample With Diametral Yoke.

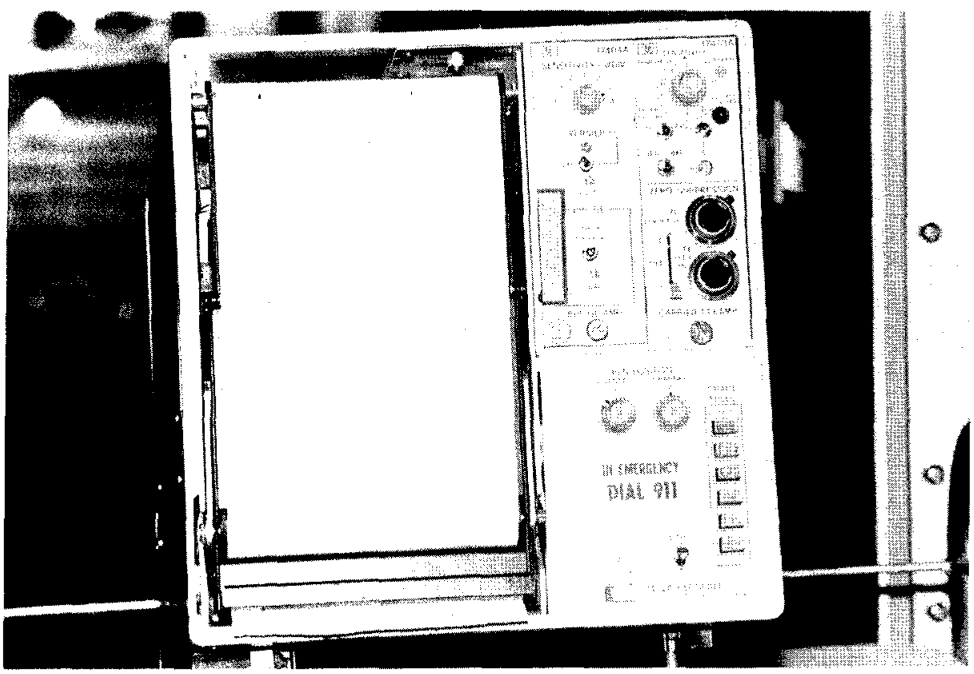


Figure 3.13. Two-Channel Oscillographic Recorder (Hewlett Packard Model 7402A).

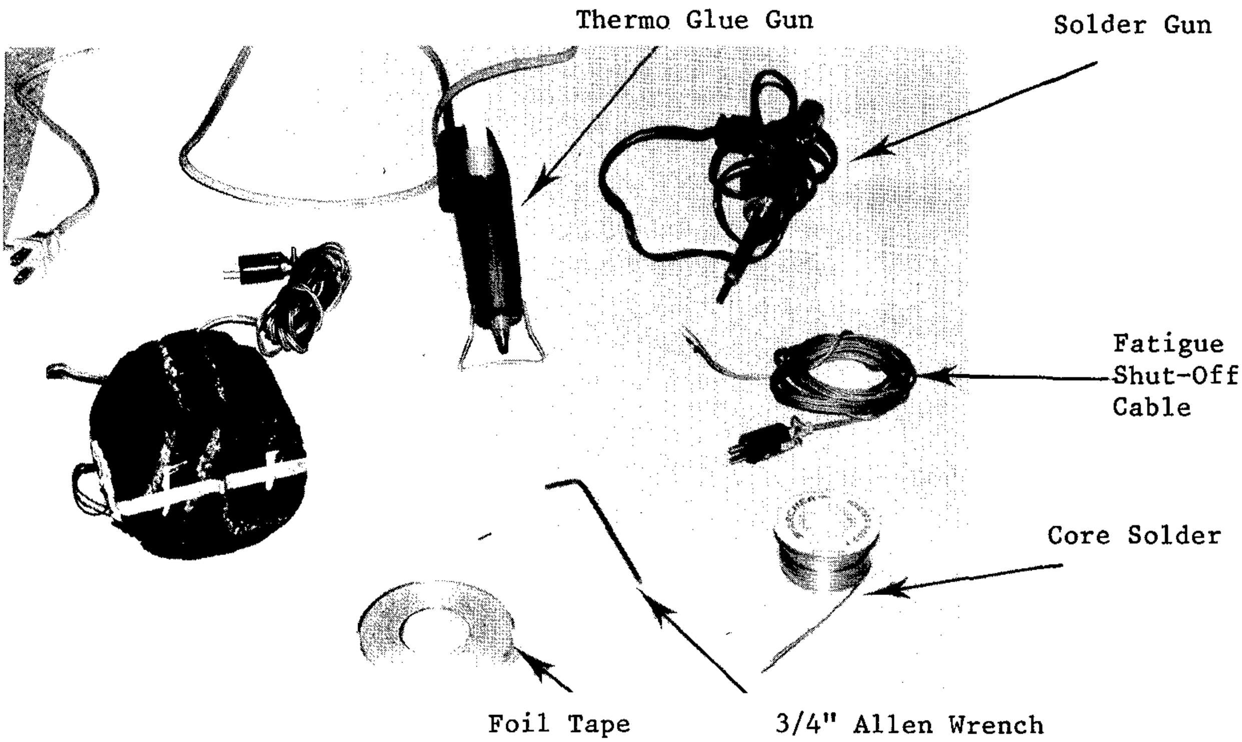


Figure 3.14. Specimen Setup for Fatigue Testing.

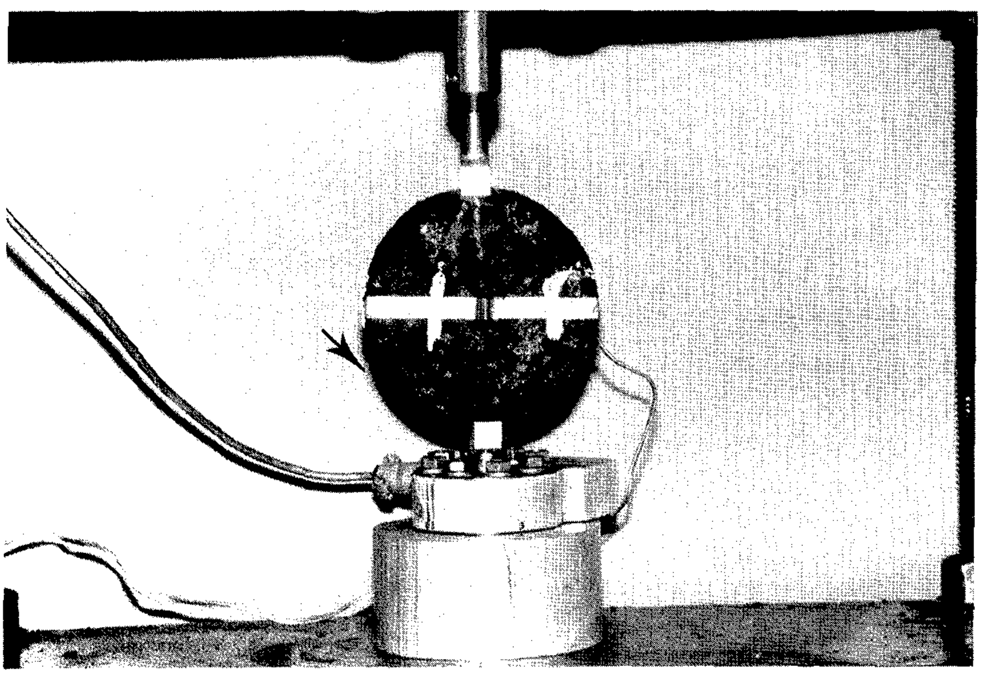


Figure 3.15. Specimen Orientation for Diametral Fatigue.

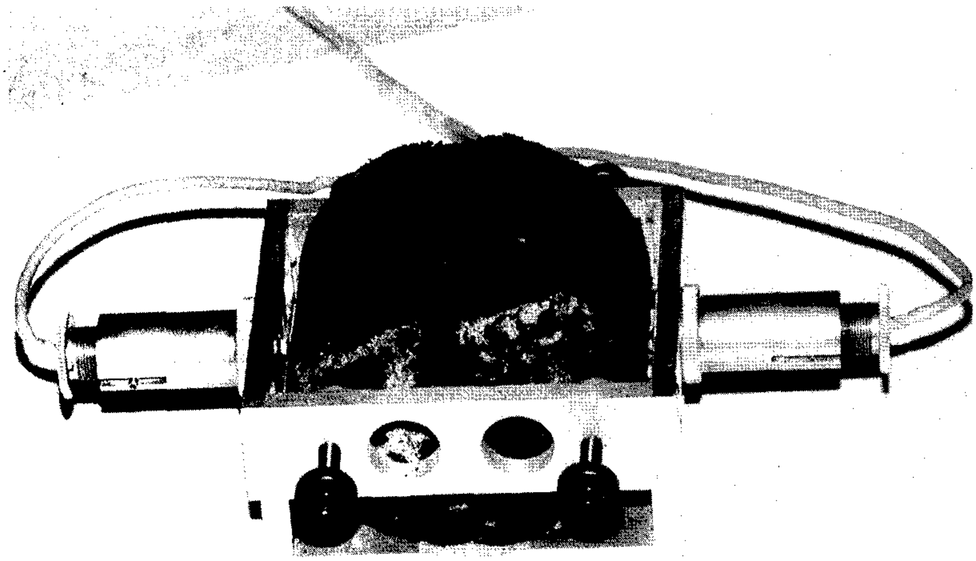


Figure 3.12. Sample With Diametral Yoke.

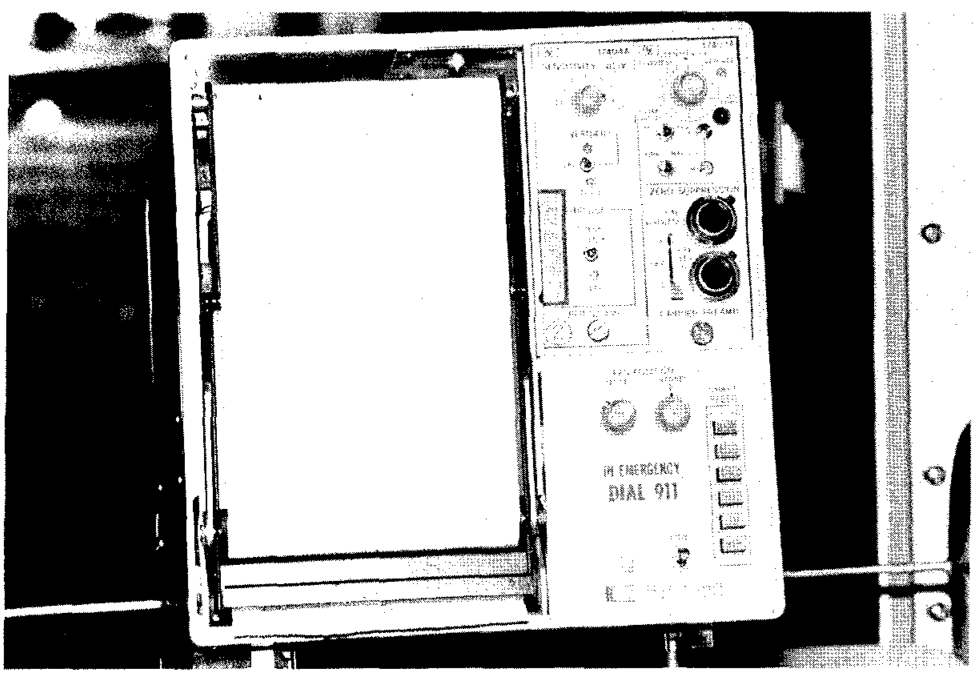


Figure 3.13. Two-Channel Oscillographic Recorder (Hewlett Packard Model 7402A).

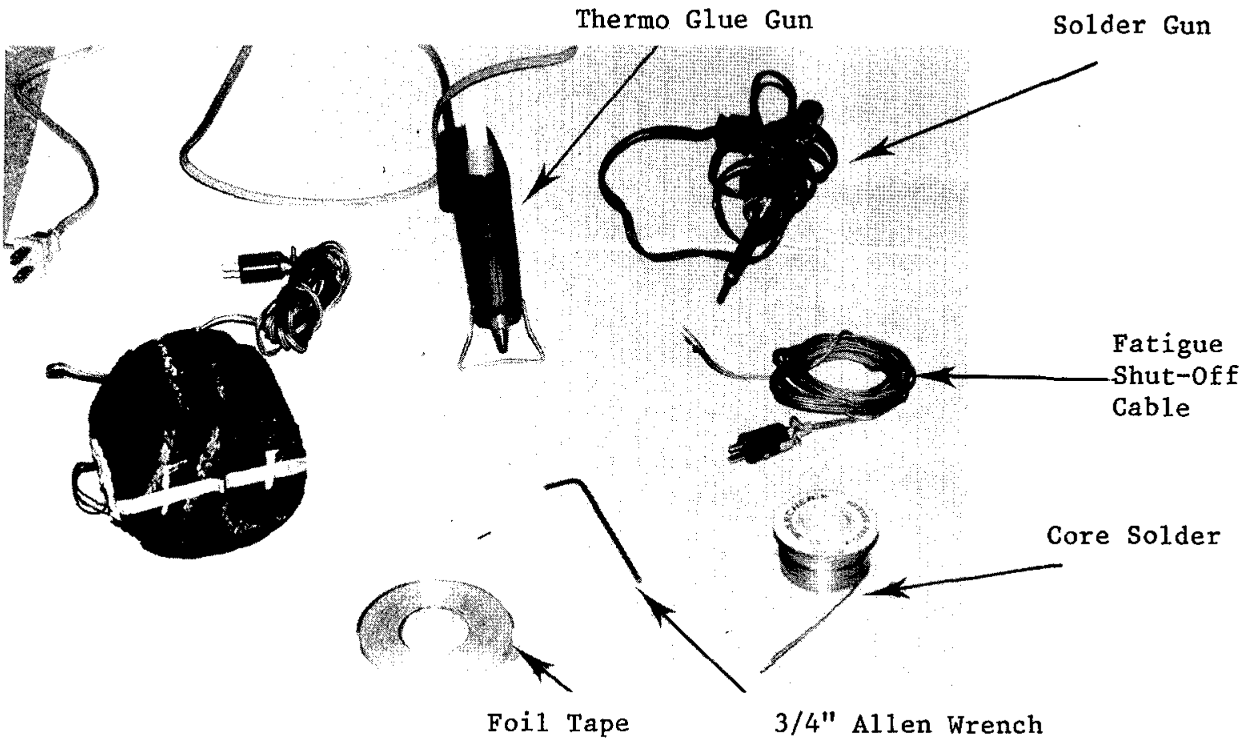


Figure 3.14. Specimen Setup for Fatigue Testing.

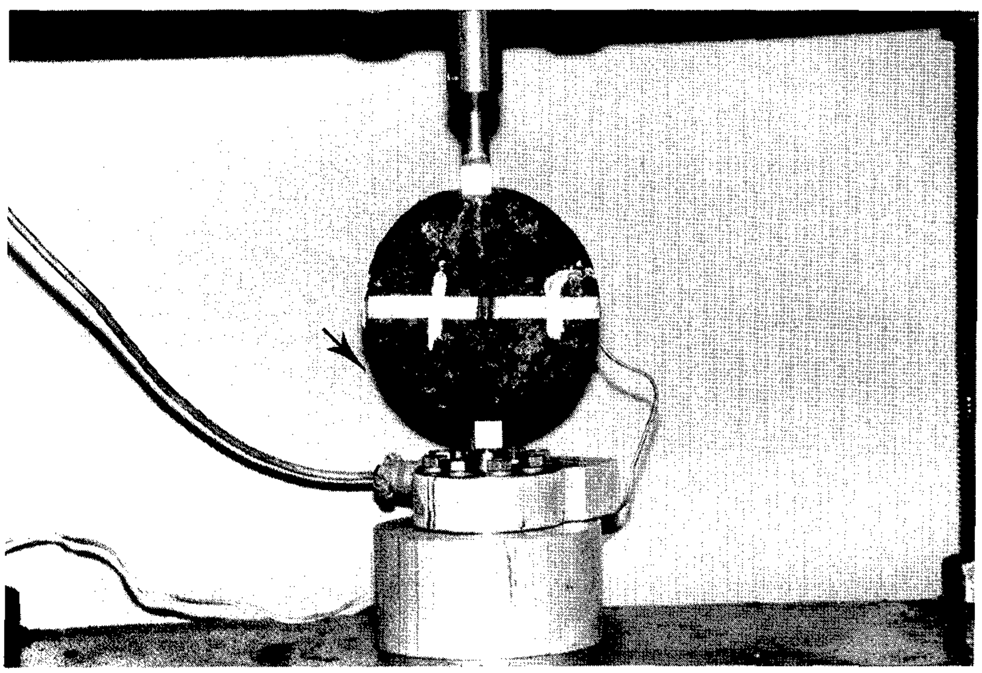


Figure 3.15. Specimen Orientation for Diametral Fatigue.

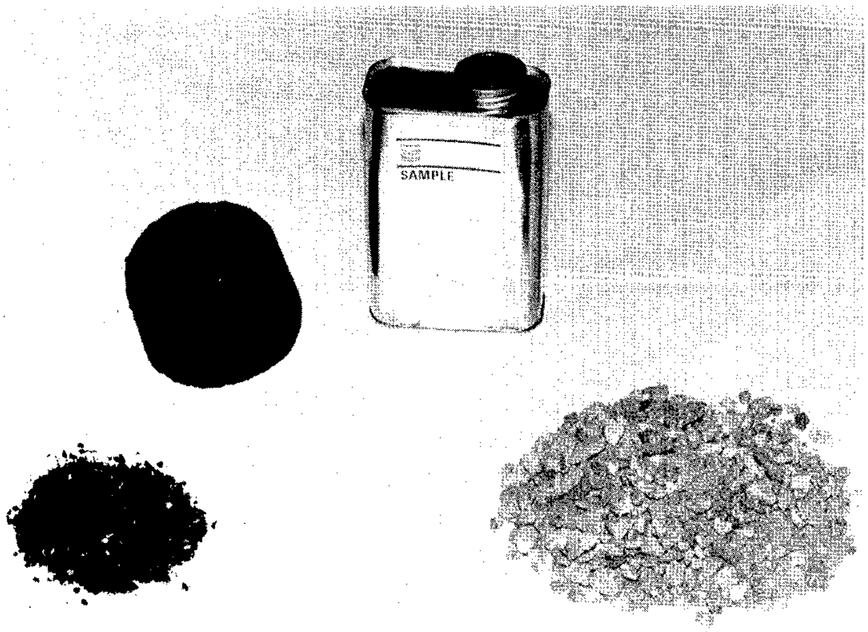


Figure 3.1. Material Components for Specimen Preparation.

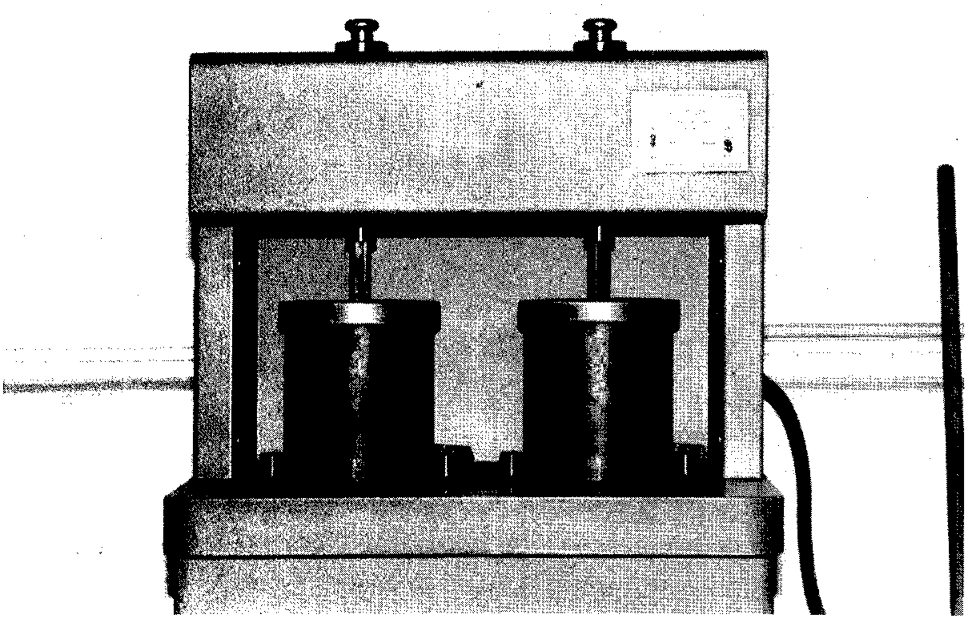


Figure 3.2. Cox Mixer.

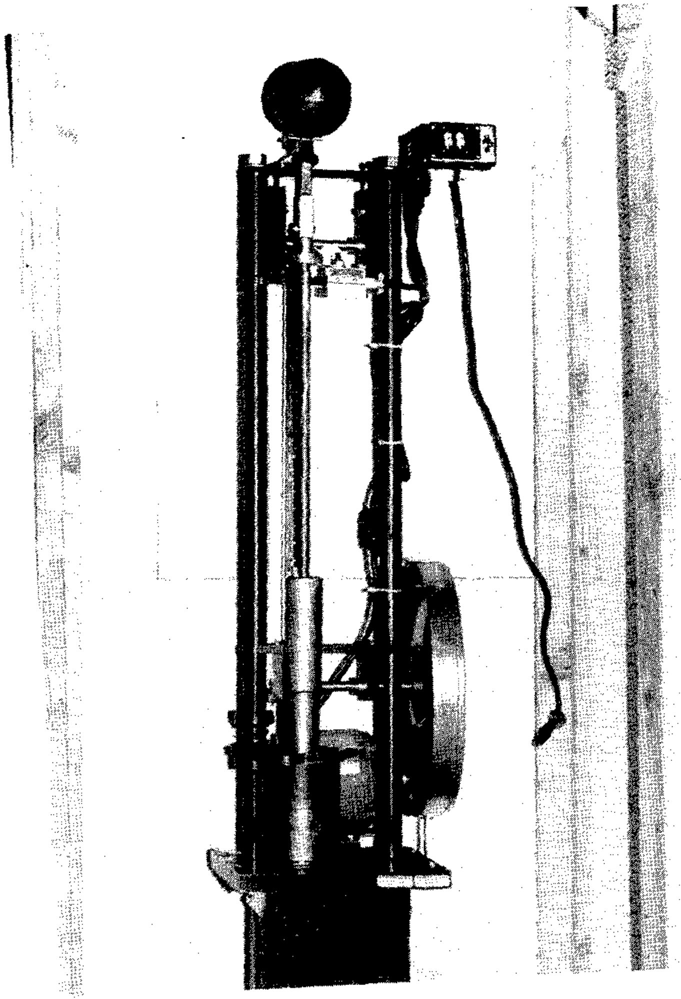


Figure 3.3. Marshall Assembly.

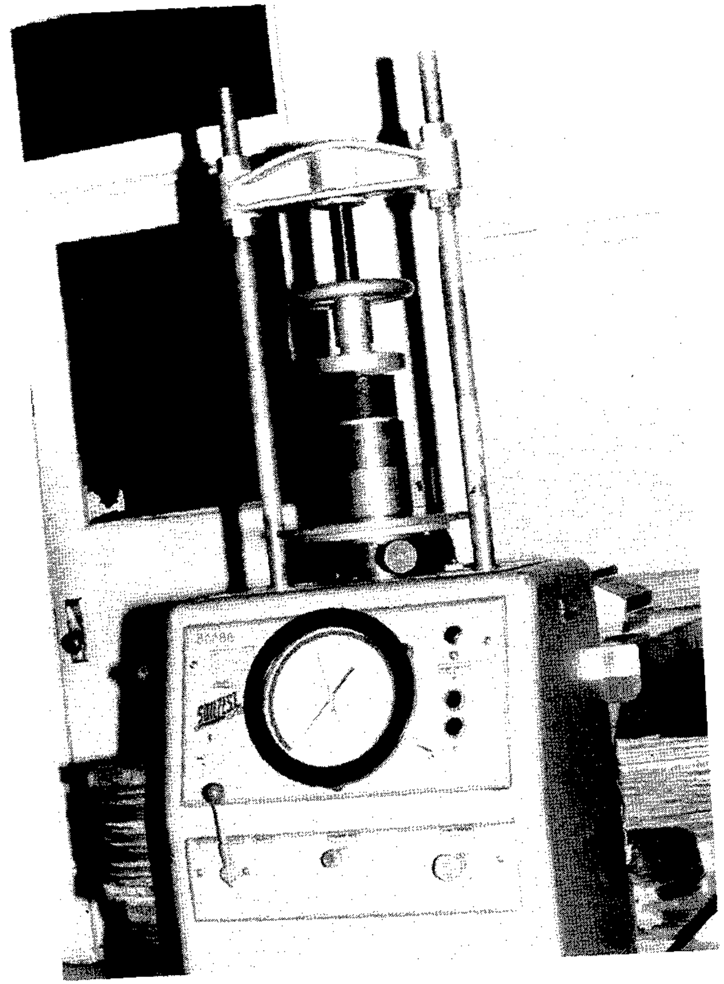


Figure 3.4. Sample Extrusion Assembly.

4.0 TEST RESULTS

The results of mix design tests, modulus tests, and fatigue tests at +10°C and -6°C, and the effect of temperature and aging on modulus for different mix combinations are presented in this chapter.

4.1 Mix Design

The standard Marshall samples were tested for flow, stability, void content, and diametral modulus. All tests for flow and stability were conducted using an MTS machine with a rate of loading of 2 inches per minute. The tests for diametral modulus were conducted using a load duration of 0.1 s, a frequency of 1 Hz, and at a temperature of 22° ± 2° C.

Tables 4.1 to 4.8 summarize the results of tests for percent of void content, stability, unit weight, and flow at various asphalt contents. Also shown is the recommended design asphalt content with the corresponding stability, unit weight, and flow values. However, the stability, unit weight, and flow factors were not used as a criteria for mix design. Air voids (2%) were used as the sole criteria for mix design. They are shown in Figures 4.1 to 4.4. Recommended asphalt contents for each mix design combination are given below:

Aggregate Gradation	Rubber Content	Rubber Gradation (% Coarse/% Fine)	Design Asphalt Content, %
Gap-Graded	2	0/100	7.0
		60/40	7.2
		80/20	8.0
	3	0/100	7.5
		60/40	7.5
		80/20	9.3
Dense-Graded	0	No Rubber	5.5
	3	80/20	7.5

Tables 4.9 to 4.12 summarize the results of tests for modulus on each rubber gradation and rubber content. As indicated by the data in Tables 4.9 to 4.12, the conventional asphalt (no rubber) shows the highest resilient modulus with lowest design asphalt content, and the rubber asphalt with 3%

Table 4.1. Results of Mix Design (Gap-Graded Aggregate 0/100 Blend and 2% Rubber*).

% Asphalt**	Voids - %	Stability (lbs)	Unit Weight (pcf)	Flow (.01 in.)
6.0	5.1	1045	146.1	12
7.0	2.1	925	148.1*	15
8.0	1.6	761	148.2	20
9.0	0.9	556	146.0	34

Table 4.2. Results of Mix Design (Gap-Graded Aggregate 0/100 Rubber Blend and 3% Rubber*).

% Asphalt**	Voids - %	Stability (lbs)	Unit Weight (pcf)	Flow (.01 in.)
6.0	6.9	555	142.9	17
7.0	2.7	646	145.0	18
8.0	1.6	564	145.7	20
9.0	1.0	688	145.1	20

*Rubber Content is % by weight of aggregate.
**Asphalt Content is % by weight of aggregate.

Table 4.3. Results of Mix Design (Ga-pGraded Aggregate 60/40 Rubber Blend and 2% Rubber*).

% Asphalt**	Voids - %	Stability (lbs)	Unit Weight (pcf)	Flow (.01 in.)
6.0	4.5	803	145.7	20
7.0	2.7	673	147.3	21
8.0	1.2	740	147.2	22

Table 4.4. Results of Mix Design (Gap-Graded Aggregate 60/40 Rubber Blend and 3% Rubber*).

% Asphalt**	Voids - %	Stability (lbs)	Unit Weight (pcf)	Flow (.01 in.)
6.0	5.7	577	142.8	21
7.0	2.4	659	144.9	22
8.0	1.7	635	145.3	23

*Rubber Content is % by weight of aggregate.
**Asphalt Content is % by weight of aggregate.

Table 4.5. Results of Mix Design (Gap-Graded Aggregate 80/20 Rubber Blend and 2% Rubber*).

% Asphalt**	Voids - %	Stability (lbs)	Unit Weight (pcf)	Flow (.01 in.)
6.0	4.7	806	145.8	17
7.0	3.2	846	146.1	18
8.0	2.0	665	147.6	23

Table 4.6. Results of Mix Design (Gap-Graded Aggregate 80/20 Rubber Blend and 3% Rubber*).

% Asphalt**	Voids - %	Stability (lbs)	Unit Weight (pcf)	Flow (.01 in.)
6.0	5.2	565	142.9	21
7.0	3.6	513	144.5	24
8.0	3.1	435	144.6	30
9.0	2.4	430	144.0	33

*Rubber Content is % by weight of aggregate.
**Asphalt Content is % by weight of aggregate.

Table 4.7. Results of Mix Design (Dense-Graded Aggregate 80/20 Rubber Blend and 3% Rubber*).

% Asphalt**	Voids - %	Stability (lbs)	Unit Weight (pcf)	Flow (.01 in.)
6.0	8.2	498	142.4	19
7.0	3.3	410	146.6	21
8.0	1.8	553	145.8	22

Table 4.8. Results of Mix Design (Dense-Graded Aggregate Control).

% Asphalt**	Voids - %	Stability (lbs)	Unit Weight (pcf)	Flow (.01 in.)
5.0	2.3	1530	152.4	8
6.0	1.7	1420	153.0	10
7.0	1.0	1350	152.4	13

*Rubber Content is % by weight of aggregate.
**Asphalt Content is % by weight of aggregate.

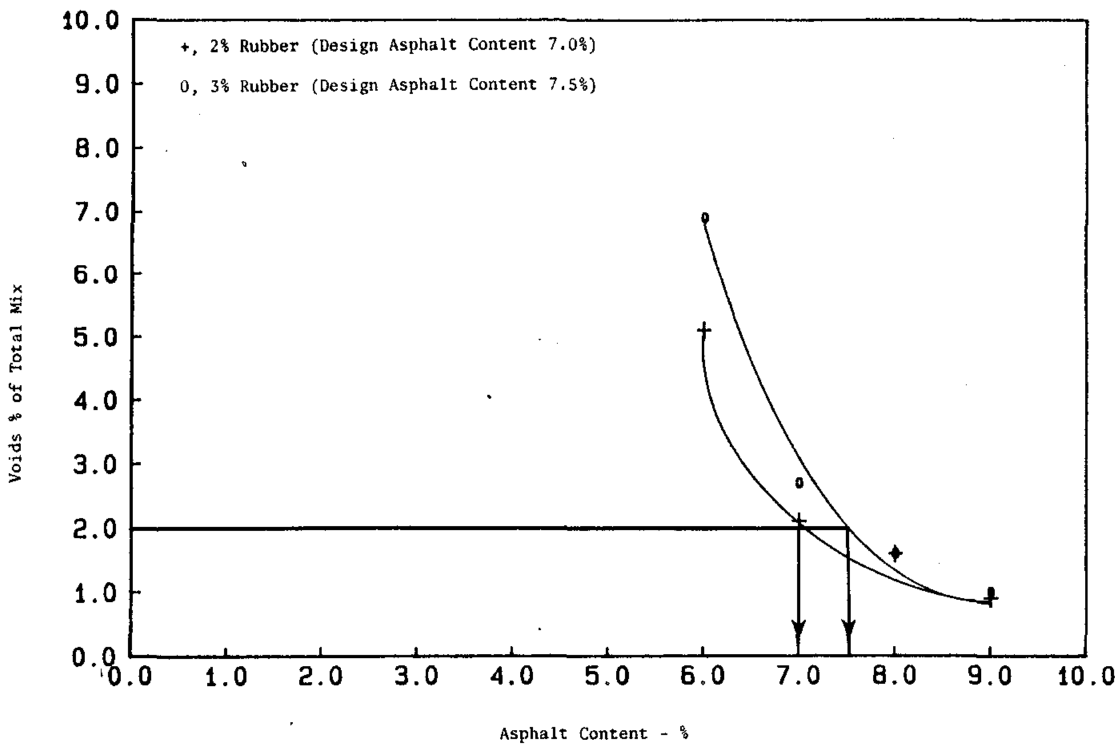


Figure 4.1. Voids vs. Asphalt Content for Gap-Graded Mix - Fine Rubber.

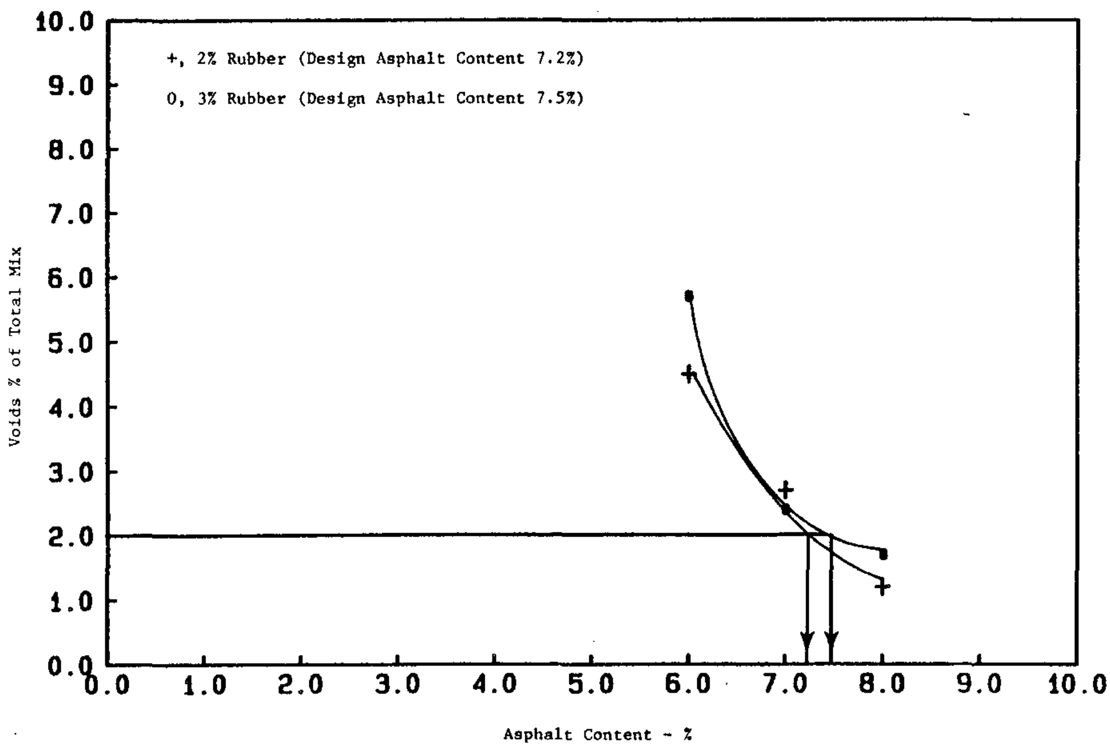


Figure 4.2. Voids vs. Asphalt Content for Gap-Graded Mix - Medium Rubber.

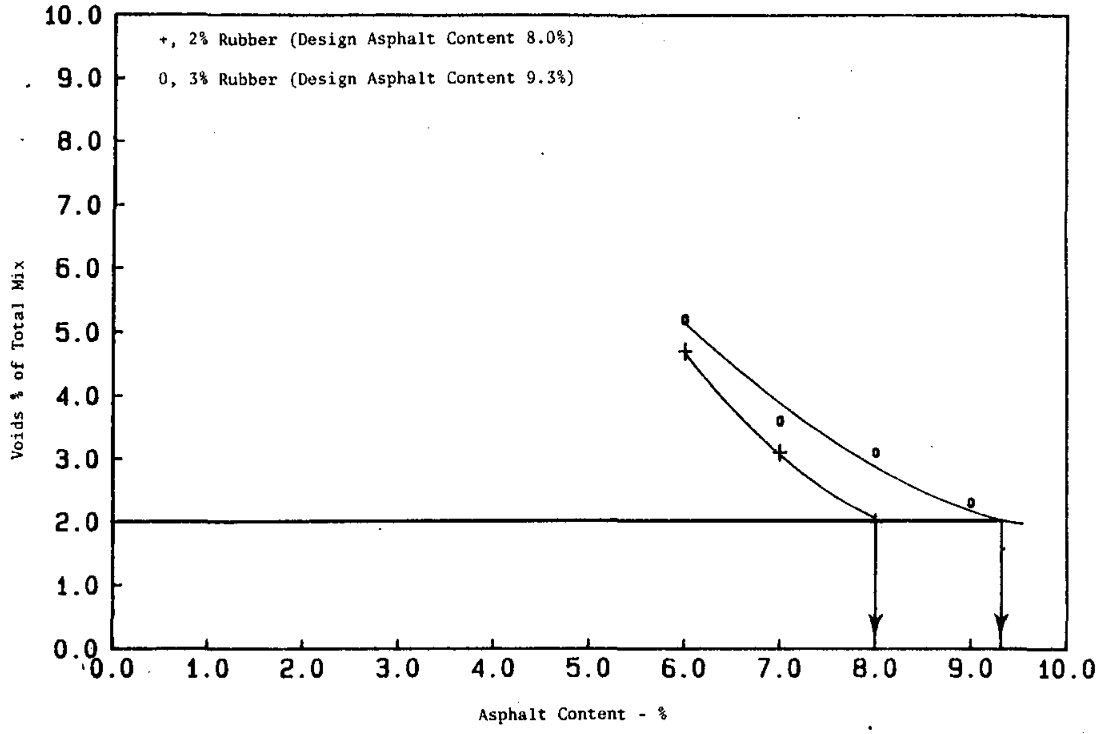


Figure 4.3. Voids vs. Asphalt Content for Gap-Graded Mix - Coarse Rub

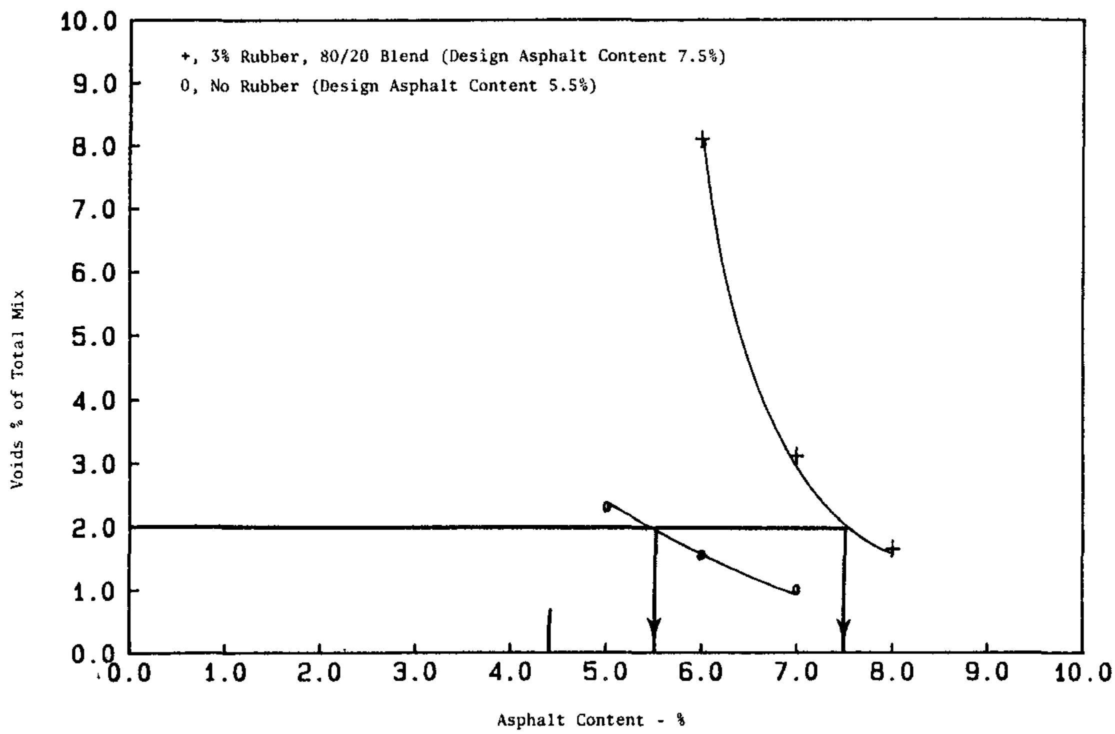


Figure 4.4. Voids vs. Asphalt Content for Dense-Graded Mix.

Table 4.9. Summary of Modulus Data for Gap-Graded Mixes - Fine Rubber (Strain Level 100 Microstrain).

Asphalt Contents %, AC-5	Temperature (°C)	Modulus (ksi)
	a) 2% Rubber (0/100)	
6	20.2	92
7	21.5	88
8	22.5	66
9	20.2	58
	b) 3% Rubber (0/100)	
6	20.2	68
7	20.0	62
8	22.5	58
9	20.0	62

NOTE: 1) Load duration: 0.1 sec.
2) Load frequency: 1 rep./sec.

Table 4.10. Summary of Modulus Data for Gap-Graded Mixes - Medium Rubber (Strain Level 50 Microstrain).

Asphalt Contents %, AC-5	Temperature (°C)	Modulus (ksi)
	a) 2% Rubber (60/40)	
6	21.0	109
7	21.5	76
8	22.5	58
	b) 3% Rubber (60/40)	
6	21.5	99
7	21.8	74
8	21.5	55

NOTE: 1) Load duration: 0.1 sec.
2) Load frequency: 1 rep./sec.

Table 4.11. Summary of Modulus Data for Gap-Graded Mixes - Coarse Rubber (Strain Level 50 Microstrain).

Asphalt Contents %, AC-5	Temperature (°C)	Modulus (ksi)
	a) 2% Rubber (80/20)	
6	23.2	94
7	23.0	84
8	23.0	45
9	23.0	39
	b) 3% Rubber (80/20)	
6	22.0	37
7	22.5	35
8	23.0	34
9	22.5	27

Note: 1) Load duration: 0.1 sec.
2) Load frequency: 1 rep./sec.

Table 4.12. Summary of Modulus Data for Dense-Graded Mixes - Coarse Rubber (Strain Level 100 Microstrain).

Asphalt Contents %, AC-5	Temperature (°C)	Modulus (ksi)
	a) 3% Rubber (80/20)	
6	20	55.0
7	19	51.0
8	20	45.0
	b) 0% Rubber, Dense-Graded	
6	20.5	164
7	20.6	162
8	20.8	124

NOTE: 1) Load duration: 0.1 sec.
2) Load frequency: 1 rep./sec.

rubber 80/20 blend shows the lowest resilient modulus with highest design asphalt content.

4.1.1 Discussion of Results

The effects of rubber content, rubber gradation, and aggregate gradation on design asphalt content and resilient modulus at room temperature are described in the following sections.

4.1.1.1 Effect of Rubber Content and Rubber Gradation. The effect of two rubber contents (2% and 3%) on design asphalt content for three different rubber gradations (fine, medium, and coarse) and two different aggregate gradations (gap and dense) were evaluated. The effect of rubber gradation and content is shown by Figure 4.5. The mixture with coarse rubber gradation required the highest design asphalt content, while the mixture with fine rubber gradation required the lowest design asphalt content. Figure 4.6 shows the rubber-modified mix requires approximately 2% more asphalt cement than a conventional mix.

The effect of rubber content on resilient modulus is shown in Figures 4.7 and 4.8. The highest asphalt content, and lowest resilient modulus, was achieved at 3% coarse rubber with gap-graded aggregate. Figure 4.8 shows that the control mix has the highest stiffness with the lowest design asphalt content.

4.1.1.2 Effect of Aggregate Gradation. The effect of aggregate gradation on design asphalt content is noticeable. For example, the design asphalt content at 2% voids for dense-graded aggregate is 1.8% less than the gap-graded aggregate. Figure 4.9 shows this relationship.

The effect of aggregate gradation on resilient modulus is shown in Figure 4.10. The dense-graded aggregate has a higher resilient modulus than gap-graded aggregate.

4.2 Mix Properties at +10°C

4.2.1 Resilient Modulus and Fatigue

Twenty different mix combinations were tested at 100 microstrain in a +10°C environmental chamber for resilient modulus and fatigue (Table 4.13).

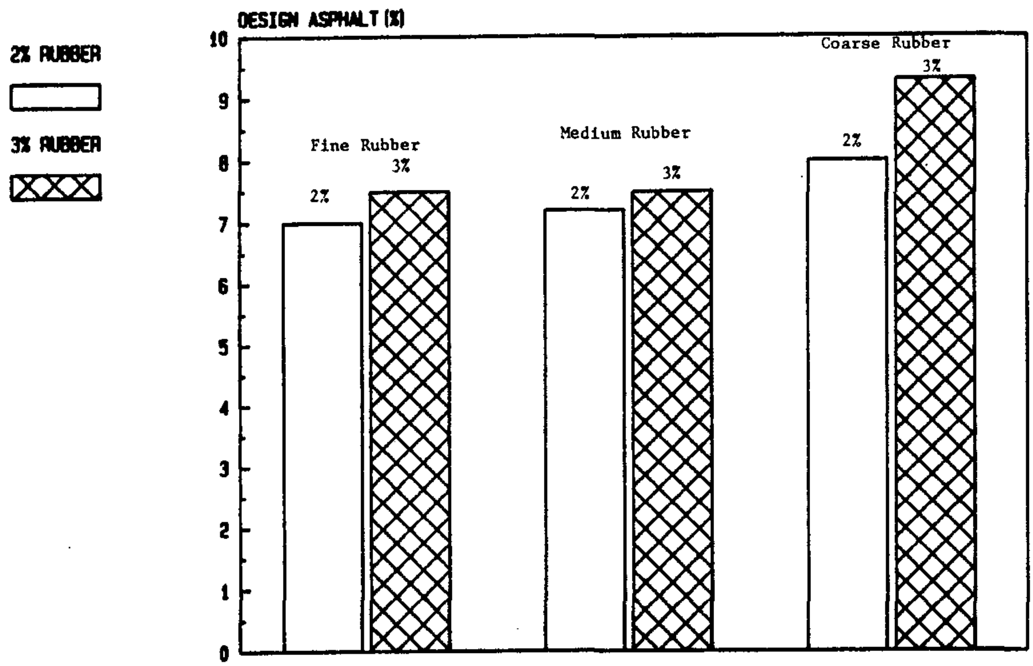


Figure 4.5. Effect of Rubber Gradations and Content on Design Asphalt Content.

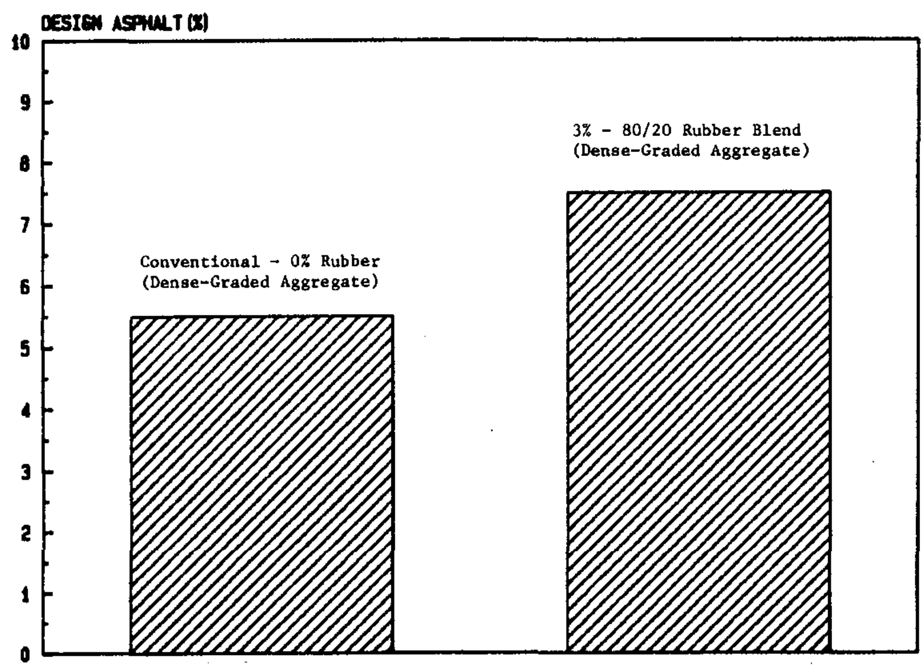


Figure 4.6. Comparison of Design Asphalt Content Conventional vs. 3% Rubber.

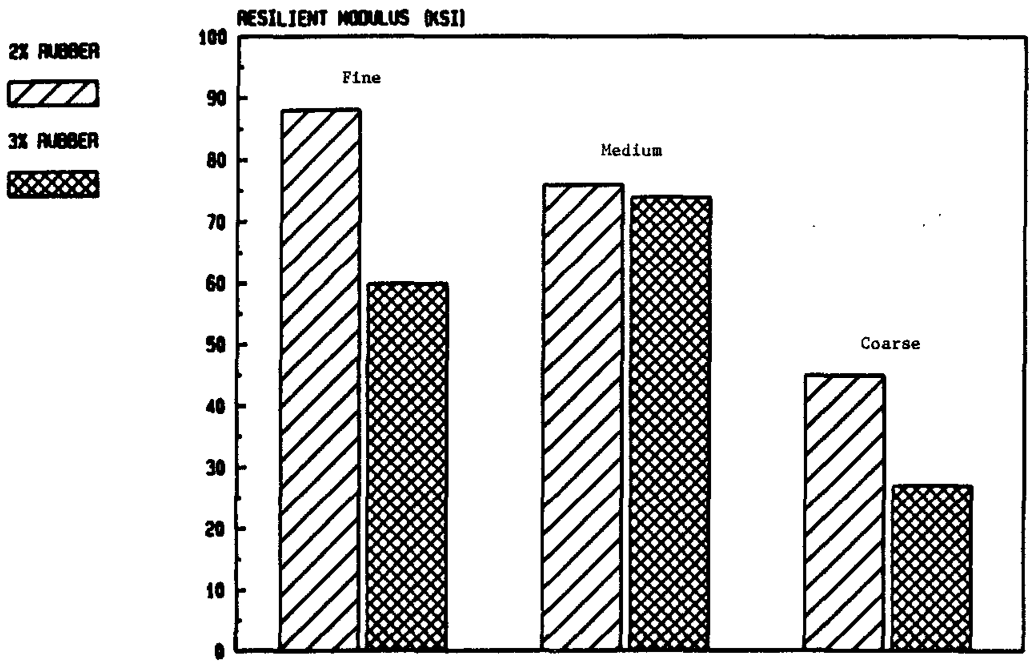


Figure 4.7. Effect of Rubber Content on Resilient Modulus at 22 ± 2°C.

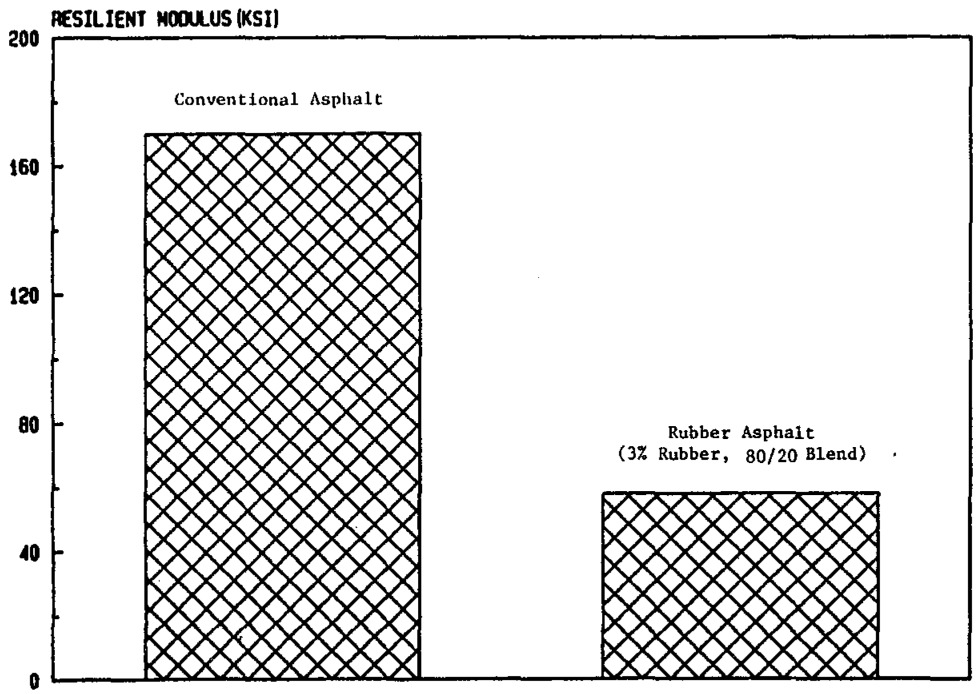


Figure 4.8. Comparison of Resilient Modulus Conventional vs. Rubber Asphalt at 22 ± 2°C.

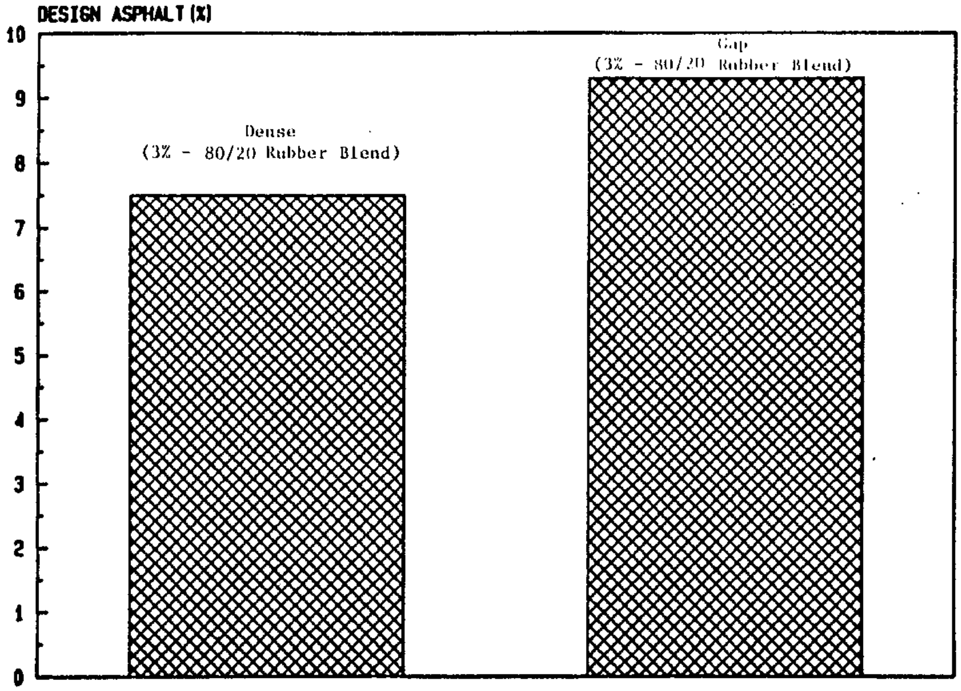


Figure 4.9. Effect of Aggregate Gradation on Design Asphalt Content.

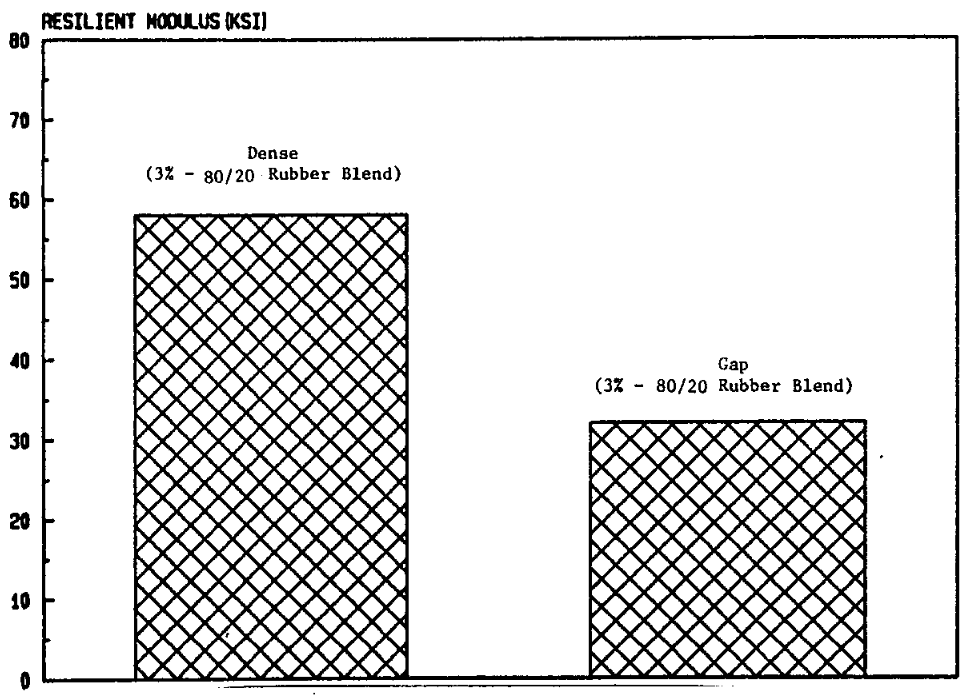


Figure 4.10. Effect of Aggregate Gradation on Resilient Modulus at 20 ± 2°C.

Table 4.13. Specimen Identification.

Specimen Identification	Rubber Content (%)	Rubber Blend (% Fine/% Coarse)	Mixing/Compaction Temperature (°F)	Asphalt Content (%)	Aggregate Gradation	Cure Time (hrs)	Surcharge (lbs)
A*	3	80/20	375/265	9.3	Gap	0	0
B	3	80/20	375/265	9.3	Gap	2	0
C*	3	80/20	375/265	9.3	Gap	0	5
D	3	80/20	425/265	9.3	Gap	0	0
E	3	80/20	425/265	9.3	Gap	2	0
F	3	80/20	425/265	9.3	Gap	0	5
G	3	80/20	375/210	9.3	Gap	0	0
H	3	60/40	375/265	7.5	Gap	0	0
I	3	0/100	375/265	7.5	Gap	0	0
J	3	80/20	425/210	9.3	Gap	0	0
K*	2	80/20	375/265	8.0	Gap	0	0
L	2	60/40	375/265	7.2	Gap	0	0
M*	2	0/100	375/265	7.0	Gap	0	0
N*	3	80/20	375/265	7.5	Dense	0	0
O	3	80/20	375/265	7.5	Dense	2	0
P	3	80/20	375/265	7.5	Dense	0	5
Q	3	80/20	425/265	7.5	Dense	0	0
R	3	80/20	425/265	7.5	Dense	0	0
S	3	80/20	375/210	7.5	Dense	0	0
T*	0	0	375/265	5.5	Dense	0	0

*Mix combinations used to establish fatigue curves.

For all dynamic tests, samples were subjected to a constant load, applied at 60 cycles per minute, with a load duration of 0.1 s. A 28-pound seating load was applied to all samples.

At least three samples for each combination were tested. The results of all tested samples were presented in Appendix C. The results of resilient modulus and fatigue for 20 different mixes are summarized in Table 4.14.

The effects of aggregate gradation, rubber gradation, rubber content, mixing temperature, surcharge, cure time, and air voids are discussed in the following sections.

4.2.1.1 Effect of Aggregate Gradation (Gap vs. Dense). The effects of aggregate gradation on resilient modulus and fatigue life for three different mixing conditions are shown in Figures 4.11 and 4.12. These figures show that the mixtures with gap-graded aggregate in all three mixing conditions have lower resilient modulus and higher fatigue life than the mixtures with dense-graded aggregate.

4.2.1.2 Effect of Rubber Gradations (Fine, Medium, and Coarse). The resilient modulus and fatigue life for three different rubber gradations (fine, medium, and coarse) are compared in Figures 4.13 and 4.14. The mixture with fine rubber has the highest modulus and lowest fatigue, and the mixture with coarse rubber has the lowest modulus and highest fatigue life. These results contradict those obtained by ADOTPF on Peger Road where 2% additional fine rubber extended the fatigue life in all cases, as well as increasing the modulus (Figures 2.12 and 2.13).

4.2.1.3 Effect of Rubber Content (2% vs. 3%). The effect of rubber content on resilient modulus and fatigue is shown in Figures 4.15 and 4.16. The samples with 3% rubber content generally have lower resilient modulus than the samples with 2% rubber content (Figure 4.15). The rubber content variations did not show any significant impact on fatigue life (Figure 4.16), with the exception of the fine rubber (0/100) samples. These fine rubber results agree with the ADOTPF observations that a high content of fine rubber may greatly increase fatigue life.

Table 4.14. Summary of Resilient Modulus and Fatigue Life. (Test Temperature: +10°C; Strain Level: 100 Microstrain)

Mix ID	Number of Samples Used in Calculations	Air Voids (%)		MR (ksi)		N_f	
		$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ
A	4	1.99	0.11	411	22	27,993	3,728
B	4	2.09	0.03	414	46	23,800	3,558
C	4	2.07	0.12	360	19	48,240	4,627
D	4	2.00	0.05	405	31	40,117	11,026
E	3	2.02	0.03	438	43	26,199	4,096
F	5	1.96	0.24	393	103	82,360	7,235
G	3	4.34	0.34	375	17	42,710	4,131
H	5	2.20	0.17	614	73	13,155	4,203
I	4	2.44	0.26	528	87	16,663	2,004
J	4	4.16	0.31	374	14	22,200	5,406
K	3	2.26	0.17	471	22	28,858	4,683
L	3	2.19	0.30	720	38	13,197	5,474
M	3	2.69	0.11	814	114	9,536	4,316
N	5	2.94	0.20	674	55	16,506	6,730
O	4	2.28	0.13	858	68	11,620	6,268
P	4	2.01	0.06	649	60	18,311	7,065
Q	4	2.01	0.09	803	105	7,500	1,942
R	3	2.03	0.21	702	20	17,296	3,945
S	3	4.58	0.89	352	23	13,113	3,725
T	5	2.13	0.25	1,105	67	9,323	2,758

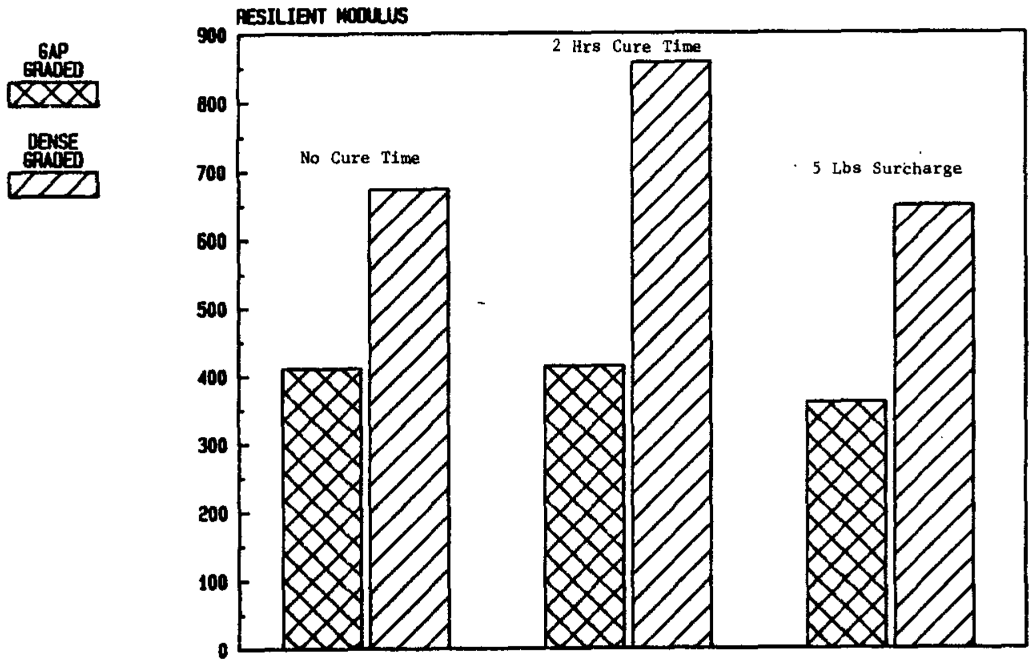


Figure 4.11. Effect of Aggregate Gradation, Cure Time, and Surcharge on Resilient Modulus at +10°C (3% Rubber 80/20 Blend).

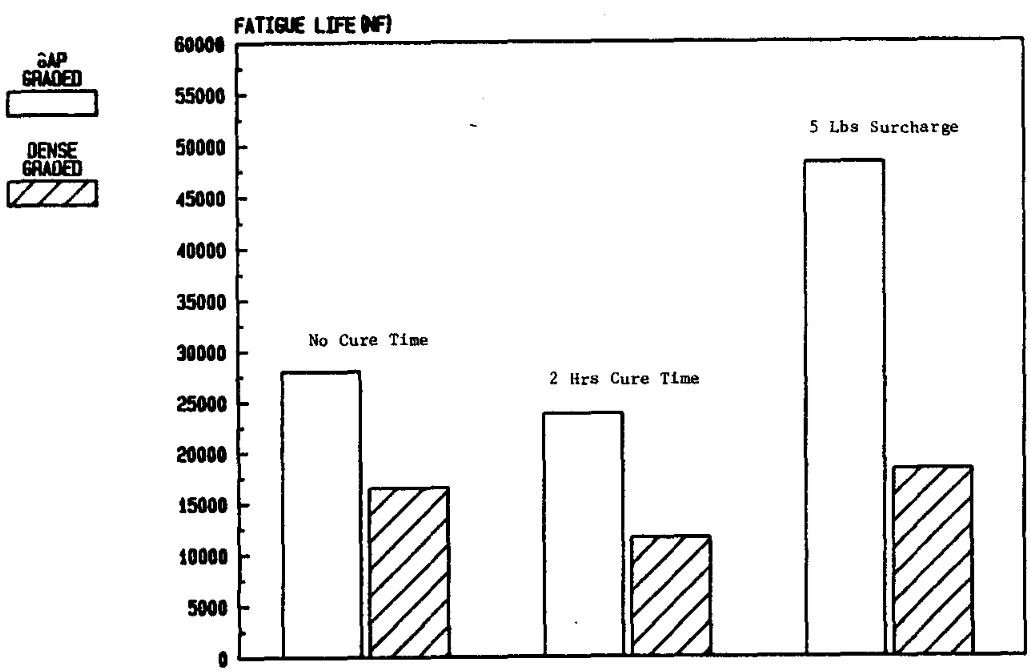


Figure 4.12. Effect of Aggregate Gradation, Cure Time, and Surcharge on Fatigue Life at +10°C (3% Rubber 80/20 Blend).

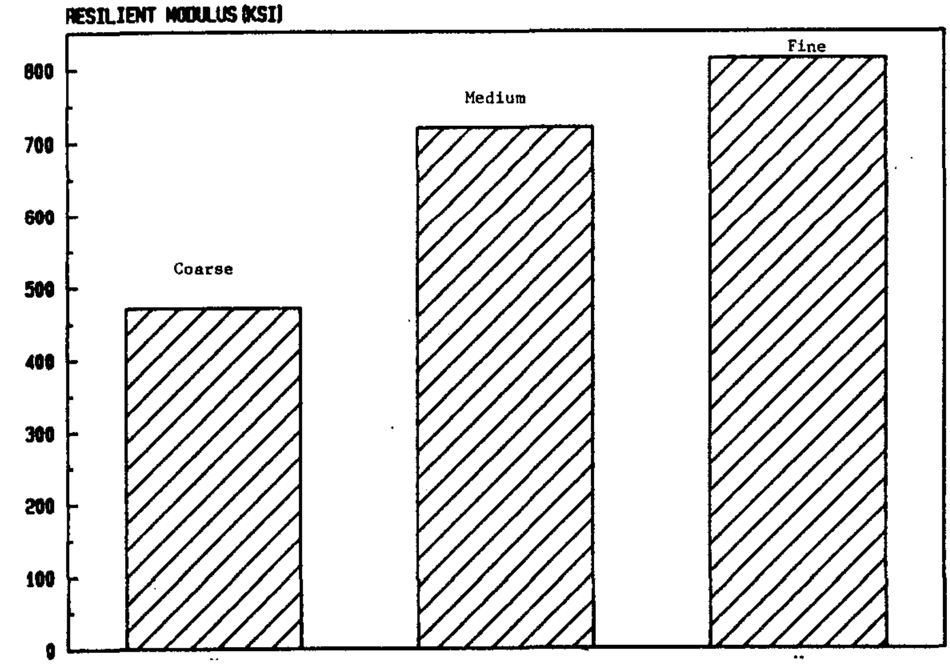


Figure 4.13. Effect of Rubber Gradations on Resilient Modulus at +10°C (Gap-Graded Aggregate).

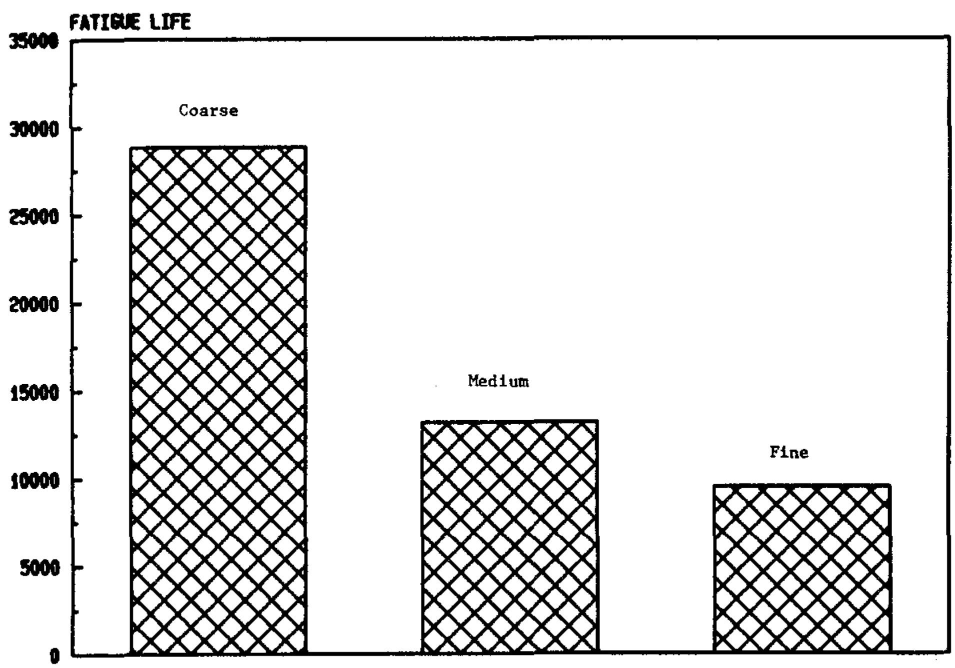


Figure 4.14. Effect of Rubber Gradation on Fatigue Life at +10°C (Gap-Graded Aggregate).

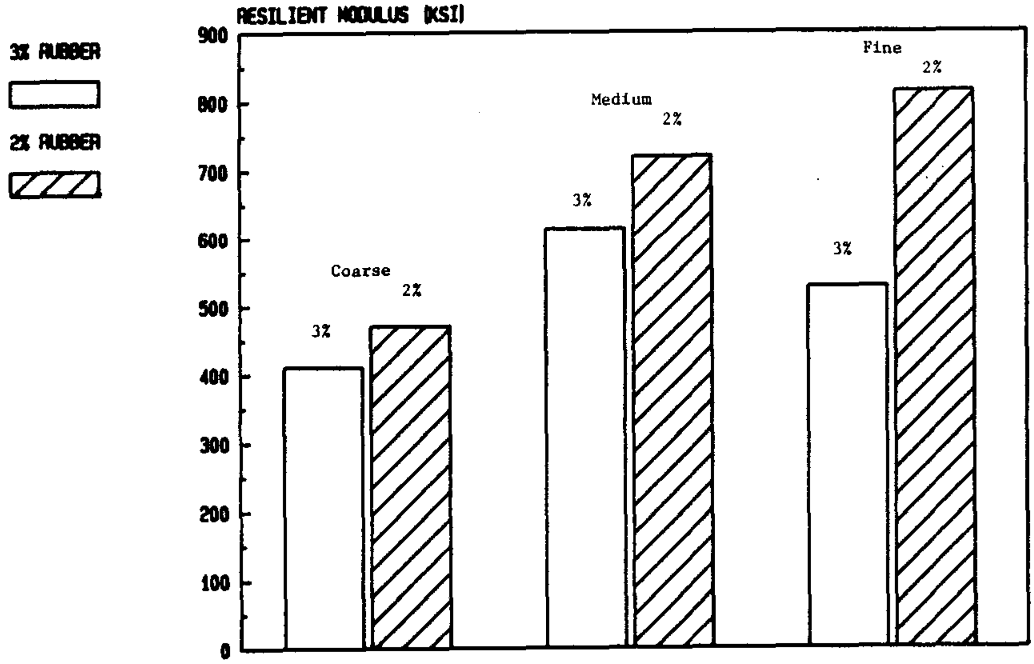


Figure 4.15. Effect of Rubber Content on Resilient Modulus at +10°C (Gap-Graded Aggregate).

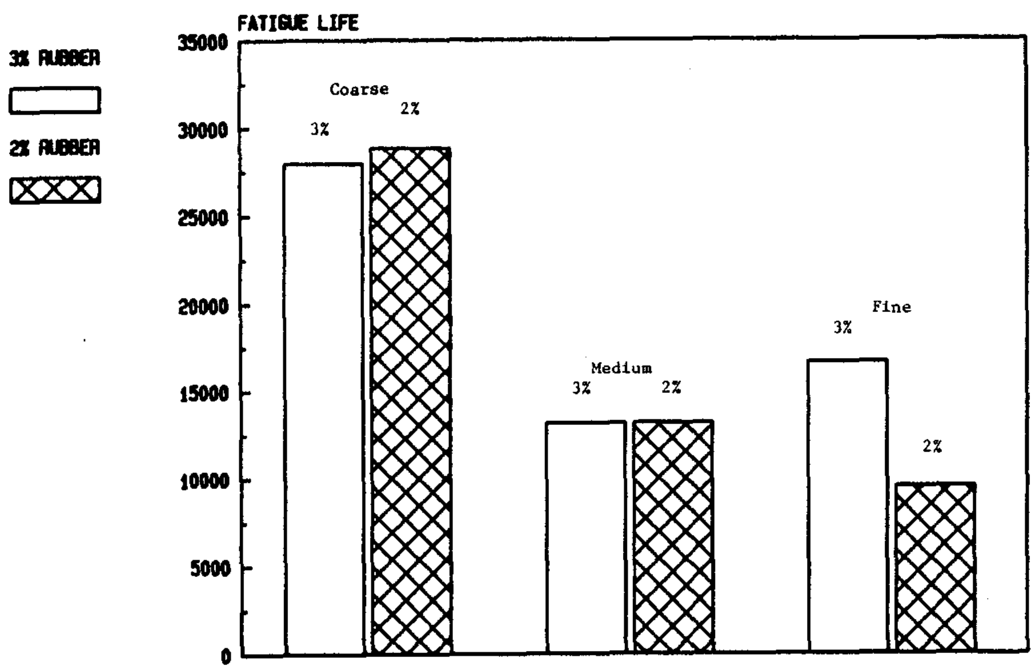


Figure 4.16. Effect of Rubber Content on Fatigue Life at +10°C (Gap-Graded Aggregate).

4.2.1.4 <u>Effects of Mixing Temperature (375°F vs. 425°F)</u>. The effects of mixing temperature on resilient modulus and fatigue life is shown in Figures 4.17 and 4.18. There were no significant differences in resilient modulus for the two temperatures, but in some cases, the fatigue lives for samples with 425°F mixing temperature were higher than the samples with 375°F mixing temperature. This may be due to the type of fatigue failure. The gap- and dense-graded materials, which had no cure or a surcharge application, failed by fracturing the sample. The gap-graded material, which had a surcharge application or was cured, failed by plastic deformation.

4.2.1.5 <u>Effect of Cure Time (0 vs. 2 hrs)</u>. To evaluate the effect of cure time, samples were cured in the mold open to air at 375°F and 425°F for 2 hours prior to compaction. The cure time did not have an effect on the modulus (Figure 4.19), but had an effect on fatigue life (Figure 4.20). For example, the fatigue life for samples cured at 425°F decreased by 35%, while the fatigue life for samples cured at 375°F mixing temperature decreased by 15%. These are shown in Figures 4.19 and 4.20. The results do not compare with those of Alaska DOT and PF on cores with additional 2% fine rubber and cured 45 min at +400°F in closed containers. This extra rubber, plus extended cure time, increased fatigue life.

4.2.1.6 <u>Effects of Surcharge (0 vs. 5 lbs)</u>. The effect of surcharge on resilient modulus and fatigue life is shown in Figures 4.21 and 4.22. The five-pound surcharge had little effect on modulus, but a significant effect on fatigue life with gap-graded aggregate, and a slight effect on the fatigue life for dense-graded aggregate.

4.2.1.7 <u>Effect of Air Voids (2% vs. 4%)</u>. The resilient modulus slightly decreased when the air void content increased from 2% to 4% for the gap-graded mix (Figure 4.23). However, the modulus of the dense-graded mix was reduced by 50% when the air void content was increased. The difference in sensitivity to air voids between gap-graded (9.3%) and dense-graded (7.5%) mixes can be attributed to asphalt content. The increase in asphalt content for a gap-graded mix reduces the modulus even at a low air void content. Therefore, the modulus is showing a dependency on asphalt content and its interaction in the "abnormal" aggregate gaps.

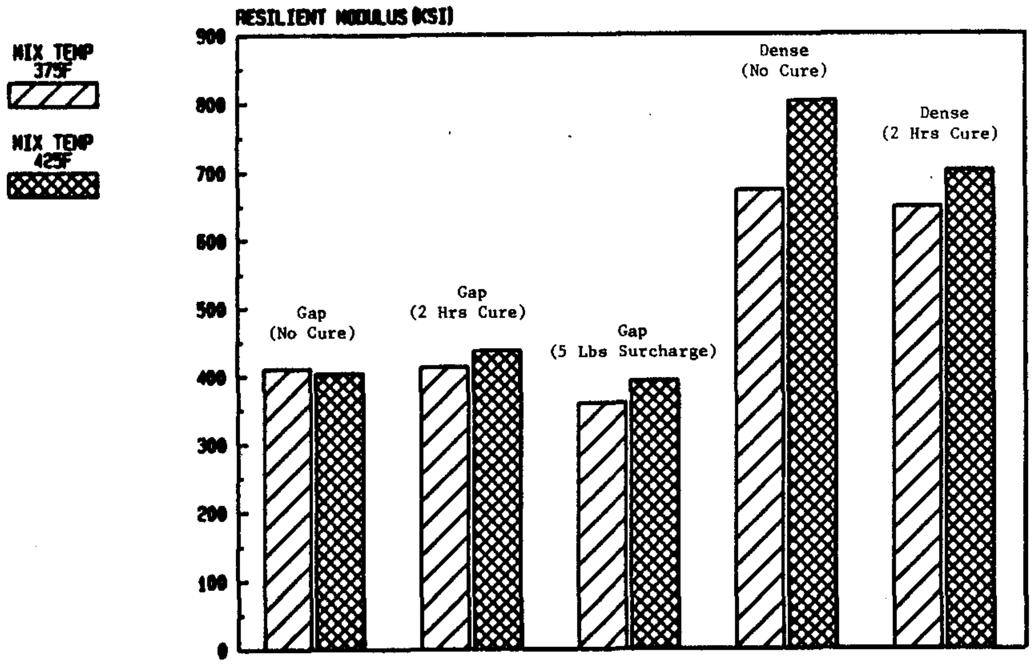


Figure 4.17. Effect of Mixing Temperature on Resilient Modulus at +10°C (3% Rubber 80/20 Blend).

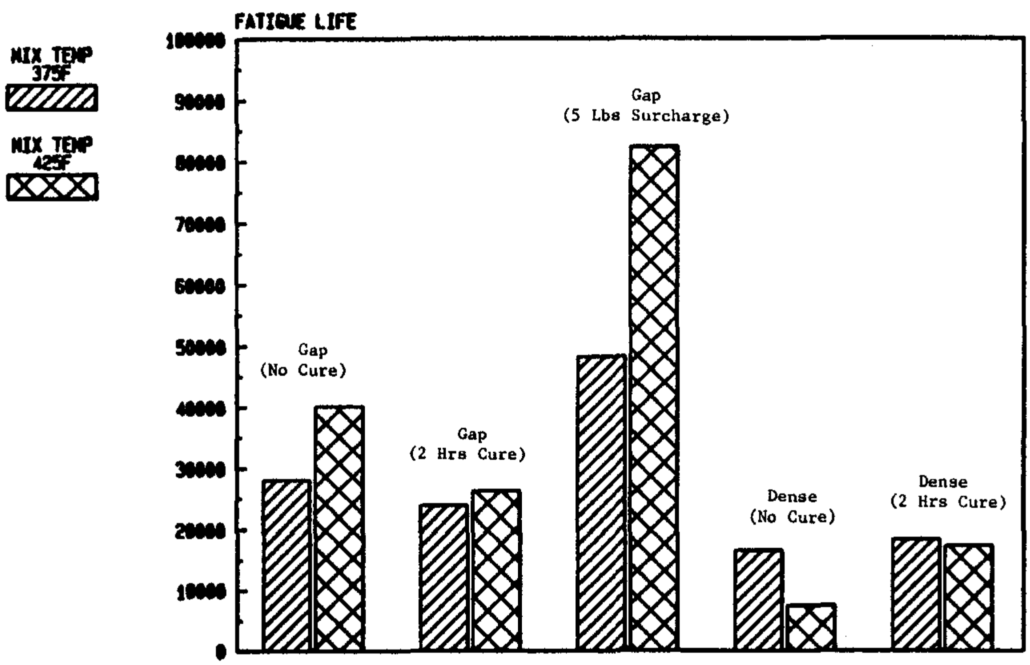


Figure 4.18. Effect of Mixing Temperature on Fatigue Life at +10°C (3% Rubber 80/20 Blend).

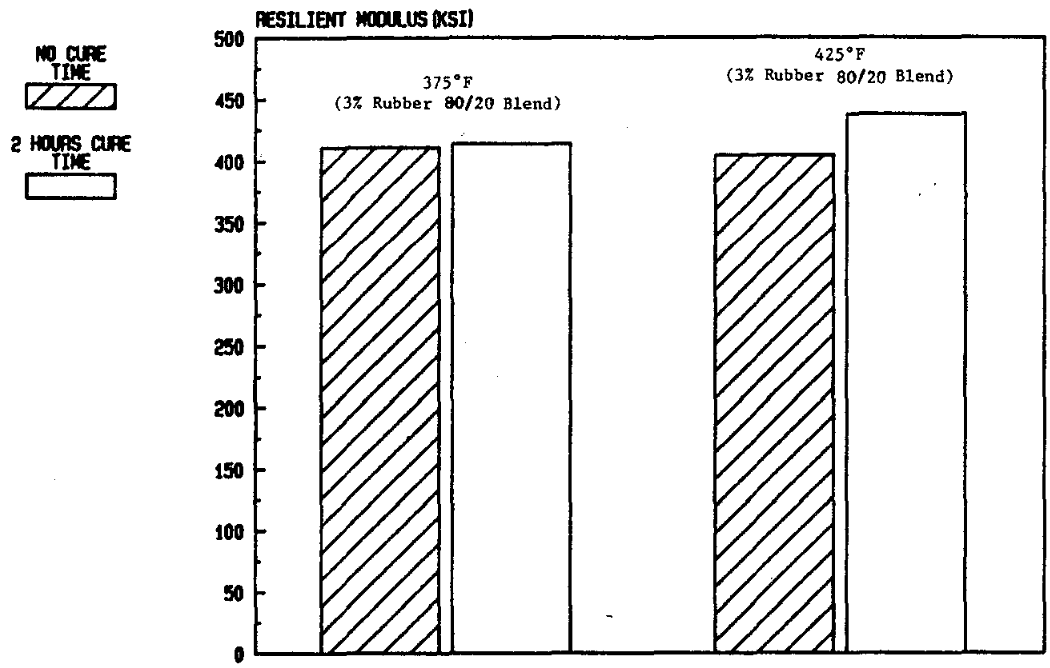


Figure 4.19. Effect of Cure Time at 375°F and 425°F With Gap-Graded Aggregate at +10°C.

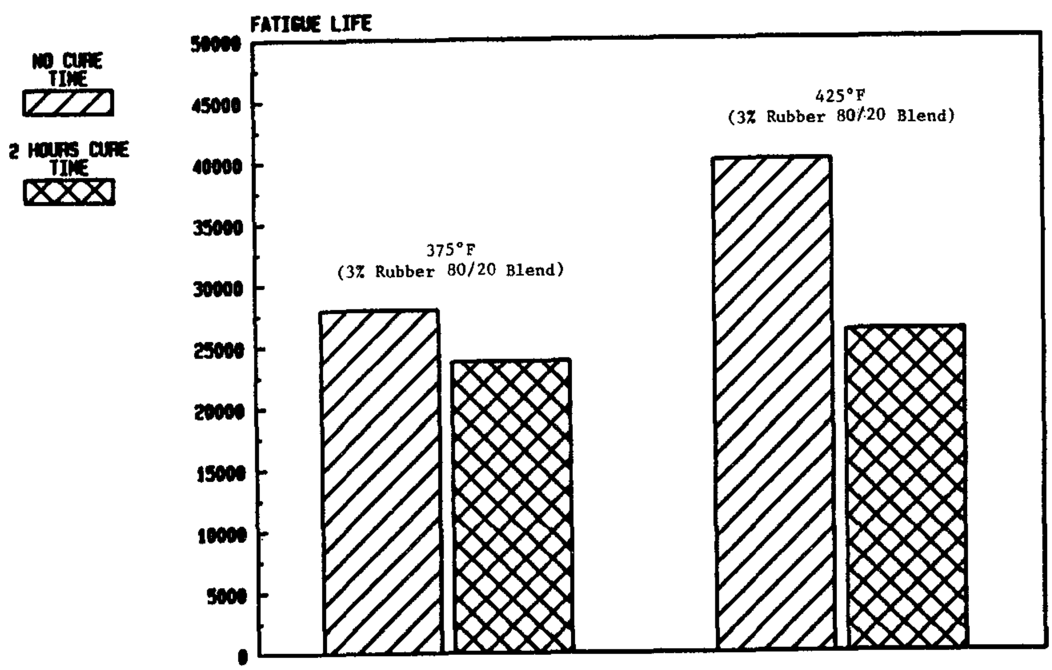


Figure 4.20. Effect of Cure Time at 375°F and 425°F With Gap-Graded Aggregate at +10°C.

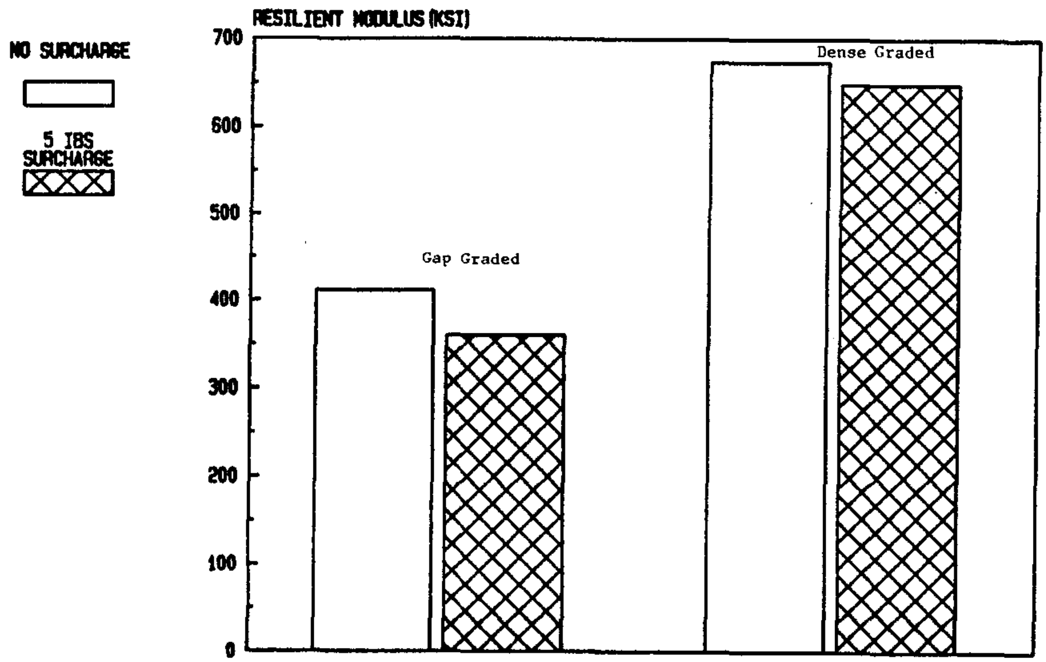


Figure 4.21. Effect of Surcharge on Resilient Modulus at +10°C (3% Rubber 80/20 Blend).

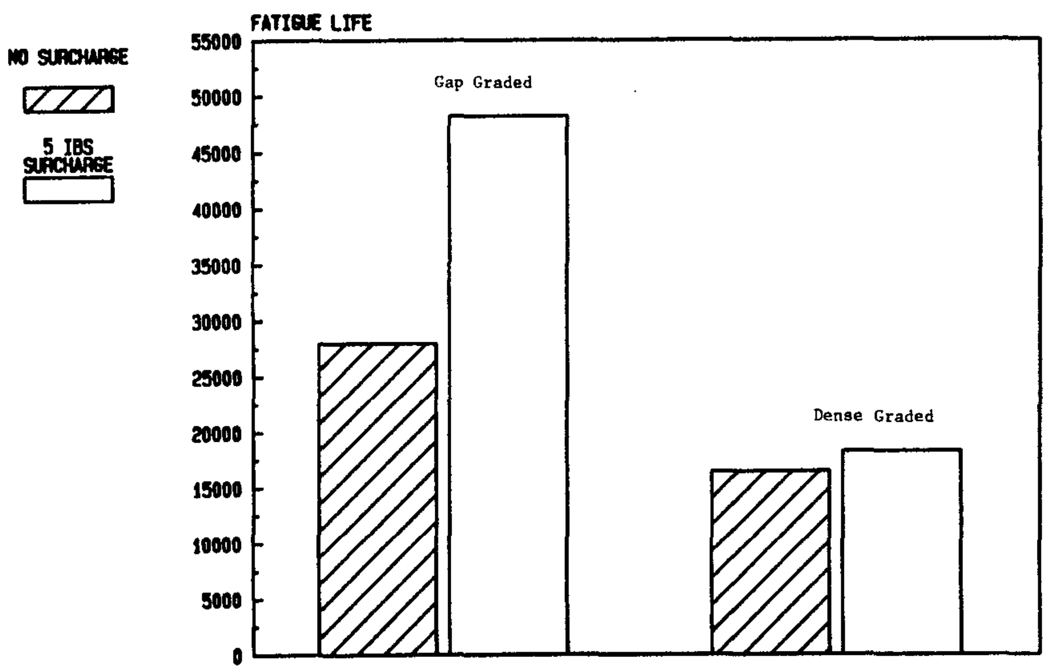


Figure 4.22. Effect of Surcharge on Fatigue Life at +10°C (3% Rubber 80/20 Blend).

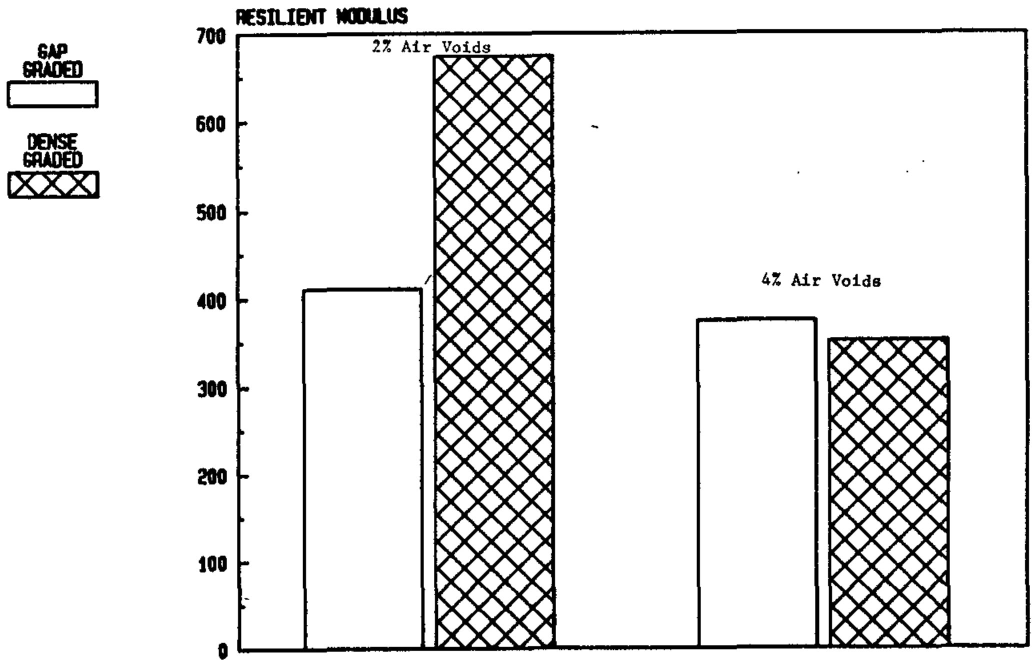


Figure 4.23. Effect of Air Voids on Resilient Modulus at +10°C (3% Rubber 80/20 Blend).

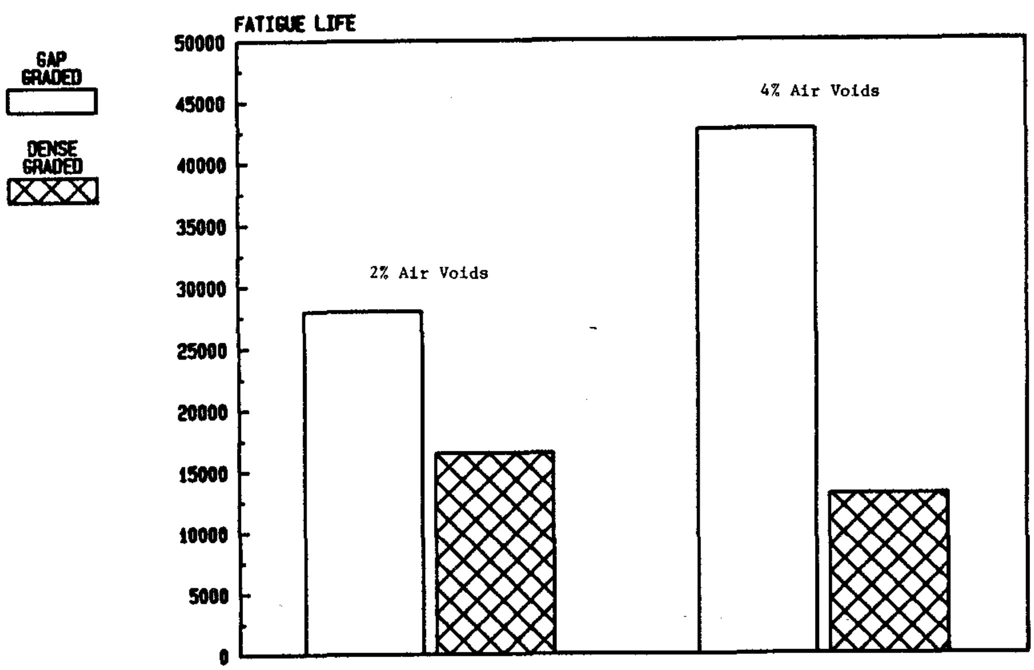


Figure 4.24. Effect of Air Voids on Fatigue Life at +10°C (3% Rubber 80/20 Blend).

The fatigue life of the dense-graded mix reduced with an increase in air voids (Figure 4.24). This behavior is similar to that of conventional dense-graded mixes. However, the fatigue life for the gap-graded rubber mix increased with an increase in air voids. This is contrary to the conventional relationship between air voids and fatigue life. Therefore, selection of the optimum asphalt content by using air voids as the sole criteria, may not produce the optimum mix properties in rubber mixes. The mode of failure may be another reason for these contrary results. The mode of failure for all of the gap-graded specimens at 2% air void were by brittle fracture. The specimens at 4% air void were failed by plastic deformation. Further study appears to be required to evaluate the effects of air voids.

4.2.1.8 Comparison of Rubber-Modified vs. Conventional Mix at +10°C. The resilient modulus of conventional asphalt mix was approximately twice the value obtained for dense-graded rubber mix and almost three times the value for gap-graded rubber mix (Figure 4.25). This relates directly to the 9.3% asphalt used in gap-graded rubber mix versus 7.5% in dense-graded rubber and 5.5% in conventional mix.

The fatigue life for each mix type corresponds with the modulus values (Figure 4.26). The higher the modulus, the lower the fatigue life.

4.2.2 Fatigue Results at +10°C

Fatigue curves were prepared for five different mix combinations--samples with identification symbols A, C, M, N, and T. The fatigue life for each combination was evaluated at three different strain levels. At least three specimens were tested at each level of tensile strain.

A linear relationship exists between the logarithm of the applied tensile strain and the logarithm of fatigue life, which can be expressed in the form (37):

$$N_f = a\ (\varepsilon_t)^{-b} \qquad (4.1)$$

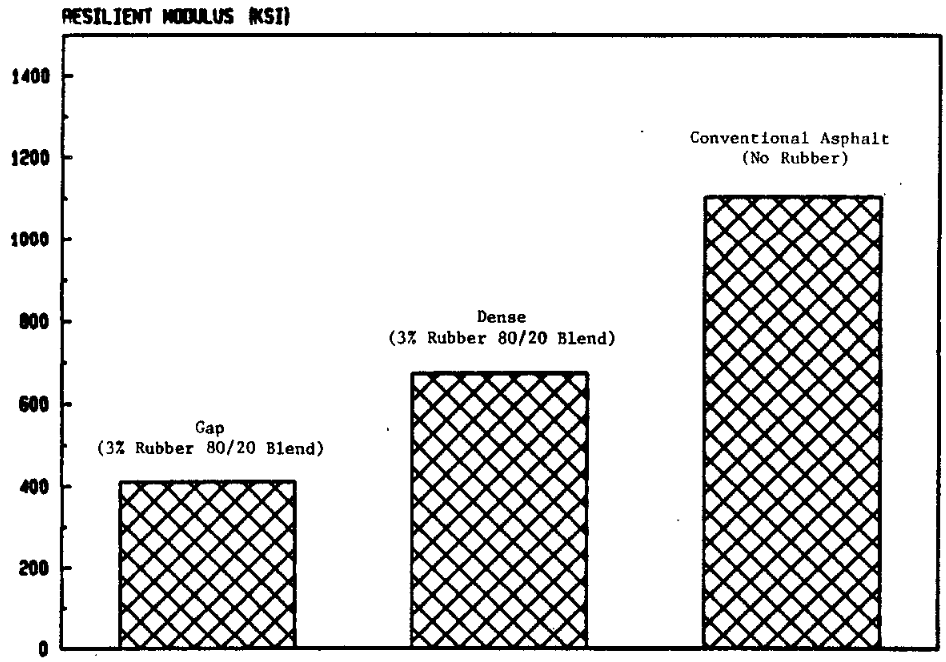


Figure 4.25. Effect of Rubber Content and Aggregate Gradation on Resilient Modulus at +10°C.

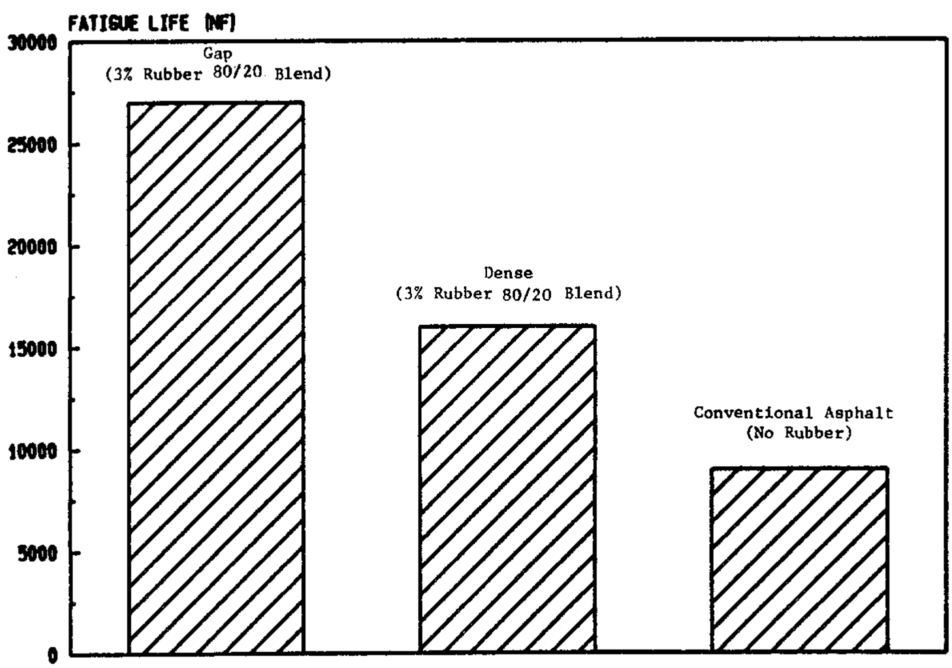


Figure 4.26. Effect of Rubber Content and Aggregate Gradation on Fatigue Life at +10°C.

where

ε_t = initial tensile strain, in./in.

a = antilog of the intercept of the logarithmic relationship

b = slope of the logarithmic relationship between fatigue life and initial strain.

Values of "a" and "b" are affected by mix type, asphalt content, rubber gradation, rubber content, and aggregate gradation. A low value of "a" usually indicates a low fatigue life, assuming the fatigue curves are parallel to one another.

The results of the fatigue tests are summarized in Table 4.15. The averaged logarithm fatigue life values versus logarithm of strains are shown as a linear relationship in Figure 4.27. The conventional mix has the lowest "a" value, while the rubberized asphalt with surcharge has the highest "a" value. The fatigue life equations are shown in Figure 4.27 together with R^2, or coefficient of determination. R^2 values tend to be greater than 0.95. This is attributed to the precise testing techniques and limited number of strain levels (three strain levels) at which each mix combination was tested.

If the performance of the pavement is based on fatigue, Figure 4.27 shows the rubber-modified mixes to be superior to conventional asphalt mixes.

4.3 Mix Properties at -6°C

4.3.1 Resilient Modulus and Fatigue

Twenty different mix combinations were tested at 100 microstrain in a -6°C environmental chamber for resilient modulus and fatigue (Table 4.13). For all dynamic tests, samples were subjected to a constant load, applied at 60 cycles per minute, with a load duration of 0.1 s. A 50-pound seating load was applied to all samples.

At least three samples for each combination were tested. The results of all tested samples are presented in Appendix C. The results of resilient modulus and fatigue for 20 different mixes are summarized in Table 4.16.

The effects of aggregate gradation, rubber gradation, rubber content, mixing temperature, surcharge, cure time, and air voids are discussed in the following sections.

Table 4.15. Summary of Fatigue Lifes at Different Strain Levels (+10° C).

Sample Identification	Fatigue Life Micro-strain Level 85	 100	 150
A	44,073	27,993	5,904
C	62,036	48,240	10,490
M	20,985	9,536	3,550
N	32,454	16,506	6,247
T	12,997	9,323	2,826

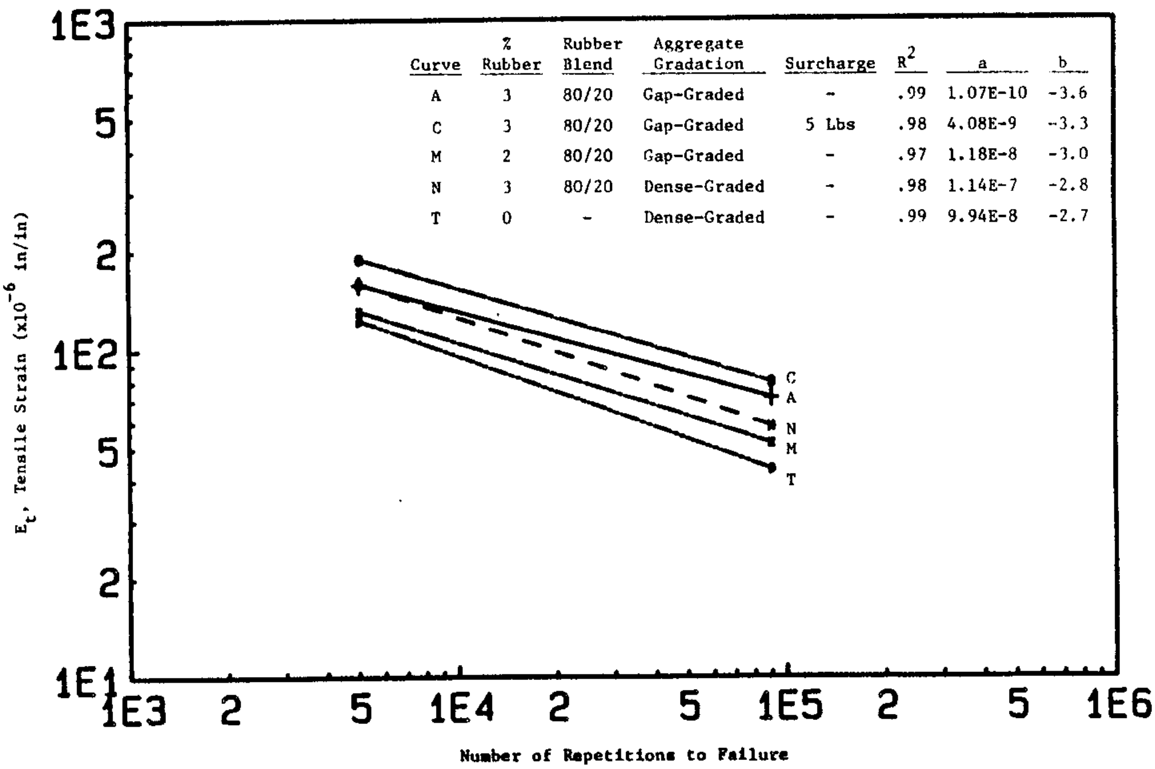


Figure 4.27. Laboratory Fatigue Curves at +10°C.

Table 4.16. Summary of Resilient Modulus and Fatigue Life.
(Test Temperature: -6° C; Strain Level: 100 Microstrain)

Mix ID	Number of Samples Used in Calculations	Air Voids (%)		MR (ksi)		N_f	
		$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ
A*	3	2.17	0.06	1,872	27	29,237	3,629
B	3	2.19	0.12	2,044	128	29,736	2,991
C	3	2.18	0.08	2,084	83	25,070	7,600
D	3	2.14	0.08	2,165	18	22,515	1,504
E	3	2.09	0.03	2,149	52	24,174	1,996
F	4	2.13	0.12	2,047	58	20,768	3,887
G	3	4.08	0.27	1,713	194	46,751	20,326
H	3	2.05	0.08	2,356	175	47,990	256
I	4	2.24	0.09	2,149	74	41,194	5,471
J	3	4.02	0.17	1,787	113	43,271	4,617
K	3	2.12	0.07	2,351	50	89,062	7,012
L	3	2.22	0.05	2,488	127	75,325	4,920
M	2	2.33	0.16	2,588	34	41,788	2,075
N*	3	2.22	0.19	2,414	212	118,186	15,670
O	3	2.15	0.24	2,592	161	97,032	18,825
P	3	2.21	0.09	2,225	100	84,153	5,007
Q	3	2.12	0.05	2,116	94	93,651	4,198
R	3	2.02	0.11	1,939	133	81,141	8,354
S	3	4.50	0.23	1,443	177	137,682	24,996
T*	3	2.25	0.13	3,163	133	15,536	2,562

*Specimens used to establish fatigue curves.

4.3.1.1 Effect of Aggregate Gradation (Gap vs. Dense). The effects of aggregate gradation on resilient modulus and fatigue life for three different mixing conditions are shown in Figures 4.28 and 4.29. These figures show that the mixture with gap-graded aggregate in all three mixing conditions have lower resilient modulus and lower fatigue life than the mixtures with dense-graded aggregate.

At - 6°C, the effect of aggregate on fatigue life was reversed from the results at +10°C. The reason for this behavior is not clear. A possible explanation is that there were differences in the modes of failure between the dense-graded and gap-graded mixtures. At both temperatures (+10°C and -6°C) most of the samples with gap-graded aggregate failed by deformation failures. However, the samples with dense-graded aggregate at +10°C failed by breakage bond between rubber, asphalt, and aggregate. At -6°C, most of the samples with dense-graded aggregate failed by fatigue cracking (aggregate fracture) in a uniform tensile plane.

4.3.1.2 Effect of Rubber Gradation (Fine, Medium, and Coarse). The resilient modulus and fatigue life for three different rubber gradations (fine, medium, and coarse) were compared. The mixture with coarse rubber has the lowest modulus and highest fatigue life. This is shown in Figures 4.30 and 4.31. The results at +10°C have the same relationship (coarse rubber has the lowest modulus and highest fatigue life) as those found at -6°C.

4.3.1.3 Effect of Rubber Content (2% vs. 3%). The effect of rubber content on resilient modulus and fatigue for gap-graded mixes is shown in Figures 4.32 and 4.33. The samples with 3% rubber generally have lower resilient modulus than the samples with 2% rubber (Figure 4.32). The rubber content reduction (3% to 2%) increased the fatigue life by 2 to 3 times. These results compare directly with those found at +10°C.

4.3.1.4 Effect of Mixing Temperature (375°F vs. 425°F). The effect of mixing temperature on resilient modulus and fatigue life are shown in Figures 4.34 and 4.35. There were no significant differences in resilient modulus for two mixing temperatures. The fatigue lives for samples with 425°F mixing temperature in all cases were lower than the samples with 375°F mixing. The

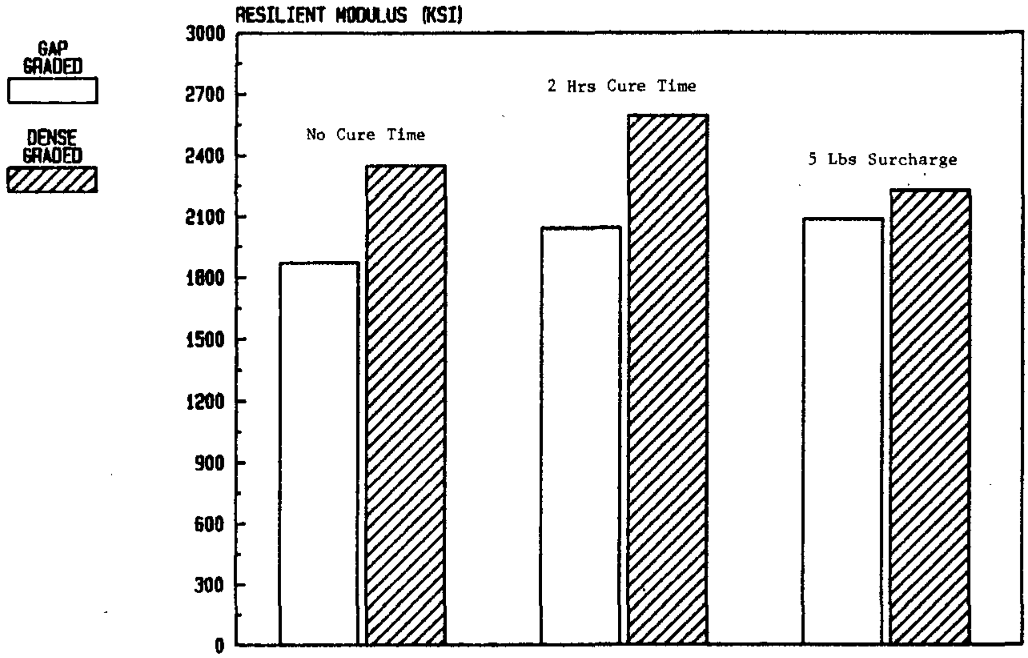


Figure 4.28. Effect of Aggregate Gradation, Cure Time, and Surcharge on Resilient Modulus at -6°C (3% Rubber 80/20 Blend).

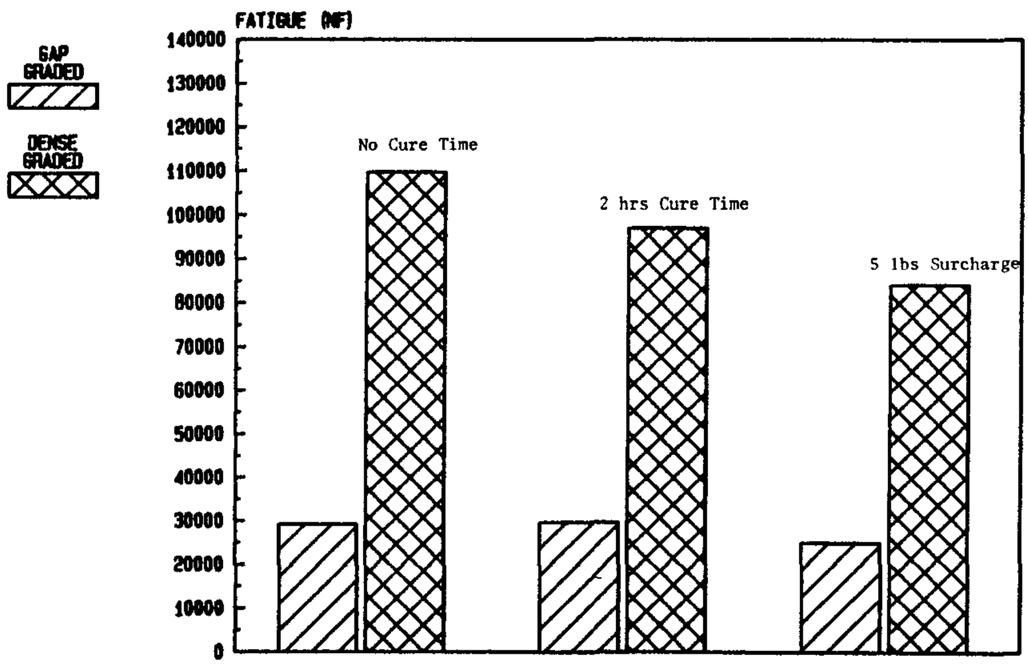


Figure 4.29. Effect of Aggregate Gradation, Cure Time, and Surcharge on Fatigue Life at -6°C (3% Rubber 80/20 Blend).

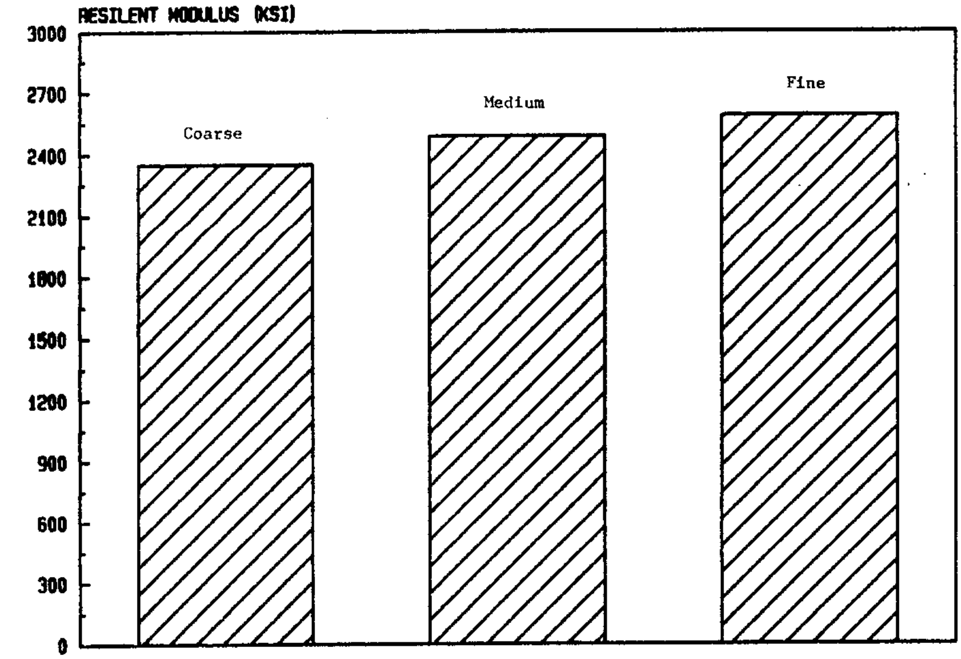


Figure 4.30. Effect of Rubber Gradations on Resilient Modulus at -6°C (Gap-Graded Aggregate, 2% Rubber).

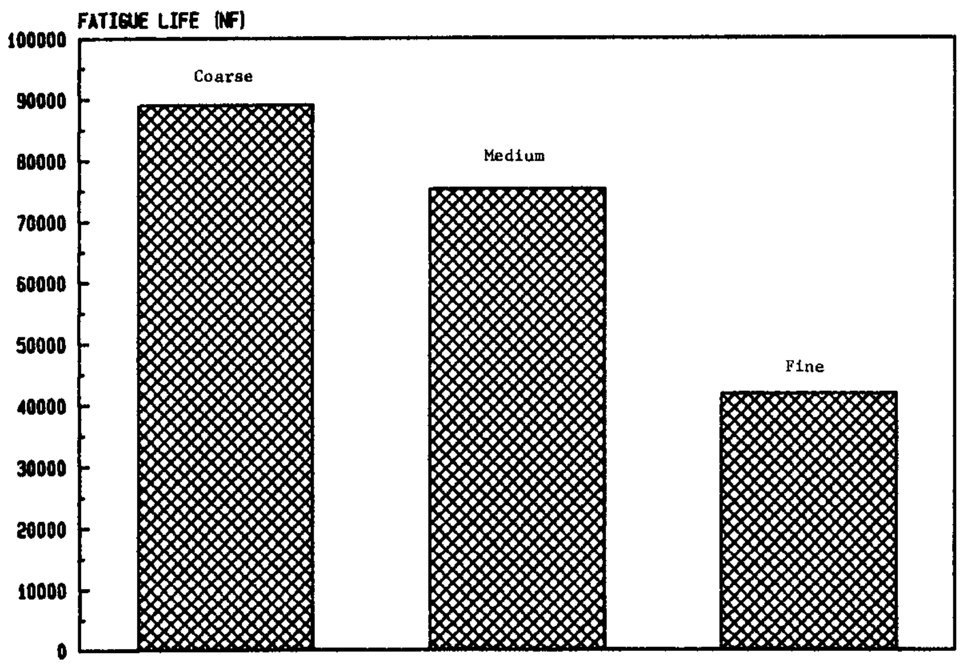


Figure 4.31. Effect of Rubber Gradations on Fatigue Life at -6°C (Gap-Graded Aggregate, 2% Rubber).

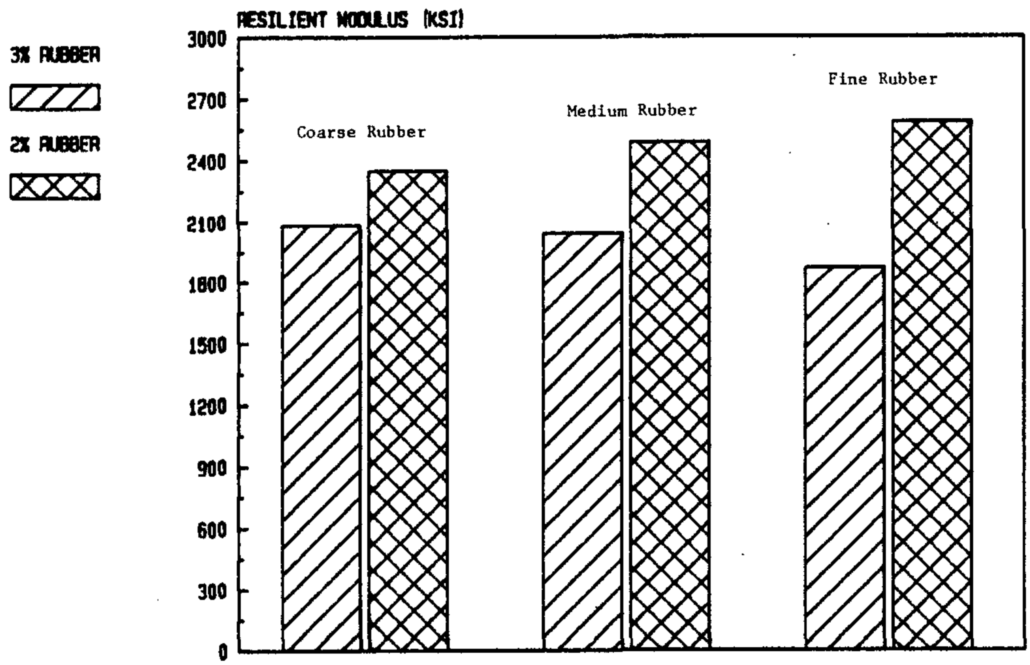


Figure 4.32. Effect of Rubber Content and Grading on Resilient Modulus at -6°C (Mixes with Gap-Graded Aggregate).

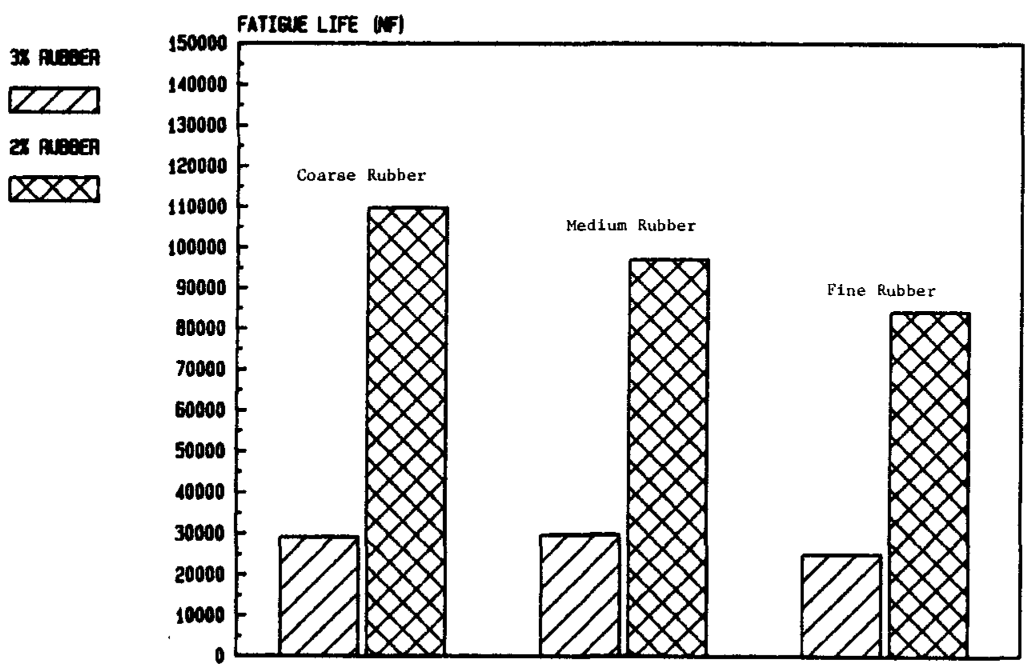


Figure 4.33. Effect of Rubber Content and Grading on Fatigue Life at -6°C (Mixes with Gap-Graded Aggregate).

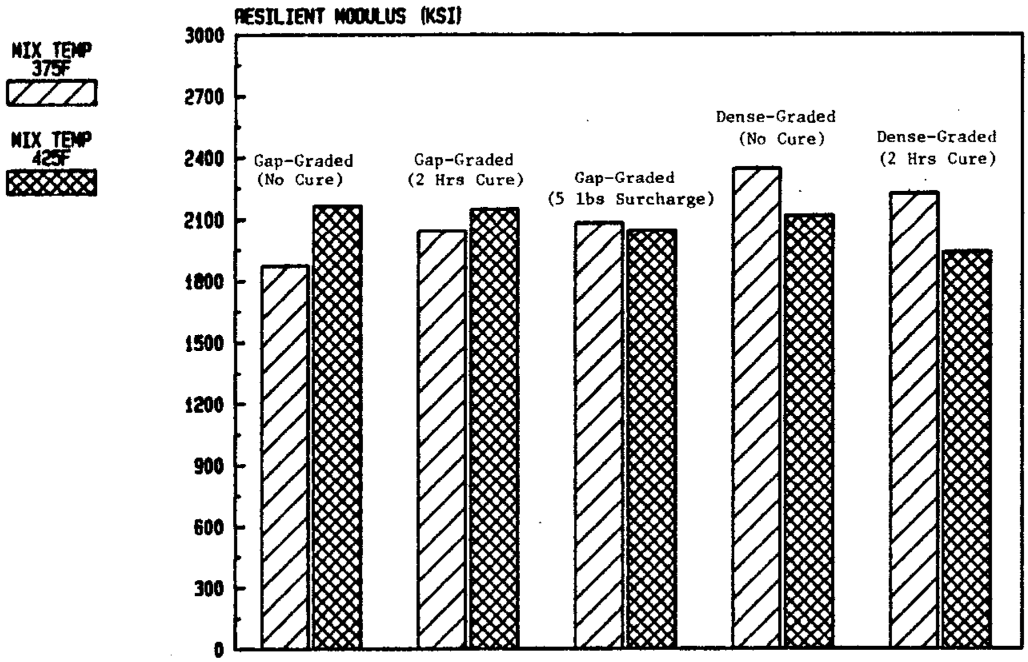


Figure 4.34. Effect of Mixing Temperature on Resilient Modulus at -6°C (3% Rubber 80/20 Blend).

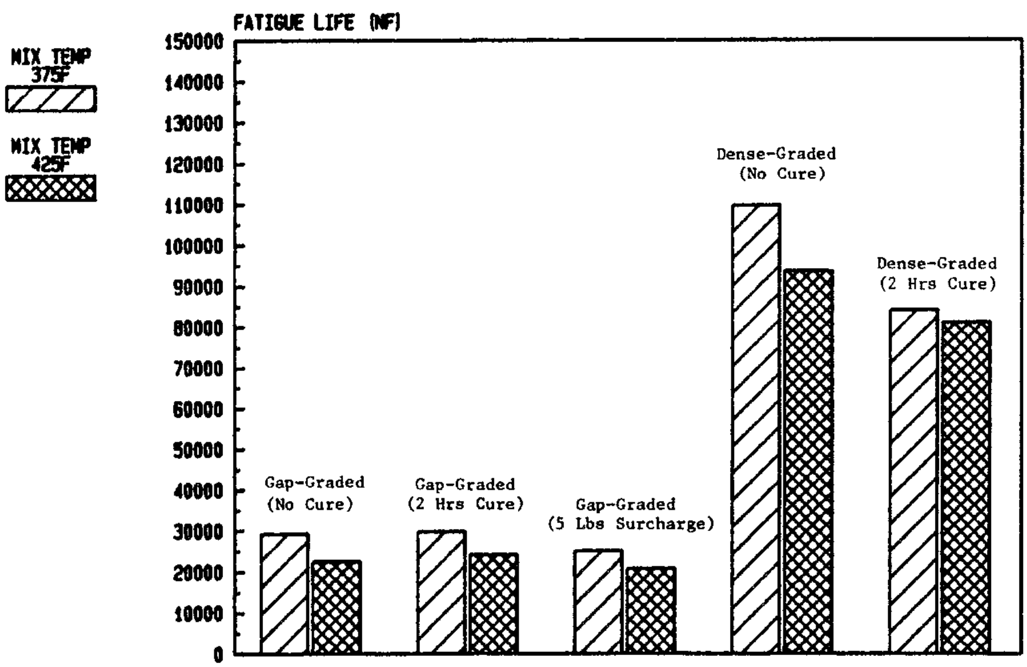


Figure 4.35. Effect of Mixing Temperature on Fatigue Life at -6°C (3% Rubber 80/20 Blend).

results at +10° C have the same relationship (lower fatigue life at higher mixing temperature) as those found at -6°C. This is probably due to excessive oxidation of the asphalt cement at the higher temperatures.

4.3.1.5 Effect of Cure Time (0 vs. 2 hrs.). To evaluate the effect of cure time, samples were placed in the mold and cured in 375°F and 425°F ovens for 2 hours prior to compaction. The effect of cure time on resilient modulus and fatigue life for gap-graded and dense-graded aggregate is shown in Figures 4.36 and 4.37. These figures show that the effect of cure time on resilient modulus and fatigue is not significant. This is contrary to the results at +10°C. In most cases (gap-graded aggregate, coarse rubber), the cure time increased modulus and fatigue life at -6° C very slightly.

4.3.1.6 Effect of Surcharge (0 vs. 5 lbs.). The effect of surcharge on resilient modulus and fatigue life is shown in Figures 4.38 and 4.39. These figures show that the effect of surcharge on resilient modulus is very slight, but the samples with surcharge have a lower fatigue life than the samples with no surcharge. These results are contrary with those found at +10°C. This is due to a change of behavior of rubber at low temperature. Generally rubber lost its elasticity characteristic at low temperatures.

4.3.1.7 Effect of Air Voids (2% vs. 4%). The resilient modulus slightly decreased when the air void content increased from 2% to 4% for the gap-graded aggregate mix (Figure 4.40). However, the modulus of the dense-graded aggregate mix was reduced by 40% when the air void content was increased. The difference in sensitivity to air voids between gap-graded aggregate (9.3%) and dense-graded aggregate (7.5%) mixes can be attributed to asphalt content.

The fatigue life for both dense-graded and gap-graded mixes increased with an increase in air voids (Figure 4.41). This is contrary to the conventional relationship between air voids and fatigue life. The main reason for this inconsistent behavior is the mode of fatigue failure of the specimens. All of the specimens with 4% air voids failed by plastic deformation, while the specimens with 2% air voids failed by fracturing the sample.

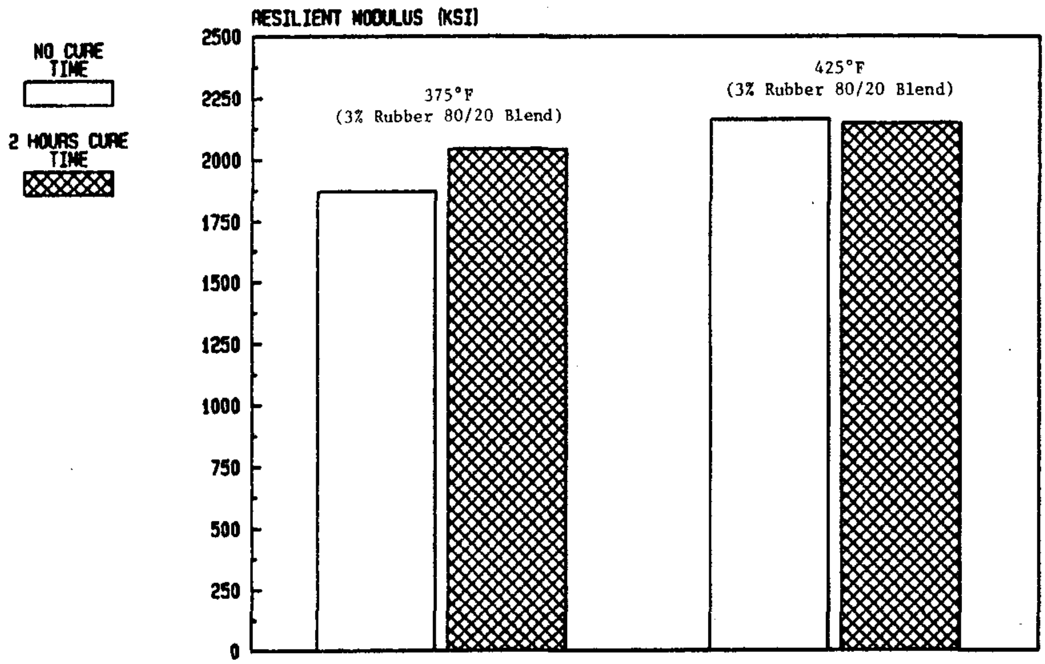


Figure 4.36. Effect of Cure Time at 375°F and 425°F With Gap-Graded Aggregate at -6°C.

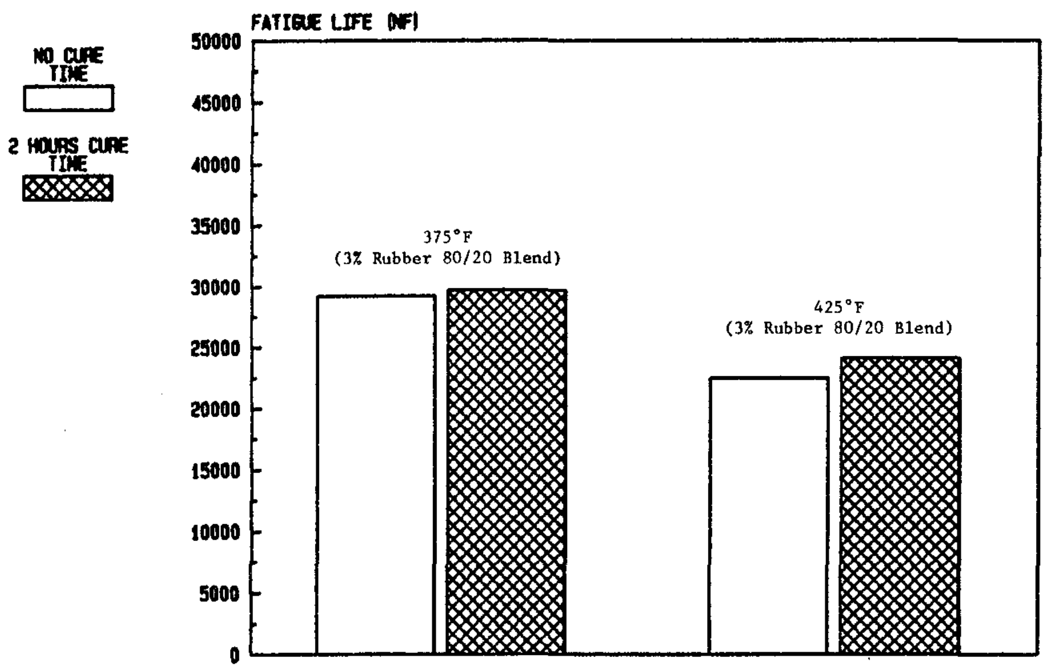


Figure 4.37. Effect of Cure Time at 375°F and 425°F With Gap-Graded Aggregate at -6°C.

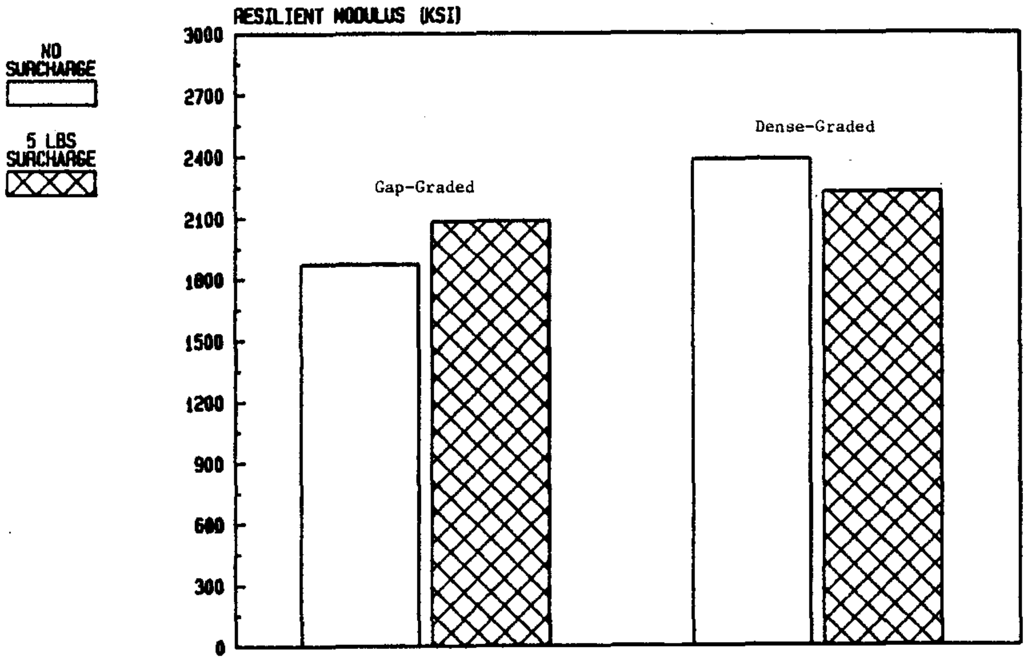


Figure 4.38. Effect of Surcharge on Resilient Modulus at -6°C (3% Rubber 80/20 Blend).

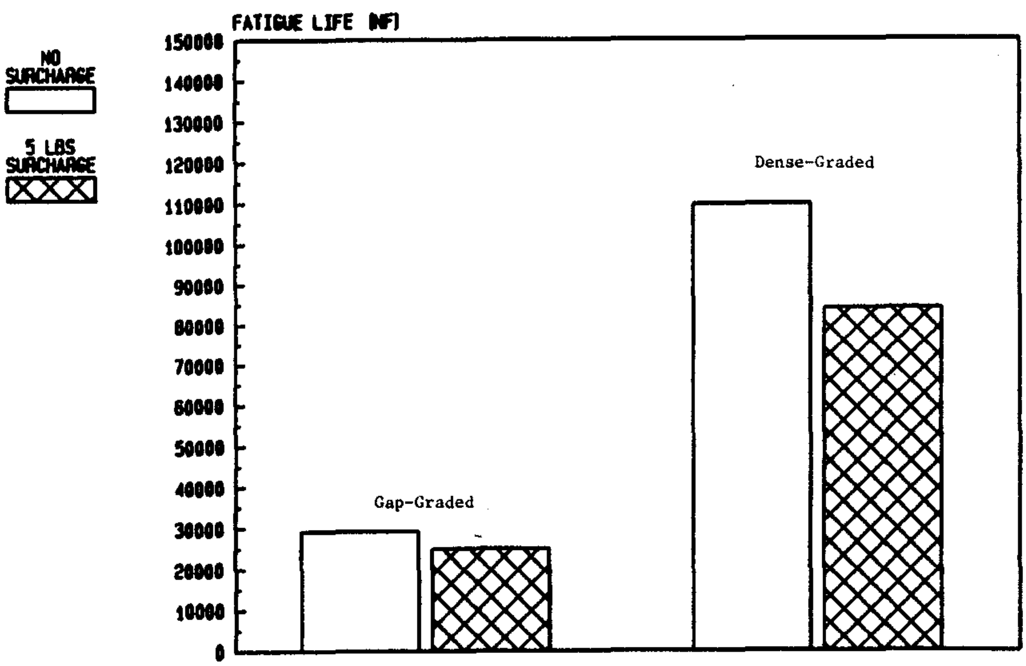


Figure 4.39. Effect of Surcharge on Fatigue Life at -6°C (3% Rubber 80/20 Blend).

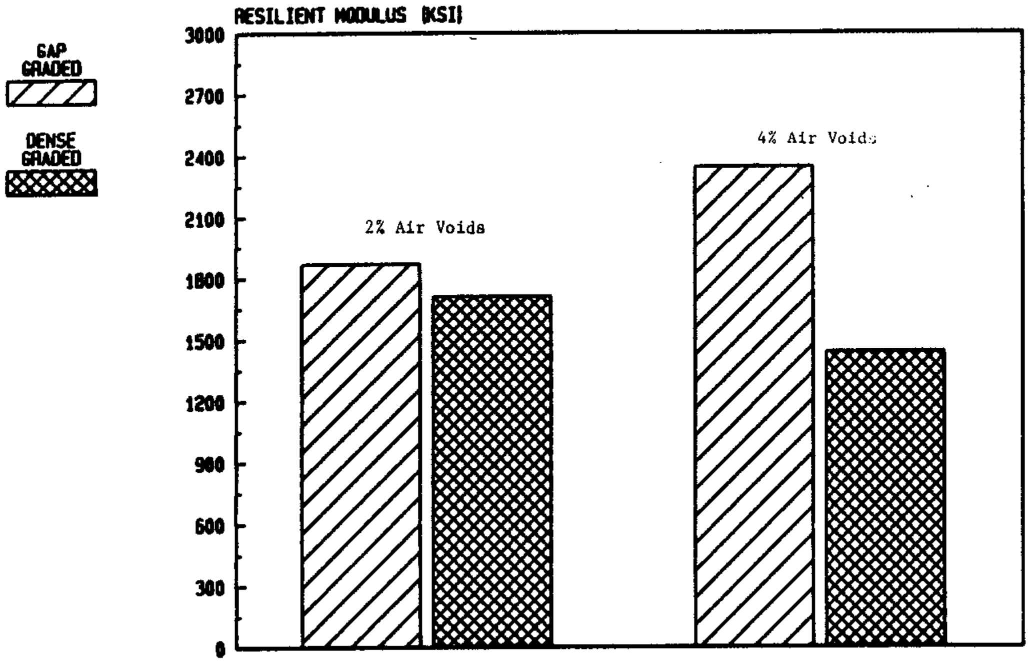


Figure 4.40. Effect of Air Voids on Resilient Modulus at -6°C (3% Rubber 80/20 Blend).

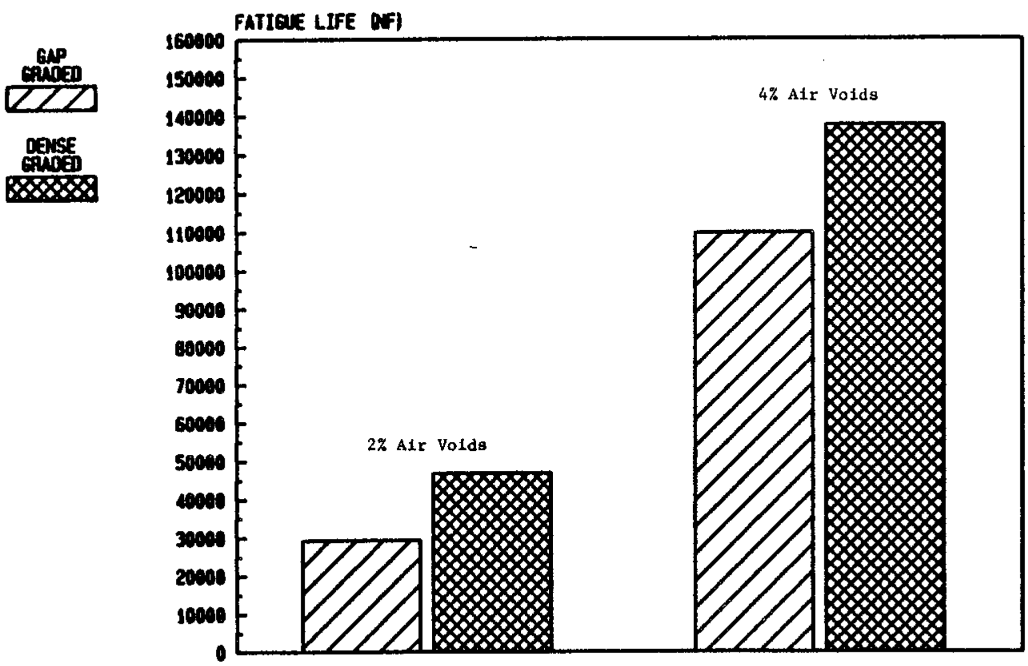


Figure 4.41. Effect of Air Voids on Fatigue Life at -6°C (3% Rubber 80/20 Blend).

4.3.1.8 Comparison of Rubber-Modified vs. Conventional Mix. The resilient modulus of conventional asphalt mix was approximately 40% higher than gap-graded rubber mix and 25% higher than dense-graded rubber mix (Figure 4.42). This relates directly to 9.3% asphalt used in gap-graded rubber mix versus 7.5% in dense-graded rubber and 5.5% in conventional mix.

The fatigue life of conventional asphalt mix is approximately 600% lower than dense-graded rubber mix and 88% lower than gap-graded rubber mix (Figure 4.43). This confirms the high fatigue characteristics of rubber-modified asphalt mixes. However, the results at -6°C show a difference in the optimum aggregate grading as compared to the mixes tested at +10°C. At -6°C the dense-graded aggregate had the best fatigue life. At +10°C the gap-graded aggregate had the highest fatigue life.

4.3.2 Fatigue Results at -6°C

Fatigue curves were prepared for three different mix combinations--samples with identification symbols A, N, T. The fatigue life for each combination was evaluated at three different strain levels. At least three specimens were tested at each level of tensile strain.

The results of fatigue tests are summarized in Table 4.17. The averaged logarithm fatigue life values versus logarithm of strains are shown as a linear relationship in Figure 4.44.

4.4 Effect of Temperature on Modulus of Rubber Asphalt Mixtures

Twenty different mix combinations were tested at three different temperatures for resilient modulus. The specimen temperatures were controlled by three linear response thermistors as described in Section 3.3.2. Tests for diametral modulus were conducted at 100 microstrain, using a load duration of 0.1 s and a frequency of 1 Hz.

Table 4.18 summarizes the results of resilient modulus at different temperatures for all 20 mix combinations. The effect of temperature on resilient modulus for typical rubberized asphalt mixture are shown in Figures 4.45 and 4.46. The results show that the rubber-modified asphalt modulus has a linear relationship with temperature. As temperature decreases, the modulus increases with a constant slope.

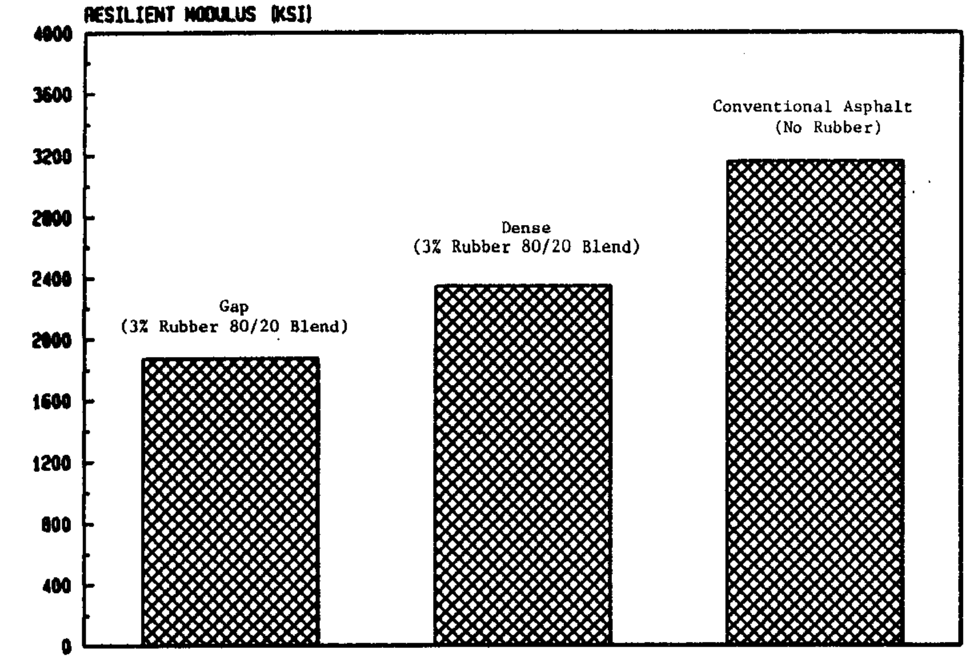


Figure 4.42. Effect of Rubber Content and Aggregate Gradation on Resilient Modulus at -6°C.

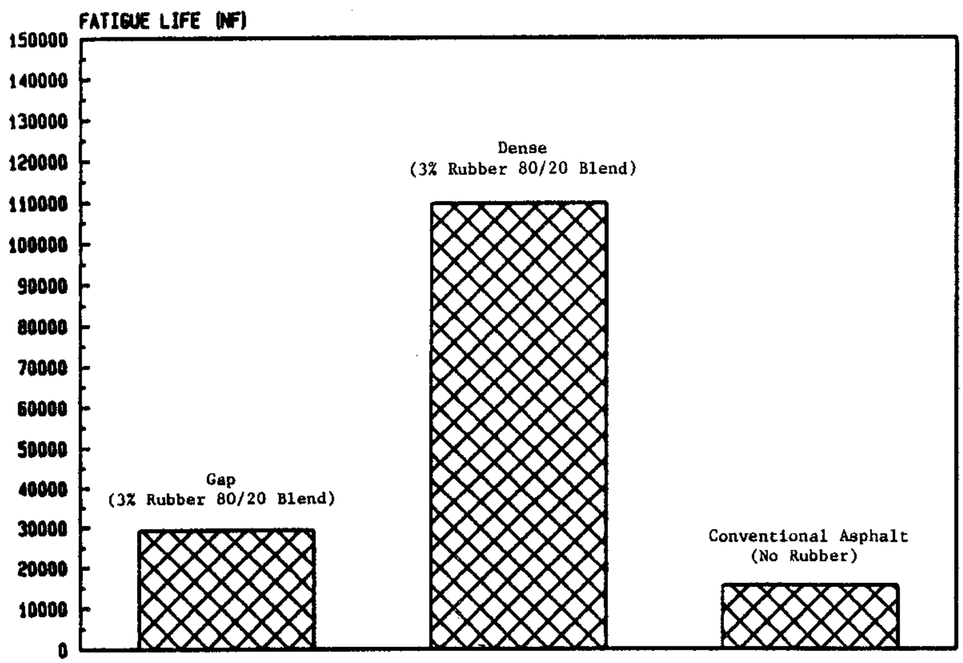


Figure 4.43. Effect of Rubber Content and Aggregate Gradation on Fatigue Life at -6°C.

Table 4.17. Summary of Fatigue Lives at Different Strain Levels (-6°C).

Sample Identification	Fatigue Life: Micro-strain Level 70	100	130
A	68,752	29,237	19,263
N	199,227	118,186	73,262
T	14,250	8,526	2,526

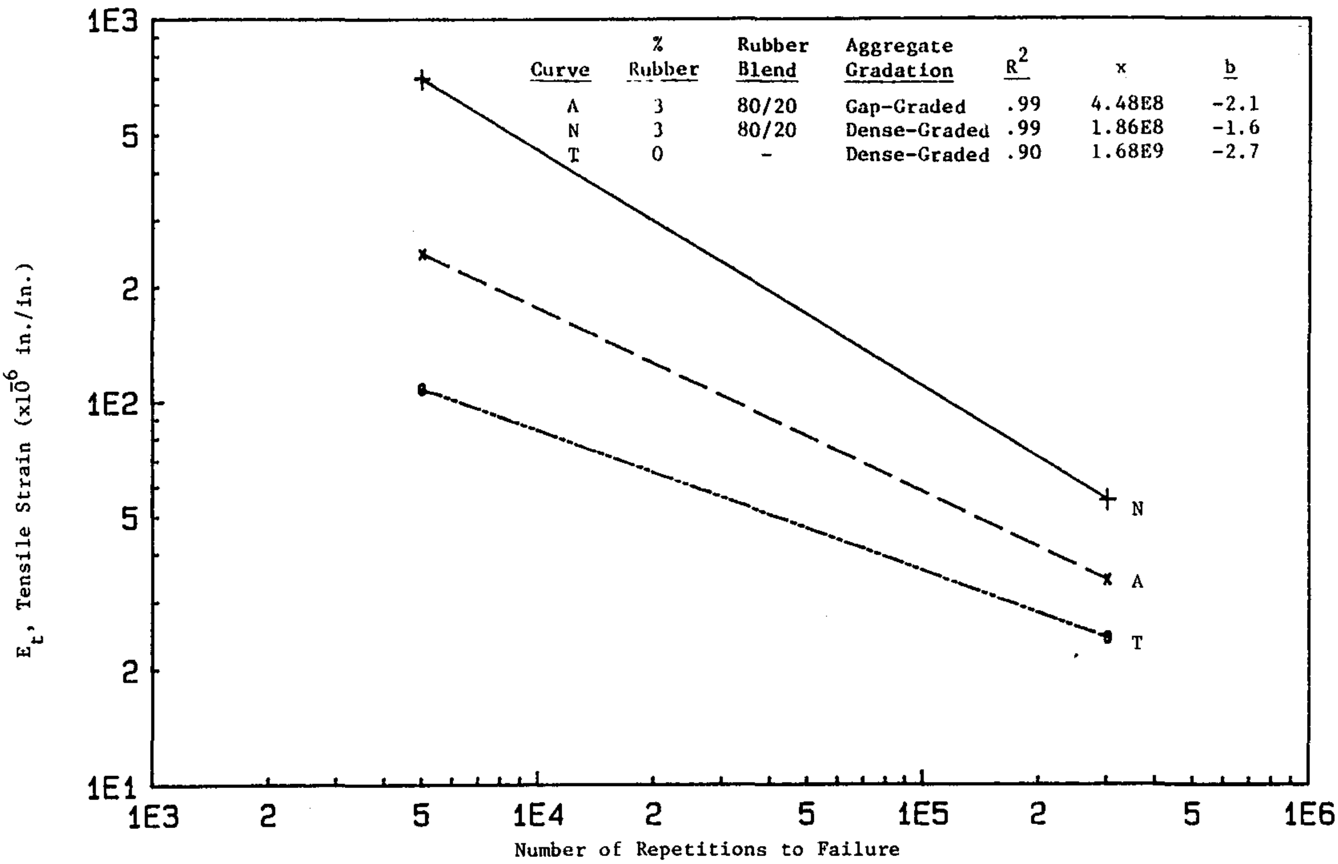


Figure 4.44. Laboratory Fatigue Curves at -6°C.

Table 4.18. Summary of Resilient Modulus at Three Different Temperatures.

Sample ID	Resilient Modulus (ksi)	Temperature (^{o}C)
A	39	24
A	388	10
A	1,842	-7
B	56	24
B	307	10
B	2,191	-7
C	50	24
C	361	10
C	2,000	-7
D	49	23
D	335	10
D	1,809	-7
E	53	23
E	373	10
E	2,157	-7
F	49	23
F	383	10
F	2,049	-7
G	51	22
G	285	11
G	1,747	-7
H	98	22
H	511	13
H	2,301	-7
I	91	22
I	464	12
I	2,049	-7
J	40	24
J	311	10
J	1,657	-7
K	83	24
K	454	10
K	2,583	-7
L	107	24
L	603	10
L	2,616	-7
M	124	22
M	606	12
M	2,613	-7
N	99	23
N	673	10
N	2,651	-7
O	157	23
O	811	10
O	2,503	-6
P	88	24
P	667	10
P	2,111	-6
Q	113	24
Q	811	11
Q	2,027	-6
R	72	23
R	409	10
R	1,947	-6
S	57	22
S	209	13
S	1,610	-6
T	167	22
T	1,146	11
T	3,354	-6

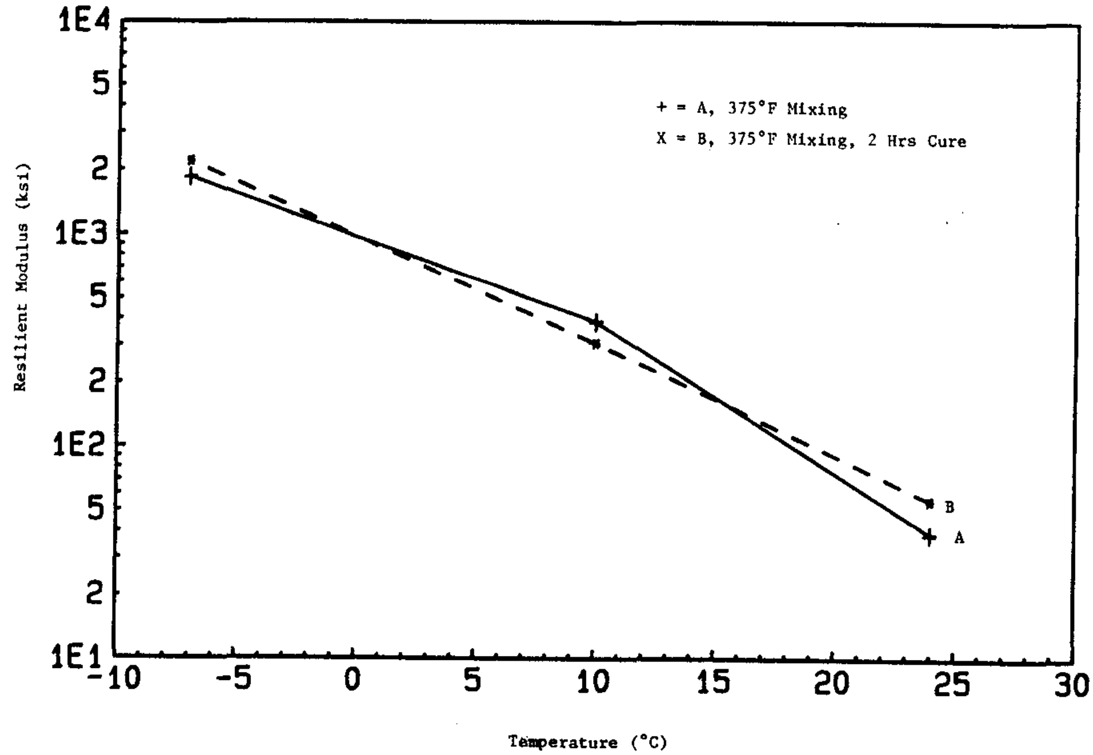


Figure 4.45. Effect of Temperature on Resilient Modulus for Mixes with Gap-Graded Aggregate (3% Rubber 80/20 Blend).

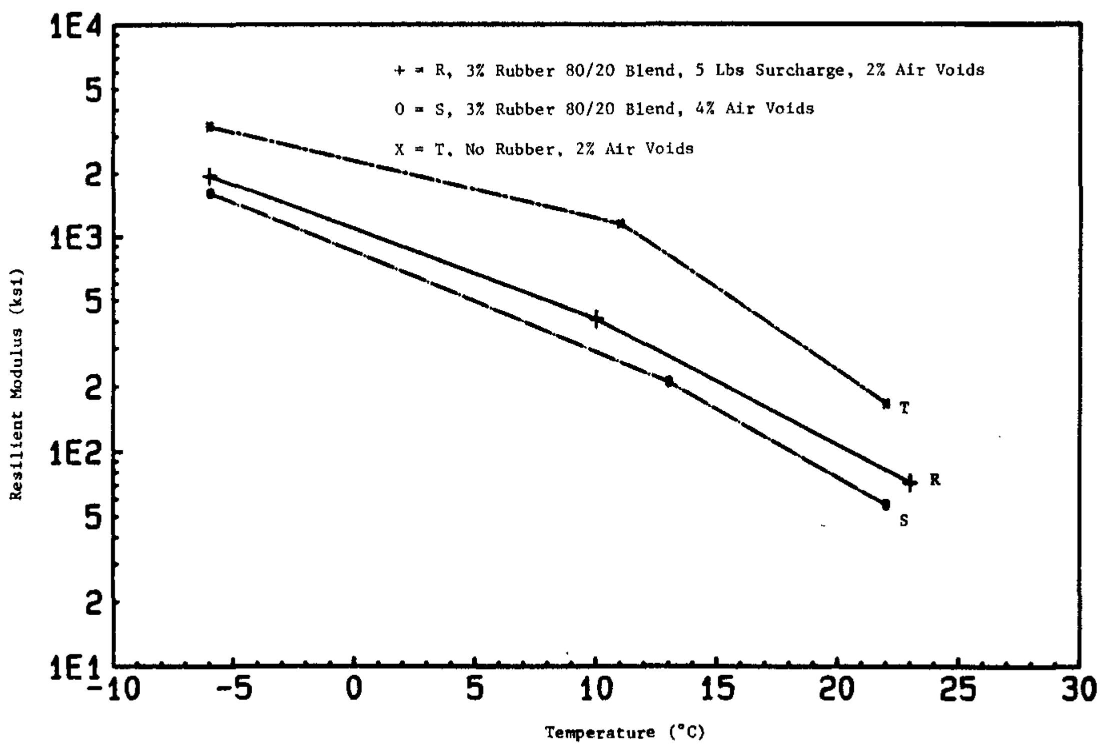


Figure 4.46. Effect of Temperature on Resilient Modulus for Dense-Graded.

To evaluate the time it takes the rubber-asphalt sample to reach a stable temperature (inside, outside), a small study was undertaken. A rubberized asphalt specimen was placed in the environmental chamber, the environmental chamber was set at -14°C, and one thermistor was attached to the surface and one attached to the inside of the specimen. The temperatures in the chamber, on the surface, and inside of the specimen were monitored at 5-minute intervals. Table 4.19 summarizes the results of the temperature recordings at different time intervals. Figure 4.47 shows the relationship between time and dropping temperature at the surface and inside of the rubberized asphalt specimen.

4.5 Effect of Temperature on Resilient Modulus for Reclaimed Rubber

To analyze the effect of temperature on the elastic properties of the reclaimed rubber, five rubber cubes (4x4x4-inch nominal size from medium and high density panels) were tested at eight different temperatures. The test temperatures chosen were 18°, 0°, -10°, -15°, -26°, -37°, -48°, and -65°. The temperature range was selected to investigate the amount of stiffening at temperatures approximating arctic conditions versus temperature on a mild summer day. To obtain the cube temperatures, a "dummy" cube was used which had a thermistor located 1 inch below the surface in the center of the square. The tests were run when the average of the two readings reached the desired temperature.

The load application device was an MTS Model No. 810-12 with x-y recorder attached (Figure 4.48). The cube was placed between two pieces of 3/4-inch plywood to reduce temperature loss by conductance in the metal bearing plates (Figure 4.49). A load versus displacement diagram was obtained by applying a load ranging from 0 to 200 psi (3200 to 3250 pounds) and graphing the vertical displacement of the rubber cube. The loading and unloading sequence cycled five times for each test with a frequency of 10 seconds per cycle.

The summary of the sample measurements and the modulus of elasticity test results obtained at different temperatures are presented in Tables 4.20 and 4.21, respectively. To calculate the resilient modulus, the displacement was divided to total sample height to obtain strain and load divided by cross section area to obtain stress. The resilient modulus was the result of ratio stress over strain. Figure 4.50 shows the resilient modulus at different temperatures for reclaimed rubber.

Table 4.19. Summary of Temperature Drop in Rubberized Asphalt Speciman at Different Time Intervals.

Time Interval (Minute)	Temperature Inside of Specimen (^oC)	Temperature at Surface of Specimen (^oC)	Environmental Chamber Temperature (^oC)
5	20	19	-14
10	18	16	-14
15	15	14	-14
20	12	11	-14
25	10	10	-14
30	8	8	-14
35	6	6	-14
40	4	5	-14
45	3	3	-14
50	1	2	-14
55	0	0	-14
60	-1	0	-14
65	-2	-1	-14
70	-3	-2	-14
75	-4	-3	-14
80	-5	-4	-14
85	-5	-5	-14
90	-6	-5	-14
95	-7	-6	-14
100	-7	-6	-14
105	-8	-7	-14
110	-8	-7	-14
115	-9	-8	-14
120	-9	-8	-14
125	-9	-8	-14
130	-9	-8	-14
135	-9	-9	-14
140	-10	-9	-14
145	-10	-9	-14
150	-9	-10	-14
155	-9	-10	-14
160	-10	-11	-14
165	-10	-11	-14
170	-10	-11	-14
175	-10	-11	-14
180	-10	-11	-14
185	-10	-11	-14
190	-11	-11	-14
195	-11	-11	-14
220	-11	-12	-14
265	-11	-13	-14
270	-13	-11	-14
280	-13	-12	-14
290	-13	-13	-14

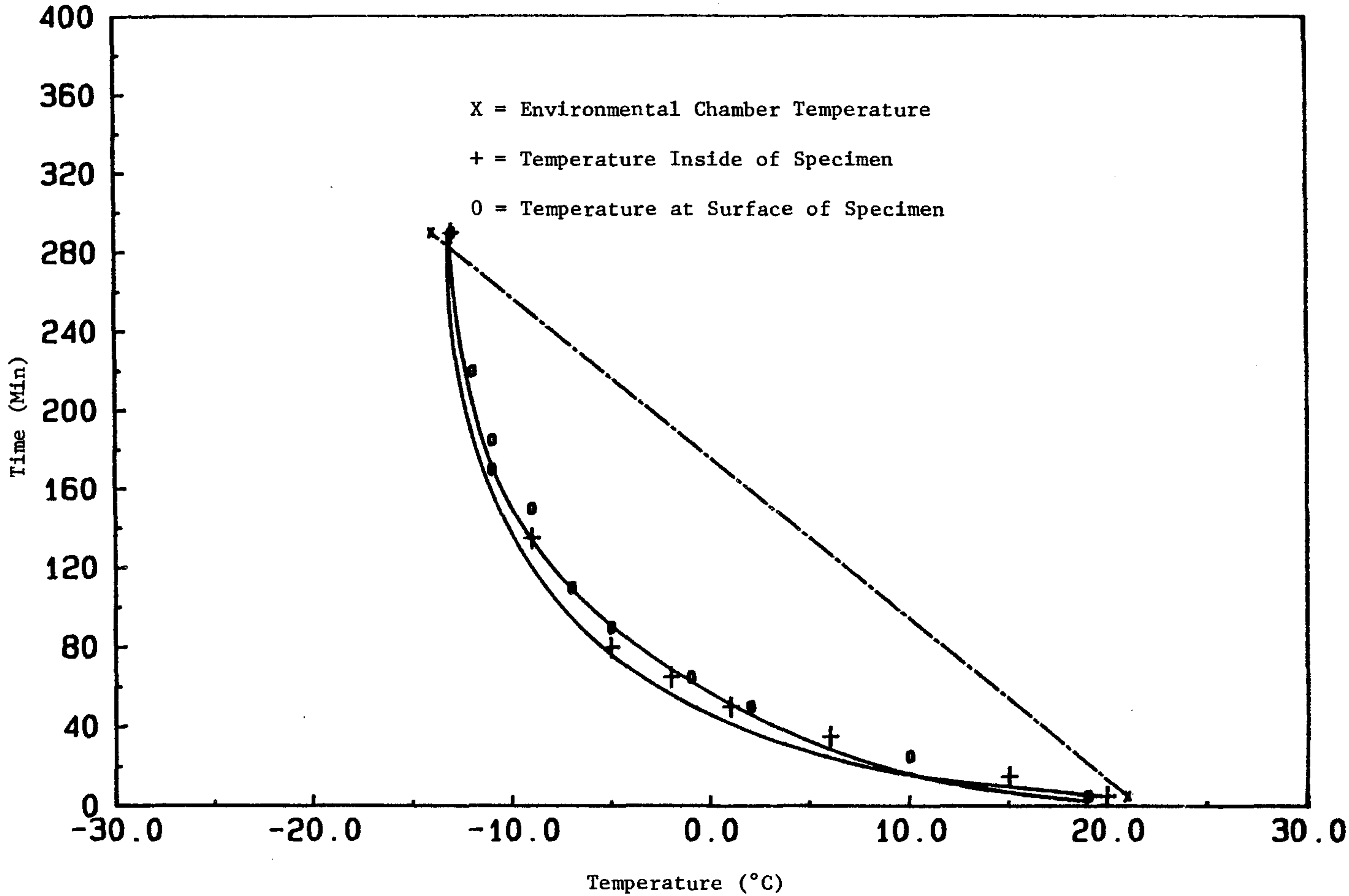


Figure 4.47. Time Required for Sample to Stabilize at Test Temperature of -13°C.

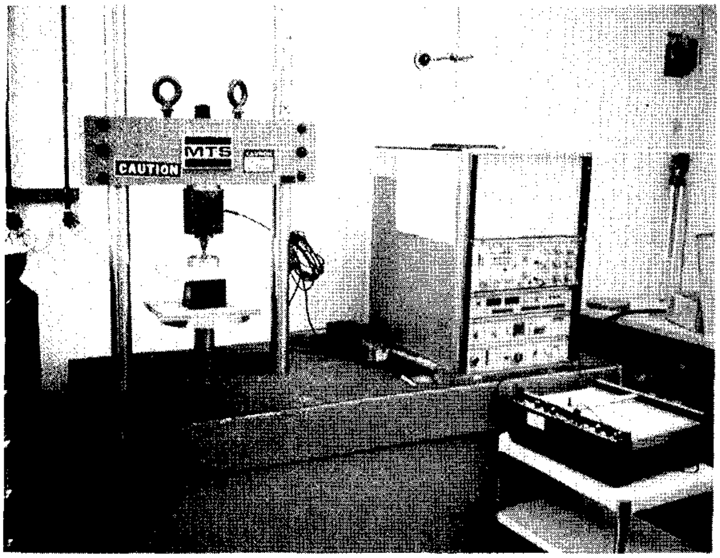


Figure 4.48. Load Application Device (MTS).

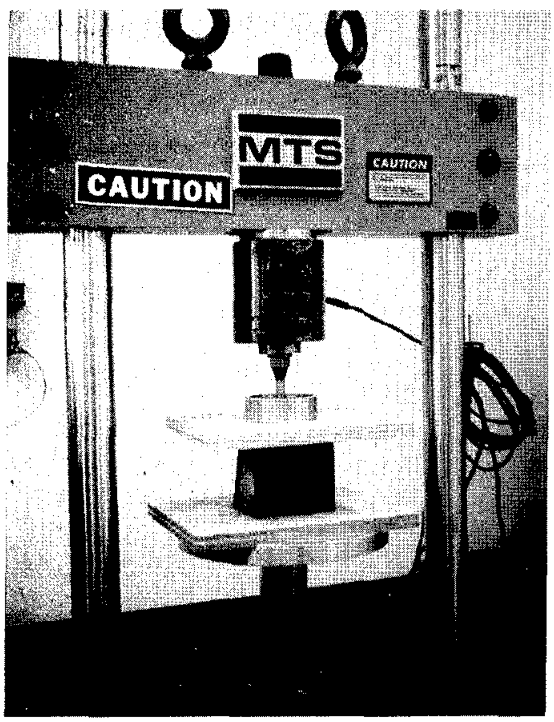


Figure 4.49. Rubber Cube Testing Setup.

Table 4.20. Sample Characterization.

Sample ID	Average Dimensions (ht x sa)	Sample Weight (lbs)	Unit Weight (lbs/ft^3)
23-Y	4-1/8 inch x 16.47 inch^2	2.704	68.78
24-Y	4-1/8 inch x 16.47 inch^2	2.690	68.42
19-B	4-1/16 inch x 15.37 inch^2	2.266	62.71
23-B	4 inch x 14.76 inch^2	2.277	66.64
24-B	4 inch x 14.30 inch^2	2.238	67.61

Table 4.21. Temperature Effects on Modulus of Elasticity.

Sample ID	Temperature (°C)	Load (lb)	Displacement (inch)	Modulus (psi)	Average Modulus (psi)
23-Y	18	3235	0.8753	926	
24-Y	18	3256	0.8655	942	924
19-B	18	3256	0.9531	903	
23-Y	0	3256	0.7683	1061	
24-Y	0	3256	0.8169	998	1017
23-B	0	3212	0.8947	973	
24-B	0	3212	0.8655	1038	
23-Y	-10	3235	0.6613	1225	
24-Y	-10	3235	0.6123	1322	1253
23-B	-10	3212	0.7590	1147	
24-B	-10	3212	0.6810	1319	
19-B	-16	3212	0.8052	1054	
23-B	-16	3212	0.8072	1078	
24-B	-16	3212	0.7586	1184	1129
19-Y	-16	3203	0.6652	1273	
23-Y	-16	3203	0.7352	1091	
24-Y	-16	3203	0.7333	1094	
19-B	-26	3210	0.5932	1430	
23-B	-26	3212	0.6419	1364	
24-B	-26	3212	0.5835	1539	1761
19-Y	-26	3212	0.4824	1760	
23-Y	-26	3203	0.3793	2115	
24-Y	-26	3203	0.3404	2356	
19-Y	-37	3212	0.3105	2816	
23-Y	-37	3212	0.5252	1532	
24-Y	-37	3190	0.5057	1580	2071
19-B	-37	3203	0.4085	2072	
23-B	-37	3203	0.4182	2076	
24-B	-37	3190	0.3793	2353	
19-Y	-48	3212	0.0973	8725	
23-Y	-48	3212	0.0973	8263	
24-Y	-48	3212	0.1400	5746	6772
19-B	-48	3212	0.1459	5819	
23-B	-48	3212	0.1751	4971	
24-B	-48	3212	0.1264	7108	
23-B	-65	3256	0.0389	22683	
24-B	-65	3256	0.0389	23413	23048

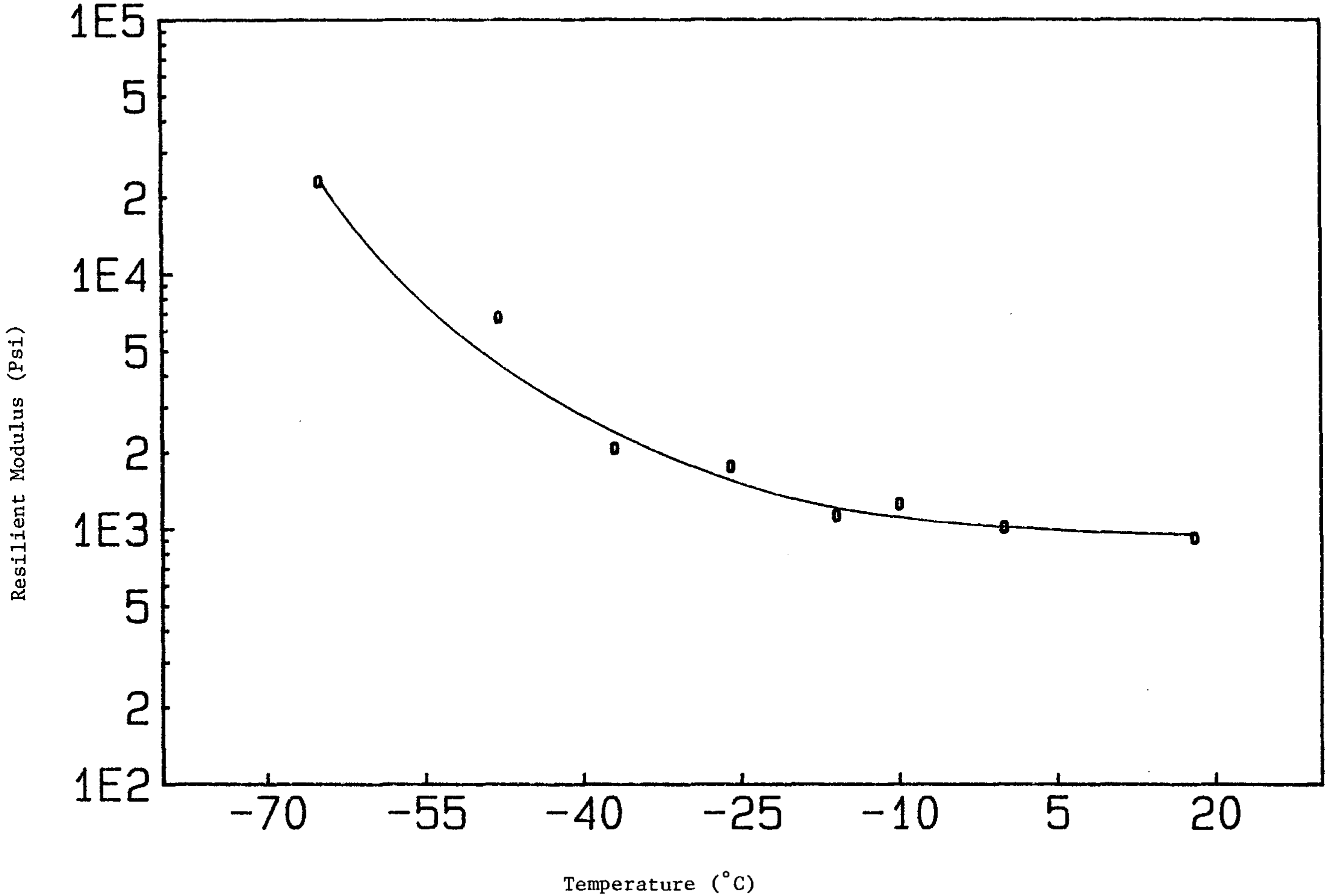


Figure 4.50. Resilient Modulus vs. Temperature for Reclaimed Rubber.

This shows the presence of rubber in the mix may reduce the resilient modulus of the mixture. However, due to the other influencing factors such as the large volume percentage of asphalt and aggregate, the effect of rubber on performance of the mix is minimal.

4.6 Effect of Aging on Resilient Modulus

To study the effect of aging on the resilient modulus, two different mix combinations (Set A and K in Table 4.13) were tested at 100 microstrain in a +10°C environmental chamber. For all dynamic tests, samples were subjected to a constant load having a duration of 0.1 s applied at 60 cycles per minute. Three samples were tested for each combination. The results of all tested samples are presented in Appendix C and summarized in Table 4.22.

The resilient modulus for both mix combinations increased over time (Figure 4.51). The mixture with higher asphalt and rubber contents showed a greater rate of increase in resilient modulus as compared to the rate of increase for the mix with less asphalt and rubber components. The samples with higher asphalt and rubber contents deformed quickly and cracking occurred on the surface of one of the samples during the aging process.

4.7 Summary

This chapter included a summary of mix design results, resilient modulus and fatigue values for various mixes, and results of tests to evaluate the effect of temperature and aging on resilient modulus of rubber-modified asphalt mixes.

The standard Marshall samples were tested for flow, stability, void content, and diametral modulus. Air voids (2%) were used as the sole criteria for mix design. However, the results indicate that as stability increases resilient modulus also increases. Samples with 2% fine rubber have the highest stability and modulus. The reverse relation is true for flow results, as flow increases the resilient modulus decreases.

Twenty different mix combinations were tested for resilient modulus and fatigue at +10°C and -6°C. The dynamic test results show that the mixture with gap-graded aggregate, 3% rubber 80/20 blend, and surcharge has the lowest resilient modulus and highest fatigue life at +10°C. The +10°C tests also indicated that as the modulus decreased, the fatigue life increased. However, the test results at -6°C show the mixture with dense-graded aggregate, 3%

Table 4.22. Summary of Resilient Modulus After Aging.

Mix ID	Number of Samples Tested	Age (Days)	M_R (ksi) $\bar{x}$	M_R (ksi) σ
A	3	1	405	17
A	3	29	414	5
A	3	81	464	23
K	3	1	557	8
K	3	29	572	13
K	3	81	592	20

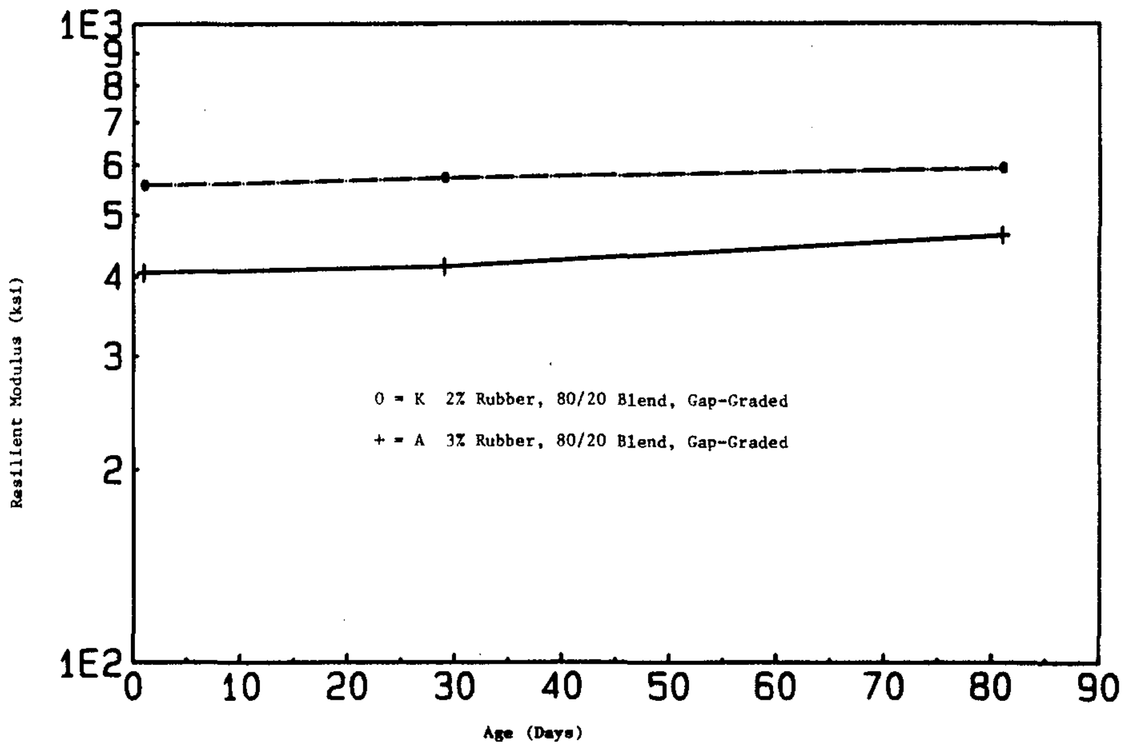


Figure 4.51. Effect of Aging on Resilient Modulus.

rubber 80/20 blend, with the highest fatigue life. Further, the results at -6°C indicated no direct relation between modulus and fatigue.

The effect of aggregate gradation on resilient modulus for both temperatures (+10°C, -6°C) are similar. The dense-graded aggregate has a higher modulus value. The effect of fatigue on aggregate gradation at two different temperatures (+10°C, -6°C) was reversed. At -6°C, the fatigue life was less for mixes with gap-graded aggregate than mixes with dense-graded aggregate. No explanation for this behavior can be offered at this time.

The effect of rubber gradation on resilient modulus at both temperatures are consistent. The mixture with coarse rubber has the lowest modulus and highest fatigue life. The higher mixing temperature increases resilient modulus in all cases. Mixes prepared with the higher mixing temperature (425°F) showed increased fatigue life for the gap-graded aggregate and decreased fatigue life for the dense-graded aggregate. The differences in asphalt content could be a strong factor in this behavior.

The effect of cure time on mix properties at both temperatures were not significant. The effect of surcharge increased the fatigue at +10°C and decreased the fatigue life at -6°C in all cases. The effect of air voids was interesting, as increasing the air voids in the mix from 2% to 4% increased the fatigue life at both temperatures. This is contrary to the conventional relationship between air voids and fatigue. Additional work is definitely needed to evaluate the effect of voids over a range of 2 to 8 percent.

Twenty different mix combinations were tested at three different temperatures (+24°C, +10°C, -7°C) for resilient modulus. The results show that the stiffness decreases, as expected, with increasing temperature.

The effect of temperature on modulus of compacted rubber buffings were analyzed. The reclaimed rubber cubes were tested at eight different temperatures. The results show that stiffness increases, as expected, with decreasing temperature. However, the rate of increase of stiffness as temperature decreases was slight (9% of increase when the temperature dropped from 18°C to 0°C).

To study the effect of aging on the resilient modulus, two different mix combinations were tested. The resilient modulus for both mix combinations increased slightly over time.

5.0 ANALYSIS OF DATA

The purpose of this chapter is to bring together selected test data and project information to estimate the effects of mixture variables on pavement life. Layered elastic theory was used with the material properties developed and project information supplied to evaluate the effect of mix variations on pavement life and to establish layer equivalencies from rubber asphalt mixes. These data are also used to evaluate the economics of rubber-modified and conventional mixes by equivalent annual cost methods. Finally, guidelines are developed to indicate the best uses for rubber-modified asphalt mixes.

5.1 Layered Elastic Analysis

One of the main benefits of rubber-modified asphalt concrete over conventional mixes is increased pavement fatigue life. However, rubber-modified asphalt concrete generally costs more per ton to produce than conventional mixes, due to the rubber costs and additional asphalt cement required. To justify this increased cost and to compare the response to wheel loadings of rubberized pavement with conventional pavement systems, elastic layered theory was used. The procedure and results of these studies for rubber-modified asphalt are described in the following sections.

5.1.1 Analysis Procedure

The Elastic Layer System Computer Program (ELSYM5) was used to analyze the typical pavement structures shown in Figure 5.1. Output from this program includes stresses, strains, and displacements. For a more complete description of ELSYM5, the reader should refer to reference (38).

As seen in Figure 5.1, three pavement structures were evaluated using ELSYM5. The layer equivalencies for three seasons (winter, spring thaw, spring/fall) were evaluated for three different surface thicknesses (2, 4, and 6 inches). The analysis for the summer season was not included because fatigue curves were not available at 20°C. The modulus for the surface and subgrade varied for each season. The base modulus was assumed to be 1.5 times the subgrade modulus. The values for surface resilient modulus were obtained from laboratory-made samples described in Sections 4.2 and 4.3. The resilient

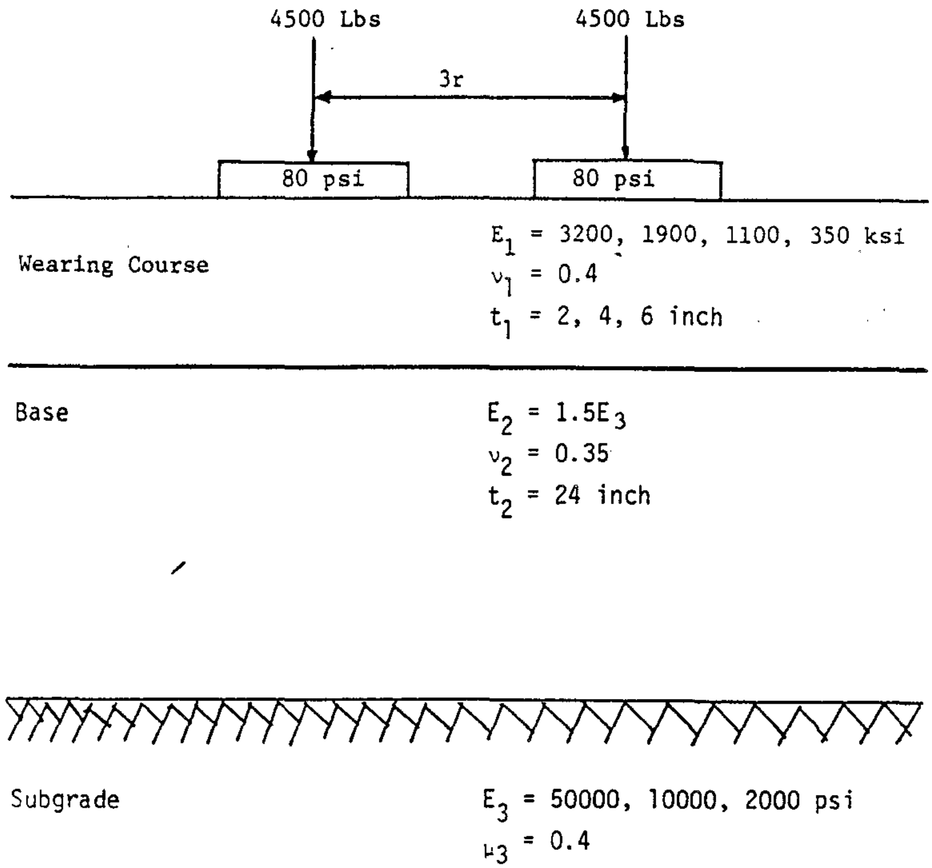


Figure 5.1. Pavement Structures Used for ELSYM5 Analysis (39).

Table 5.1. Resilient Modulus for Conventional Asphalt and Rubberized Asphalt.

M_R (psi)	Winter (-6°C)	Spring Thaw (-6°C)	Spring/Fall (+10°C)
	a) Conventional Asphalt		
Surface	3.2×10^6	3.2×10^6	1.1×10^6
Subgrade	50,000	2,000	10,000
	b) Rubberized Asphalt		
Surface	1.9×10^6	1.9×10^6	3.5×10^5
Subgrade	50,000	2,000	10,000

modulus values for subgrade were obtained from Alaska DOT & PF (39). Table 5.1 shows the surface and subgrade resilient modulus for rubberized asphalt and conventional asphalt in four different conditions.

The procedure used to determine the layer equivalency of the rubber-modified asphalt is outlined in the flow chart in Figure 5.2. The laboratory-determined fatigue curves normally indicate expected pavement lives less than field experience would indicate. To adjust these curves, a shift factor was determined by comparing the conventional mix laboratory fatigue life curves to the fatigue curves developed by Monismith (40) shown in Figure 5.3.

After the fatigue curves were shifted, representative lives were selected (10^5, 10^6, 10^7) and the allowable strains determined. These strain values were input to a plot of ε_{ac} versus thickness, and the thicknesses required for the conventional and rubber-modified mixes were determined. The ratio of the required thicknesses is the layer equivalency for rubberized asphalt.

5.1.2 Estimation of Shift Factor

As described in Section 5.1.1, a "shift" factor was developed using a typical fatigue life curve from the Monismith and laboratory results shown in Table 5.2 (40). This shift factor was determined by averaging the ratio of fatigue life from Monismith to control mix life at both the 100 and 200 microstrain levels. The shift factor of 90 corresponds to an average shift factor in the +10°C and -6°C fatigue curves.

5.1.3 Results

The results obtained from the ELSYM5 analysis, utilizing the cross sections shown in Figure 5.1, are summarized by Table 5.3. Laboratory fatigue life curves were developed for both rubber-modified and control mixes at +10°C and -6°C and shifted by a factor of 90 (Table 5.4). The shifted fatigue lives for rubber-modified and control asphaltic concrete were plotted against tensile strain for the different seasons in Figure 5.4. To determine the layer equivalency of rubber-modified asphalt, a value of repetitions to failure (N_f) was input to Figures 5.4a and b. The N_f values used were 10^5, 10^6, and 10^7. These allowable tensile strain for conventional and rubber-modified mixes for each season was thereby determined. The allowable strains were used in

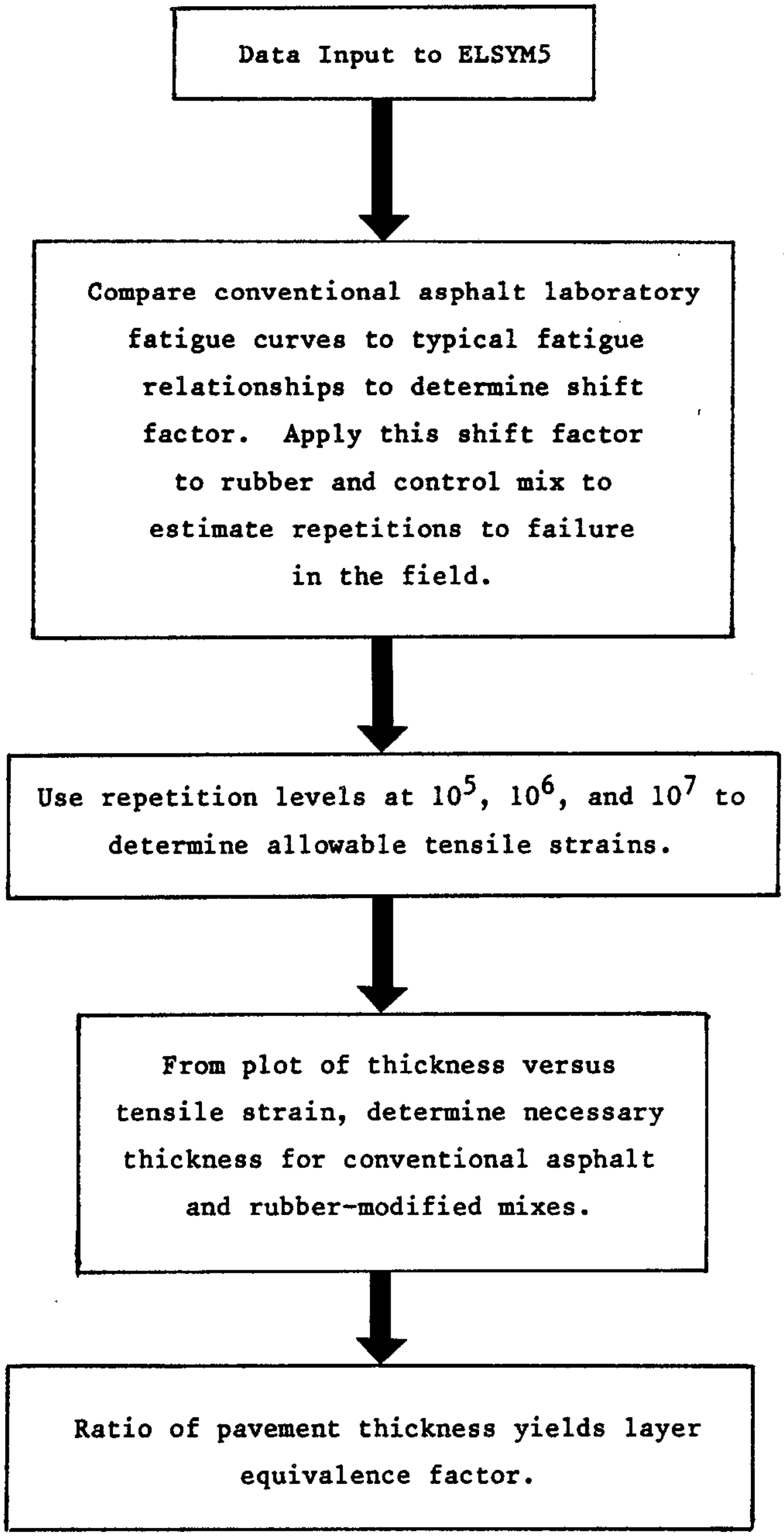
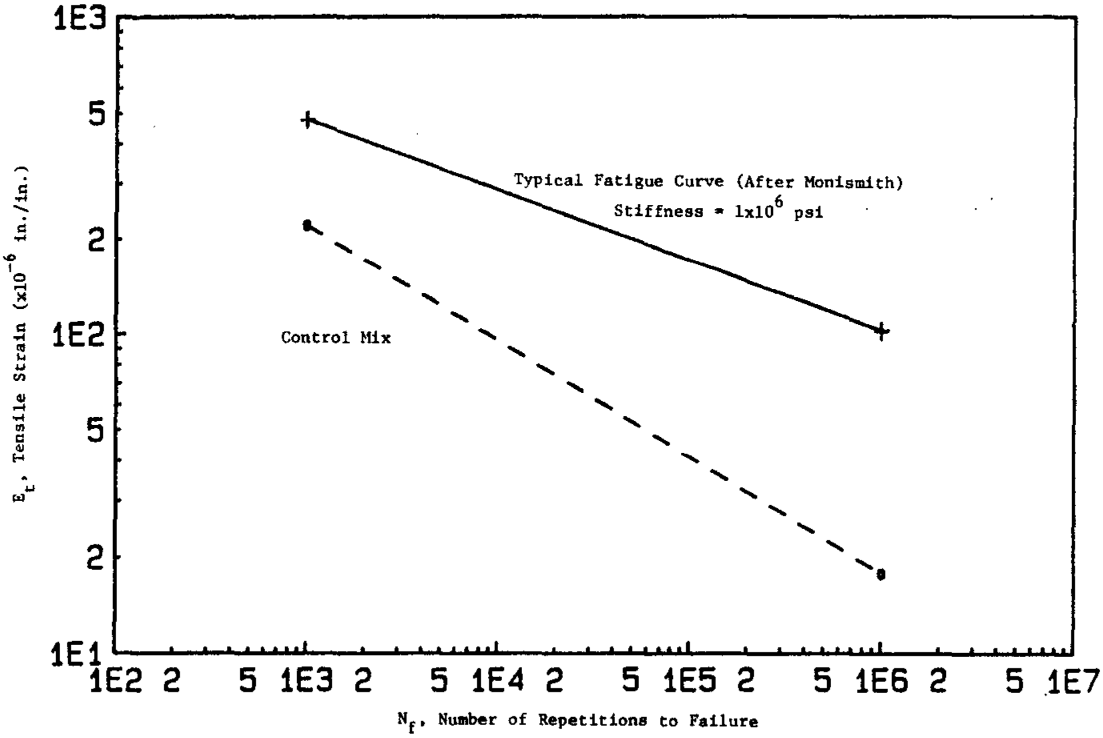
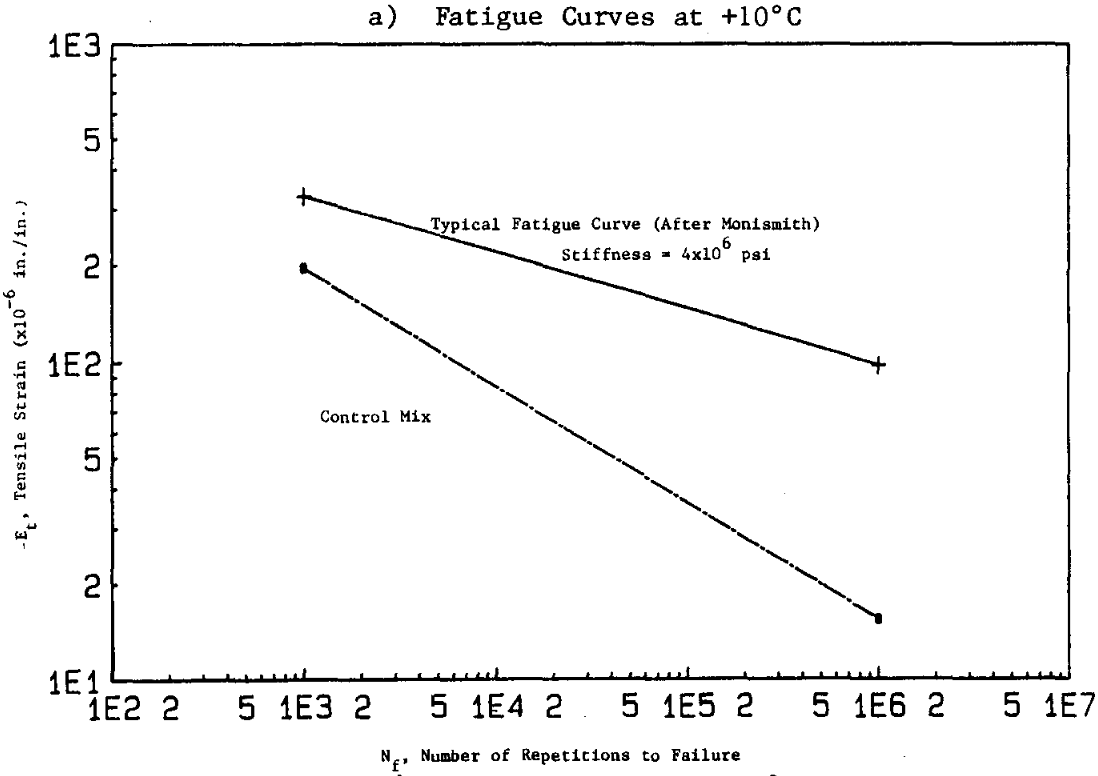


Figure 5.2. Flow Chart for Determination of Layer Equivalencies.



a) Fatigue Curves at +10°C



b) Fatigue Curves at -6°C

Figure 5.3. Comparison of Laboratory and Field Fatigue Curve.

Table 5.2. Summary of Data for Shift Factor Determination.

Source of Data	Strain	Fatigue Life
a) @ +10°C (E = 1×10^6 psi)		
Yoder and Witzak (40)	100	1,000,000
	200	601,000
	400	2,000
Laboratory Data @ +10°C	85	12,997
	100	9,323
	150	2,826
b) @ -6°C (E = 4×10^6 psi)		
Yoder and Witzak	100	800,000
	200	20,000
	400	300
Laboratory Data @ -6°C	70	14,250
	100	8,526
	130	2,526

Table 5.3. Tensile Strains from ELSYM5 Runs.

Surface Thickness (in.)	Asphalt Type*	Surface Modulus (psi)	Season	Base Modulus (psi)	Subgrade Modulus (psi)	Max. Tensile Strain ε_{ac}, in Layer 1 10^{-6} in./in.
2	AC	3,200,000	Winter	75,000	50,000	91
4	AC	3,200,000	Winter	75,000	50,000	53
6	AC	3,200,000	Winter	75,000	50,000	34
2	AR	1,900,000	Winter	75,000	50,000	114
4	AR	1,900,000	Winter	75,000	50,000	73
6	AR	1,900,000	Winter	75,000	50,000	48
2	AC	3,200,000	Spr. Thaw	3,000	2,000	320
4	AC	3,200,000	Spr. Thaw	3,000	2,000	129
6	AC	3,200,000	Spr. Thaw	3,000	2,000	69
2	AR	1,900,000	Spr. Thaw	3,000	2,000	461
4	AR	1,900,000	Spr. Thaw	3,000	2,000	197
6	AR	1,900,000	Spr. Thaw	3,000	2,000	108
2	AC	1,100,000	Spr./Fall	15,000	10,000	348
4	AC	1,100,000	Spr./Fall	15,000	10,000	187
6	AC	1,100,000	Spr./Fall	15,000	10,000	118
2	AR	350,000	Spr./Fall	15,000	10,000	591
4	AR	350,000	Spr./Fall	15,000	10,000	380
6	AR	350,000	Spr./Fall	15,000	10,000	254

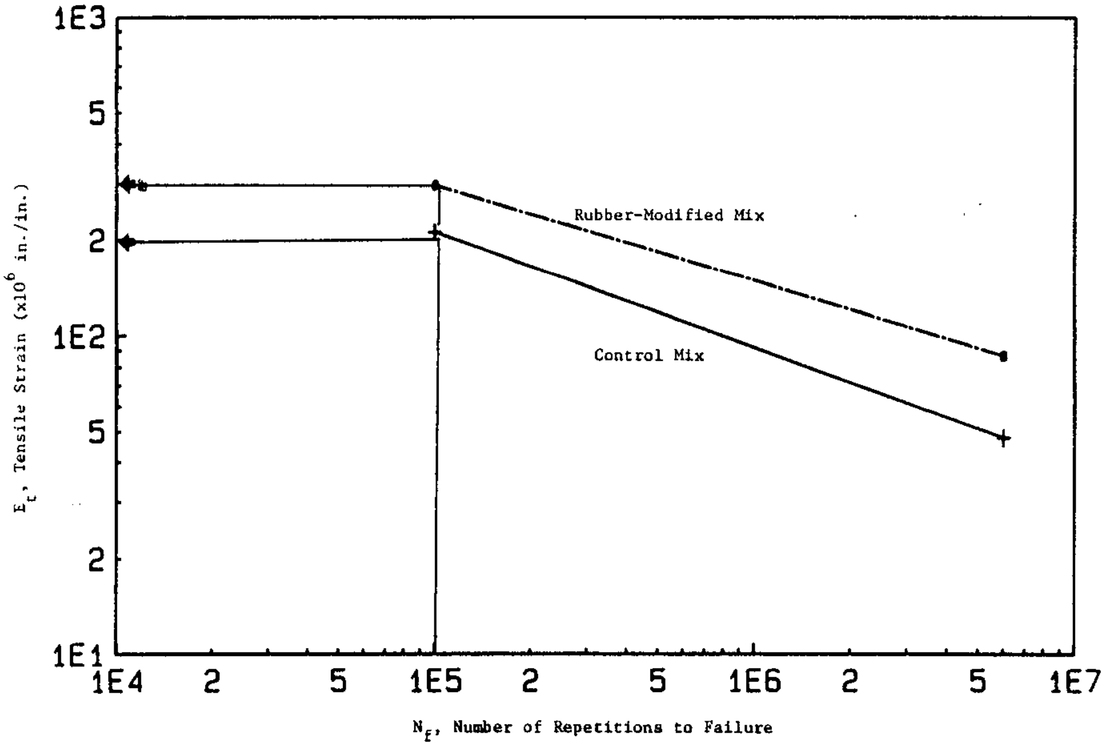
*AC = Asphalt Concrete, AR = Rubber Modified Asphalt Concrete

Table 5.4. Summary of Laboratory and Shifted Fatigue Lives.

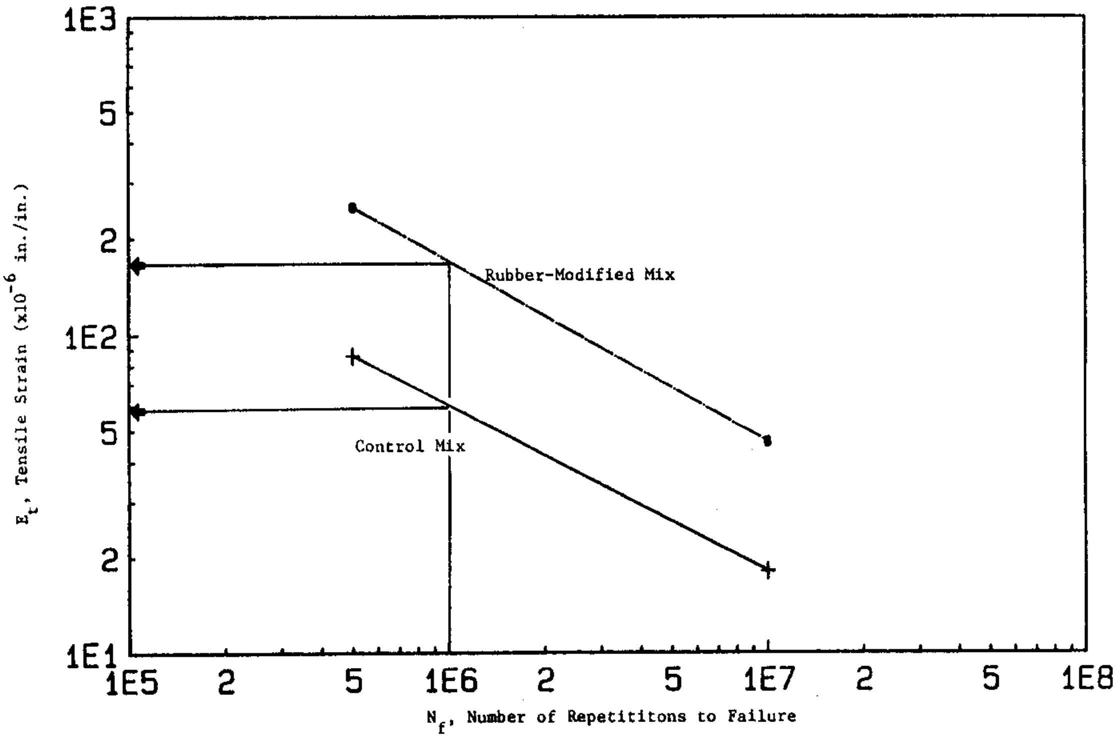
Seasons	Strain (μs)	Control Lab	Control Shifted	Rubber Asphalt Lab	Rubber Asphalt (Shifted)
Spring/Fall (+10°C)	85	12,997	1,169,730	62,036	5,583,240
	100	9,323	839,250	48,240	4,341,600
	150	2,826	254,250	10,490	944,100
Spring/Thaw and Winter (-6°C) For Gap-Graded Aggregate	70	14,250	1,282,500	57,563	5,180,670
	100	8,526	767,340	29,237	2,631,330
	130	2,526	227,340	73,262	6,593,580

Table 5.5. Summary of Layer Equivalency Results.

Season	Allowable Tensile Strain, $E_t \times 10^{-6}$ in./in.		Layer Equivalency from Figure 5.5 (AC/AR)
	Rubber-Modified	Conventional	
Spring/Fall	153	90	1.4
Spring/Thaw	260	87	1.2
Winter	260	87	1.4



a) Spring/Fall (+10°C)



b) Spring Thaw and Winter (-6°C)

Figure 5.4. Shifted Laboratory Fatigue Curves.

Figure 5.5 to obtain the required thickness for the respective mixes. The ratio of the conventional to rubber-modified mix thickness yields a layer equivalency (Table 5.5).

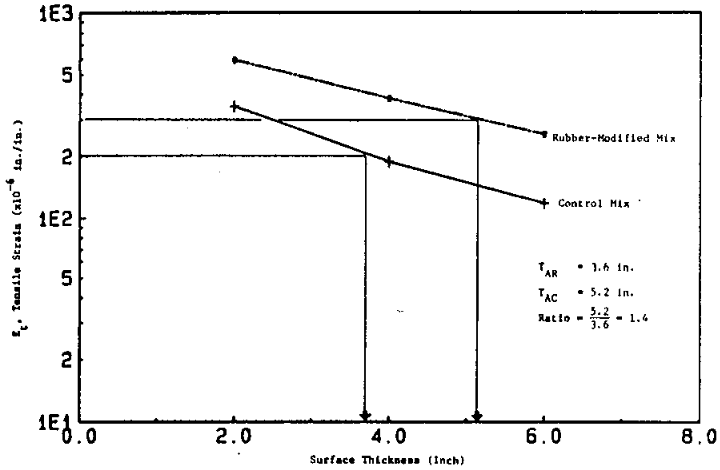
The layer equivalency ratios correspond to an approximately 20 to 30% reduction in surface thickness versus that of conventional asphaltic concrete surface.

5.2 Material Costs

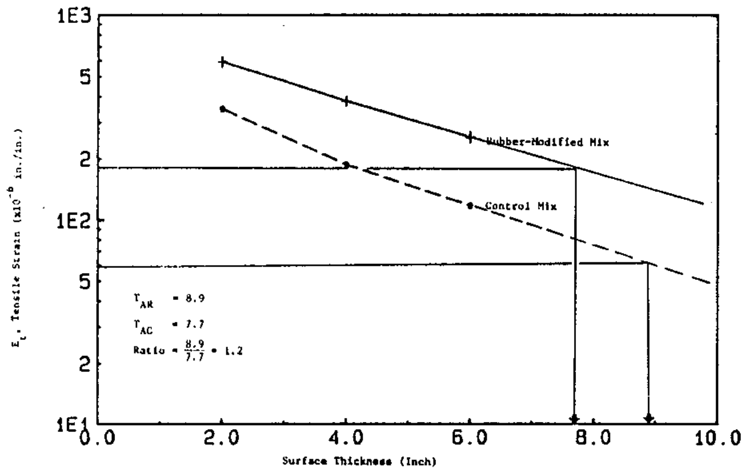
The purpose of this section is to identify the cost of the rubber-modified asphalt pavements, which have been placed in various areas throughout Alaska, as compared with the conventional form of asphalt surfacing. The total mix price and the price for the asphalt binder material, as shown in Tables 5.6, 5.7, and 5.8, were supplied by ADOTPF personnel from actual contract unit prices on projects in the Anchorage, Fairbanks, and Juneau areas (41). The binder costs already include a general contractor's markup for overhead and profit.

The rubber material used on all the projects was furnished according to Plusride specifications and supplied by Rubber Granulators of Everett, Washington (42). The quote used for rubber came directly from Rubber Granulators and was based on the equivalent price for an 80% coarse and 20% fine blend. The blend cost for materials is approximately 11.5 cents per pound with 8.5 cents per pound added for shipping to Alaska. The royalty quote of $4.50 for the rubber was obtained from All Seasons Surfacing Corporation of Bellevue, Washington (43).

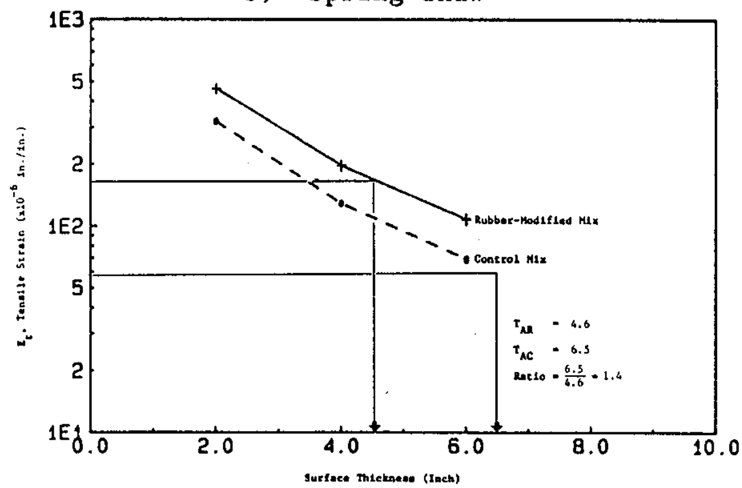
Tables 5.6, 5.7, and 5.8 also show the relative component percentages of the total mix cost. The values shown for the conventional asphalt cement (dollars per ton column) were estimated from the given values for binder and total mix cost and typical component percentages which were supplied by a Corvallis, Oregon paving contractor (44). The component percentages for the Plusride material were determined by using the given cost information for binder, rubber, royalty, and total mix, and by transferring the remaining component costs from the respective conventional mix to the rubber-modified cost column. Some of the transferred costs include a price adjustment to reflect estimated cost increases. By using these tables, the engineer can focus attention on the components of the rubber-modified process which, if



a) Spring/Fall



b) Spring Thaw



c) Winter

Figure 5.5. Required Thickness.

Table 5.6. Material Cost of Asphalt Cement and Asphalt-Rubber Binders - Anchorage Area.

Component	Conventional Asphalt Cement Binder $/Ton	Conventional Asphalt Cement Binder %	Plusride Asphalt Rubber Binder $/Ton	Plusride Asphalt Rubber Binder %
Binder	14.65	35.2	19.13	29.8
Rubber				
Material	-	-	6.90	10.8
Shipping	-	-	5.10	8.0
Aggregate	8.00	19.2	8.50	13.3
Energy Costs	1.50	3.6	1.75	2.7
Mixing	7.00	16.8	7.25	11.3
Haul	2.25	5.4	2.25	3.5
Placement	4.25	10.2	4.35	6.8
Royalties	-	-	4.50	7.0
Mark-up	4.00	9.6	4.40	6.9
TOTAL	41.65	100.0	64.13	100.0

Notes:

1. Costs are in dollars per ton of mix.

2. Costs are generally based on material for approximately 16,500 s.y. placed at 1-1/2-inch depth, 15 miles from the plant. Rubber costs include shipment from Seattle, Washington to Anchorage, Alaska. Binder cost is based on 6.5% by weight of mix for the traditional asphalt cement and 8.5% by weight of mix for the rubber-modified. The rubber was calculated to be 3% by weight of total mix.

Table 5.7. Material Cost of Asphalt Cement and Asphalt-Rubber Binders - Fairbanks Area.

	Conventional Asphalt Cement Binder		Plusride Asphalt Rubber Binder	
Component	$/Ton	%	$/Ton	%
Binder	19.50	54.9	25.50	43.0
Rubber				
Material	-	-	6.90	11.6
Shipping	-	-	5.10	8.6
Aggregate	3.50	9.9	3.75	6.3
Energy Costs	1.50	4.2	1.75	2.9
Mixing	4.00	11.3	4.50	7.6
Haul	2.25	6.3	2.25	3.8
Placement	2.50	7.0	2.60	4.4
Royalties	-	-	4.50	7.6
Mark-up	2.25	6.3	2.50	4.2
TOTAL	35.50	100.0	59.35	100.0

Notes:

1. Costs are in dollars per ton of mix.

2. Costs are generally based on material for approximately 16,500 s.y. placed at 1-1/2-inch depth, 15 miles from the plant. Rubber costs include shipment from Seattle, Washington to Fairbanks, Alaska. Binder cost is based on 6.5% by weight of mix for the traditional asphalt cement and 8.5% by weight of mix for the rubber-modified. The rubber was calculated to be 3% by weight of total mix.

Table 5.8. Material Cost of Asphalt Cement and Asphalt-Rubber Binders - Juneau Area.

	Conventional Asphalt Cement Binder		Plusride Asphalt Rubber Binder	
Component	$/Ton	%	$/Ton	%
Binder	19.00	36.3	24.80	30.1
Rubber				
Material	-	-	6.90	8.4
Shipping	-	-	5.10	6.2
Aggregate	8.00	15.3	12.00	12.7
Energy Costs	2.00	3.8	2.30	2.8
Mixing	7.90	15.1	10.75	11.4
Haul	3.00	5.7	3.00	3.6
Placement	5.50	10.5	7.00	7.4
Royalties	-	-	4.50	5.5
Mark-up	7.00	13.4	16.95	18.0
TOTAL	52.40	100.0	93.30	100.0

Notes:

1. Costs are in dollars per ton of mix.
2. Costs are generally based on material for approximately 16,500 s.y. placed at 1-1/2-inch depth, 15 miles from the plant. Rubber costs include shipment from Seattle, Washington to Juneau, Alaska. Binder cost is based on 6.5% by weight of mix for the traditional asphalt cement and 8.5% by weight of mix for the rubber-modified. The rubber was calculated to be 3% by weight of total mix.
3. The high mark-up costs shown reflect the lack of competition in the Juneau Area.

improved, might produce the greatest cost savings to placement of rubber-modified pavements.

Based on the assumptions and the given information discussed above, Tables 5.6, 5.7, and 5.8 clearly show the increase in component costs for rubber-modified pavements as compared with the conventional asphalt material. Most of the cost increases shown for a component are due to the extra work or increased material costs required in mix production. For example, increasing the oil content from 6.5% to 8.5% naturally raises the mix binder cost. Aggregate costs have been inflated because of the gap grading requirement which typically causes upward price adjustments of 5% to 50% over normal gradings. Energy costs are slightly higher to compensate for the added mixing time recommended in rubber-modified production. Mixing expenses are higher in rubber-modified production due to the additional manpower and equipment required for introducing the rubber into the batch. Reducing the additional price for these components in rubber-modified pavements would require modification to the materials and/or production processes currently in use.

The increase in placement expense and contractor's markup may be explained by assuming the contractor perceives a higher risk is involved with production and placement of rubber-modified pavements versus the conventional pavement. Perceived risk values will either increase or decrease depending on the success or failure of rubber-modified projects, and the degree to which the risk of pavement failure is shared by the State.

The cost of the Plusride material has not been adjusted to compensate for the difference in the specific gravity of the conventional asphaltic concrete as compared to the rubber-modified material. The gap-graded Plusride material studied on the Lemon Road project had core bulk specific gravities averaging approximately 8% less than that of the conventional material. This means a ton of the asphalt-rubber material would cover about 8% more area than a ton of conventional mix. A cost reduction based on lower unit weights for rubber-modified, as compared to conventional mix, was not taken into account, however, because this information was not consistent with in-place density results from the FHWA Mt. St. Helen's Plusride project (11). The St. Helen's project showed no bulk specific gravity reduction for 1-3/4-inch and 2-1/2-inch lifts for rubber-modified mixes as compared to conventional. Since the information is conflicting, no price adjustment was made. A price adjustment would also not be applicable if the State chose to use a dense-graded, rubber-modified mix because its bulk specific gravity should be approximately the same as the conventional mix. However, the patent holder, All Seasons Surfacing Corporation, has suggested using a minimum 5% additional yield to estimate quantities to avoid purchase of more rubber granules than necessary.

The price of the rubber also has some variability which should be taken into consideration. The rubber cost is dependent upon the specified rubber gradation. Fine rubber (100% passing the No. 20 screen) costs approximately 17 cents per pound versus 10.5 cents per pound for coarse rubber (less than 4% passing the No. 20 screen). The price increase for a 3% mix versus 3% of a 80/20 rubber blend mix is approximately \$3.30 per ton of mix. The rubber component cost is completed by adding 8.5 cents per pound (\$5.10 per ton) for shipping to Alaska.

Tables 5.9, 5.10, 5.11, and 5.12 contrast conventional asphalt mix prices to prices for four of the rubber-modified mixes evaluated in the OSU laboratory. The rubber-modified mix described in each of the table headings is identical to one of the mixes used to produce the unshifted fatigue curves shown in Figure 4.27. The component prices shown in each of the tables for the conventional mix were for the Anchorage area. The rubber-modified component costs for energy, mixing, haul, placement, royalties, and markup are also identical to the costs stated in Table 5.6 for the Anchorage area. The rubber-modified mix prices for Tables 5.9, 5.10, 5.11, and 5.12 were determined by calculating the appropriate binder, rubber, and/or aggregate costs from the percentages used in the laboratory mix. For example, in Table 5.9, the only component cost change from the prices given in Table 5.6 was for the binder material. The binder cost was increased from 8.5% per ton (\$19.13) for ADOTPF typical mix to 9.3% per ton (\$20.93) for the laboratory-developed mix.

5.3 Life Cycle Cost Analysis

This section presents three different methods of comparing the costs of rubber-modified mixes to a conventional mix. The first analysis uses an assumed maintenance scenario and equal surfacing thicknesses to calculate the life required for equivalent annual costs. The second analysis method uses equal surfacing thicknesses of rubber-modified and conventional asphalt pave-

Table 5.9. Estimated Costs for Rubber Asphalt Mix, 80/20 Blend, 3% Rubber - Anchorage Area.

Component	Conventional Asphalt Cement Binder $/Ton	Conventional Asphalt Cement Binder %	Rubber-Modified with 9.3% Asphalt Binder $/Ton	Rubber-Modified with 9.3% Asphalt Binder %
Binder	14.65	35.2	20.93	31.7
Rubber	-	-	12.00	18.2
Aggregate	8.00	19.2	8.50	12.9
Energy Costs	1.50	3.6	1.75	2.7
Mixing	7.00	16.8	7.25	11.0
Haul	2.25	5.4	2.25	3.4
Placement	4.25	10.2	4.35	6.6
Royalties	-	-	4.50	6.8
Mark-up	4.00	9.6	4.40	6.7
TOTAL	41.65	100.0	65.93	100.0

Notes:

1. Costs are in dollars per ton of mix.
2. Costs are generally based on material for approximately 16,500 s.y. placed at 1-1/2-inch depth, 15 miles from the plant. Rubber costs include shipment from Seattle, Washington to Anchorage, Alaska. Binder cost is based on 6.5% by weight of mix for the traditional asphalt cement and 9.3% by weight of mix for the rubber-modified. The rubber was calculated to be 3% by weight of total mix.

Table 5.10. Estimated Costs for Rubber Asphalt Mix, 80/20 Blend, 2% Rubber - Anchorage Area.

Component	Conventional Asphalt Cement Binder $/Ton	Conventional Asphalt Cement Binder %	Rubber-Modified with 8.0% Asphalt Rubber $/Ton	Rubber-Modified with 8.0% Asphalt Rubber %
Binder	14.65	35.2	18.00	30.5
Rubber	-	-	8.00	13.6
Aggregate	8.00	19.2	8.50	14.4
Energy Costs	1.50	3.6	1.75	3.0
Mixing	7.00	16.8	7.25	12.3
Haul	2.25	5.4	2.25	3.8
Placement	4.25	10.2	4.35	7.4
Royalties	-	-	4.50	7.6
Mark-up	4.00	9.6	4.40	7.5
TOTAL	41.65	100.0	59.00	100.0

Notes:

1. Costs are in dollars per ton of mix.
2. Costs are generally based on material for approximately 16,500 s.y. placed at 1-1/2-inch depth, 15 miles from the plant. Rubber costs include shipment from Seattle, Washington to Anchorage, Alaska. Binder cost is based on 6.5% by weight of mix for the traditional asphalt cement and 8.0% by weight of mix for the rubber-modified. The rubber was calculated to be 2% by weight of total mix.

Table 5.11. Estimated Costs for Rubber Asphalt Mix, 60/40 Blend, 2% Rubber - Anchorage Area.

Component	Conventional Asphalt Cement Binder		Rubber-Modified with 7.0% Asphalt Rubber	
	$/Ton	%	$/Ton	%
Binder	14.65	35.2	15.75	26.7
Rubber	-	-	10.20	17.3
Aggregate	8.00	19.2	8.50	14.4
Energy Costs	1.50	3.6	1.75	3.0
Mixing	7.00	16.8	7.25	12.3
Haul	2.25	5.4	2.25	3.8
Placement	4.25	10.2	4.35	7.4
Royalties	-	-	4.50	7.6
Mark-up	4.00	9.6	4.40	7.5
TOTAL	41.65	100.0	58.95	100.0

Notes:

1. Costs are in dollars per ton of mix.

2. Costs are generally based on material for approximately 16,500 s.y. placed at 1-1/2-inch depth, 15 miles from the plant. Rubber costs include shipment from Seattle, Washington to Anchorage, Alaska. Binder cost is based on 6.5% by weight of mix for the traditional asphalt cement and 7.0% by weight of mix for the rubber-modified. The rubber was calculated to be 2% by weight of total mix.

Table 5.12. Estimated Costs for Rubber Asphalt Mixes, 80/20 Blend, 3% Rubber, Dense Aggregate Grading - Anchorage Area.

Component	Conventional Asphalt Cement Binder		Rubber-Modified with 7.5% Asphalt Binder	
	$/Ton	%	$/Ton	%
Binder	14.65	35.2	16.90	27.5
Rubber	-	-	12.00	19.5
Aggregate	8.00	19.2	8.00	13.0
Energy Costs	1.50	3.6	1.75	2.9
Mixing	7.00	16.8	7.25	11.8
Haul	2.25	5.4	2.25	3.7
Placement	4.25	10.2	4.35	7.1
Royalties	-	-	4.50	7.3
Mark-up	4.00	9.6	4.40	7.2
TOTAL	41.65	100.0	61.40	100.0

Notes:

1. Costs are in dollars per ton of mix.

2. Costs are generally based on material for approximately 16,500 s.y. placed at 1-1/2-inch depth, 15 miles from the plant. Rubber costs include shipment from Seattle, Washington to Anchorage, Alaska. Binder cost is based on 6.5% by weight of mix for the traditional asphalt cement and 7.5% by weight of mix for the rubber-modified. The rubber was calculated to be 3% by weight of total mix.

ments and only the capital cost to determine the required life for equivalent annual costs. The last method utilizes the layer equivalencies shown in Table 5.5 to compare the capital costs of rubber-modified and conventional asphalts based on unequal thicknesses.

5.3.1 Equal Annual Capital and Maintenance Costs

Table 5.13 presents a life cycle cost analysis to determine the required life for equivalent annual costs of rubber-modified mixes to a conventional mix with a life of 15 years. The table used the cost per square yard information for mix in the Anchorage area and estimated maintenance prices for crack sealing and chip sealing to calculate the required life span for each alternative. The following assumptions were made:

1) discount rate = 4.0%,
2) crack seal maintenance cost = $0.10/yd^2,
3) chip seal maintenance cost = $0.40/yd^2,
4) conventional mix cost sithout binder = $27.00/ton,
5) binder cost = $225/ton,
6) rubber cost = $400/ton,
7) A-R mix without binder and rubber cost = $33.00/ton,
8) salvage value = $0.00 at the end of pavement life (41), and
9) unit weight = 142 pcf.

The table shows that the pavement lives for the rubber-modified mixes need to be in the range of 24 to 28 years compared with 15 years for a conventional mix. Table 5.13 includes a maintenance scenario which is assumed primarily for illustrative purposes. The chip and crack seal intervals were assumed to be at quarter, half, and three-quarter points in the estimated pavement life. This assumption means maintenance intervals would increase with the increase in fatigue life.

The objective of illustrating life cycle costs in this manner is to show how typical pavement maintenance costs correlate to the relative pavement condition throughout pavement life. It assumes that a pavement with a fatigue life of 24 years will deteriorate at a slower rate than a pavement with a life of 15 years. Figure 5.6 shows the relationship which is assumed by the infor-

Table 5.13. Life Cycle Cost Comparisons with Equivalent Annual Costs.

a) Alternative No. 1: Conventional Asphaltic Concrete

Year	\$ Cost/s.y.	Description
0	6.65	3" surfacing - 6.5% A.C.
4	0.10	Crack seal
8	0.40	Chip seal
12	0.10	Crack seal
15	-	End of economic life

$AE_1(4) = 6.65\ (A/P,4,15) + 0.10\ (P/F,4,4)(A/P,4,15)$
$+ 0.40\ (P/F,4,8)(A/P,4,15) + 0.10\ (P/F,4,12)(A/P,4,15)$
$AE_1(4) = \$0.65$ s.y.

b) Alternative No. 2: 9.3% Asphalt Binder and 3% 80/20 Blend Rubber

Year	\$ Cost/s.y.	Description
0	10.53	3" surfacing
7	0.10	Crack seal
14	0.40	Chip seal
21	0.10	Crack seal
28	-	End of economic life

$AE_2(4) = 10.53\ (A/P,4,28) + 0.10\ (P/F,4,7)(A/P,4,28)$
$+ 0.40\ (P/F,4,14)(A/P,4,28) + 0.10\ (P/F,4,21)(A/P,4,28)$
$AE_2(4) = \$0.64$/s.y.

c) Alternative No. 3 and 4: 8% Asphalt Binder and 2% 80/20 Blend Rubber
and
7% Asphalt Binder and 2% 0/100 Blend Rubber

Year	\$ Cost/s.y.	Description
0	9.43	3" surfacing
6	0.10	Crack seal
12	0.40	Chip seal
18	0.10	Crack seal
24	-	End of economic life

$AE_{3,4}(4) = 9.43\ (A/P,4,24) + 0.10\ (P/F,4,6)(A/P,4,24)$
$+ 0.40\ (P/F,4,12)(A/P,4,24) + 0.10\ (P/F,4,18)(A/P,4,24)$
$AE_{3,4}(4) = \$0.65$/s.y.

d) Alternative No. 5: 7.5% Asphalt Binder, 3% 80/20 Blend Rubber, Dense-Graded Aggregate

Year	\$ Cost/s.y.	Description
0	9.81	3" surfacing
6	0.10	Crack seal
12	0.40	Chip seal
18	0.10	Crack seal
24	-	End of economic life

$AE_5(4) = 9.81\ (A/P,4,24) + 0.10\ (P/F,4,6)(A/P,4,24)$
$+ 0.40\ (P/F,4,12)(A/P,4,24) + 0.10\ (P/F,4,18)(A/P,4,24)$
$AE_5(4) = \$0.66$/s.y.

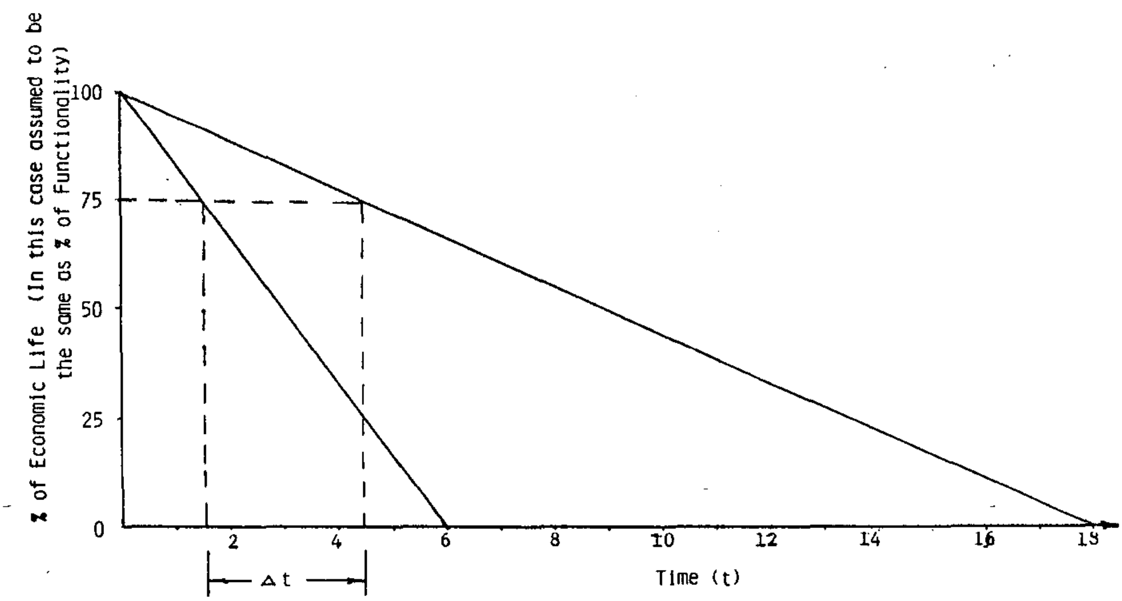


Figure 5.6. Straight Line Deterioration with Time.

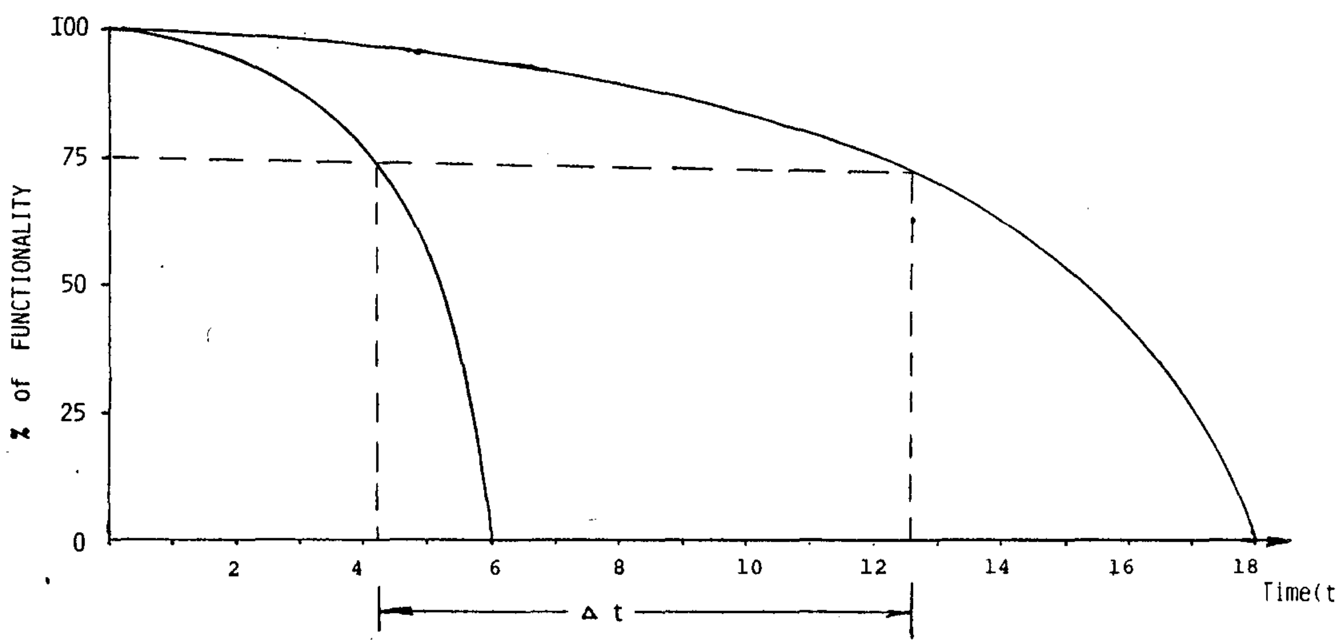


Figure 5.7. Typical Shapes for Pavement Deterioration Curves (40).

mation in Table 5.13 between the level of service of a pavement and time. The straight line deterioration rates used in the figure are not intended to follow typical pavement deterioration curves like those shown in Figure 5.7. Since deterioration curves vary from area to area, no attempt was made to estimate their shape for this cost example. It is important to note, however, that the straight line estimates give a conservative view of equivalent annual costs as compared to costs prepared by information from typical deterioration curves. The maintenance interval multipliers may stay the same (in this case, 3), but the difference in time (Δt) increases with the use of typical curves. As Δt increases, the equivalent annual costs for the rubber-modified mixtures will decrease.

By preparing and analyzing costs in this way, Table 5.13 shows the necessity for an evaluation based on the expected life of the structure. Any costs (such as those for typical maintenance) which can be deferred to a later date will make pavements with a higher capital cost appear more economically attractive in the present. In addition, Table 5.13 illustrates the importance of replicating field products to products manufactured in the lab. Pavement lives of 24 and 28 years would require better mix performance than is currently shown by the rubber-modified materials.

The approach presented in Table 5.13 could also be useful for showing the value of user cost benefits as valued over the life of the project. For instance, winter maintenance work could be cost coded and recorded in such a way that differences in maintenance costs between rubber-modified and conventional mixes could be measured. If a cost differential was found to exist, the value(s) could be added to the cash flow over the life cycle of the appropriate alternative. As another example, Plusride's surface has been reported to reduce stopping distances in adverse conditions. If this could be verified and quantified in terms of added safety benefits, the annual equivalent values of rubber-modified asphalt might be more favorable. Other possible benefits besides reduced stopping distances and decreased winter maintenance costs for the rubber-modified mixes include reducing the amount of waste tires from the environment, noise reduction, and increased nighttime visibility. The effect of these currently intangible benefits should be verified and quantified in future studies and used appropriately in this type of analysis.

5.3.2 Equal Annual Capital Cost

There is a more conservative approach to evaluating costs for conventional and asphalt rubber-modified pavements over the life of the structure. The method is conservative because it does not take into account the possibility of reduced long-term maintenance and user costs. It only considers the capital cost of the pavement system. With the capital costs of both pavement systems known and the life of the conventional system assumed, the life of the rubber-modified system to provide equivalent costs is determined by using the following:

$$X(CRF,\ n) = Y(CRF,\ n') \tag{5.1}$$

where: X^* = cost of conventional pavement in \$/ton or \$/s.y.,

Y^* = cost of rubber-modified pavement in \$/ton or \$/s.y.,

n = life of the conventional pavement in years,

n' = asphalt rubber pavement life in years, and

CRF = Capital Recovery Factor = $\dfrac{i(1+i)^n}{(1+i)^n-1}$

By substitution:

$$X(i(1+i)^n/(1+i)^n -1) = Y(i(1+i)^{n'}/(1+i)^{n'} -1) \tag{5.2}$$

where i = discount rate in decimal form.

If we define D as follows:

$$D = \frac{X}{Y}\left[\frac{i(1+i)^n}{(1+i)^n-1}\right] \tag{5.3}$$

and then solve for n', we obtain the relation for asphalt-rubber life

$$n' = \frac{\ln\left(\frac{D}{D-i}\right)}{\ln(1+i)} \tag{5.4}$$

Table 5.14 shows the average cost per ton for the mix and design lifetimes for the conventional asphaltic pavement ranging from 2 to 20 years. The table also includes the effect of using a discount rate of 3.5%, 4.0%, and 4.5%. The discount rate was based on the real cost of capital as used in

---
*X and Y must be in the same units.

Table 5.14. Comparison of Pavement Life for Equivalent Annual Capital Costs of Conventional and Asphalt Rubber-Modified Mixes.

Surfacing Alternative	Discount Rate	Life Required for Equivalent Annual Capital Cost				
Conventional Asphaltic Concrete (assumed)	-	2.0	5.0	10.0	15.0	20.0
Rubber-modified Asphaltic Concrete	3.5%	3.2	8.3	17.7	28.9	43.8
Rubber-modified Asphaltic Concrete	4.0%	3.2	8.3	18.1	30.3	48.4
Rubber-modified Asphaltic Concrete	4.5%	3.2	8.4	18.5	32.0	56.2

Notes:

1. Average cost per ton of conventional asphaltic concrete = $43.25 from Tables 5.6, 5.7, and 5.8.

2. Average cost per ton of rubber-modified asphaltic concrete = $67.65 from Tables 5.6, 5.7, and 5.8.

3. Equal Surface Thickness

constant dollar studies. The real cost of capital essentially reflects the difference between the market rate of return and inflation. This difference has historically been between 3.7% and 4.4% nationally (45).

Table 5.14 can become considerably more useful as information concerning pavement life becomes more readily available. In its present form, the table can be used as a simple tool for determining the equivalent life of rubber-modified mixes versus conventional mixes. If an HP-41 system is available, a program has been included in Appendix D for easing the computation of equivalent pavement lives.

5.3.3 Capital Cost Comparison Considering Layer Equivalencies

In Table 5.5, the required thickness of a rubber-modified mix was reduced by 1.2 to 1.4 times compared with a conventional mix using the equivalency factors developed earlier. This implies a rubber-modified mixture could be placed with a thickness ranging from approximately 2 to 2-1/2 in. and the expected fatigue life would be the same as a 3-in. conventional surfacing. Table 5.15 presents the capital cost per square yard based on varying thickness for each of the alternatives discussed in the previous section, 5.3.2.

Table 5.15 shows that the capital cost of a rubber-modified surfacing becomes advantageous only when the layer equivalency is at least in the range of 1.4 to 1.5. Therefore, by this comparison, the rubber-modified mixes would not be economically acceptable since the laboratory results showed a layer equivalency range of only 1.2 to 1.4. Like the life cycle cost analysis presented in the previous section, this capital cost comparison does not take into account possible benefits of the rubber-modified mix which have not been verified and/or quantified to date. A small increase in the capital cost may be justified if benefits such as increased de-icing capabilities, reduced adverse weather stopping distances, noise reduction, etc., could be shown to have a quantifiable positive effect on user and maintenance costs.

5.3.4 Summary Discussion

The information presented in this section shows rubber-modified asphalt mixes would require a life-span of approximately 24 to 28 years to provide the same life cost as an equivalent thickness of conventional asphalt concrete

Table 5.15. Capitol Cost Comparison Considering Layer Equivalencies.

Surfacing Alternative	Capitol Cost for Given Thickness ($/sy) 3"	2-1/2"*	2-1/4"**	2"***
A. Conventional Asphaltic Concrete	6.65	N/A	N/A	N/A
B. 9.3% Asphalt and 3% of 80/20 Rubber Blend	10.53	8.78	7.90	7.02
C. 8.0% Asphalt and 2% of 80/20 Rubber Blend	9.43	7.86	7.07	6.29
D. 7.0% Asphalt and 2% Fine Rubber	9.42	7.85	7.06	6.28
E. 7.5% Asphalt, 3% of 80/20 Rubber Blend, and Dense Graded Aggregate	9.81	8.18	7.36	6.54

*Equivalency of 1.2:1
**Equivalency of 1.33:1
***Equivalency of 1.5:1

surface which lasts 15 years. In a comparison of capital costs, thickness of the rubber-modified mix must be reduced by a factor of at least 1.4 to 1.5 for the cost to be equivalent to a conventional asphalt surface.

The rubber-modified mixes could become more economically feasible by reducing life cycle and/or capital costs. The life cycle costs could be reduced by including intangibles, such as those discussed in the previous sections. Capital costs could also be reduced in many ways. For example, Tables 5.9, 5.10, 5.11, and 5.12 show the relationship between the total mix cost and the cost for each of the mix components. Cost reductions in the mix are most sensitive to items which have the highest component percentage of cost as compared to the total mix. As an example, if the rubber components were obtained locally, up to an 8.0% savings to the total cost of the mix could result. However, if the mixing time for the rubber-modified material was made equivalent to the mixing time for a conventional mix, the cost of the mix would only be reduced by 0.4%. The effort spent in changing these factors may be the same, but the payoffs favor one cost-cutting effort more than the other. By evaluating the sensitivity of the mix price in relation to the component prices, areas which will produce the greatest cost savings to the total mix are readily identified.

5.4 Guidelines for Use of Rubber-Modified Mixes

Based on results of this study, the following guidelines are recommended for use of rubber-modified mixes:

1) Since pavements in Alaska rarely fatigue in the winter (when pavement temperatures are below freezing), the gap-graded mix is still recommended for fatigue resistance during the spring and summer times of the year.
2) The rubber-modified mixes have fatigue lives which range from 2 to 7 times longer than conventional mixes evaluated at +10°C and -6°C. This results in layer equivalencies of 1.2 to 1.4 for conventional asphalt to rubber-modified thickness. These values should be considered for use in Alaska's pavement design procedure.
3) Based on the questionnaire survey in Appendix A, most rubber-modified surface failures appear to be due to raveling. Until

the construction techniques are modified to preclude failure due to early raveling, rubber-modified mixtures should continue to be placed adjacent to a control section of a conventional surfacing. Continuing to place both mix types in adjacent locations will aid the research effort and performance evaluations because each mix can be examined under like conditions.

4) Rubber-modified mixes could be used as a crack relief layer or cushion course in overlays or two-phase surface construction. The advantage of such a use is that the rubber-modified material is placed in a position to take advantage of its high allowable tensile strain value, which correlates to its increased fatigue life. The conventional asphalt surfacing then acts as a seal and eliminates the chances for raveling of the rubber mix.

5) Though the use of the 0/100 and 60/40 blends of rubber reduced the fatigue life at both +10°C and -6°C, the resulting mixes also required less asphalt cement. The cost data in Table 5.13 would indicate this mix was nearly as cost effective as the coarse rubber blend (80/20). Alaska DOTPF should be encouraged to try some of these blends in order to reduce the total asphalt requirements and reduce early raveling.

6) Reducing the rubber content from 3 to 2% had little effect on fatigue life at +10°C, but increased fatigue life at -6°C. Alaska DOTPF should consider reducing the rubber content to 2%.

7) Use of dense graded aggregate with the 80/20 rubber blend also greatly reduces the asphalt content that is needed for the gap-graded mix. Though the fatigue life is reduced at +10°C, it is greatly increased at -6°C. Alaska DOTPF should consider its use in future test sections.

8) Currently intangible benefits of rubber-modified asphalt mixes such as reduced winter maintenance costs and reduced stopping distances need further study. If these can be

quantified and they prove to be positive, rubber asphalt mixes may become more economically attractive.

5.5 Summary

This chapter presented the layered elastic analysis of data. The layered elastic theory was used with the material properties determined in the laboratory and project information supplied by ADOTPF. The theory was used to evaluate the effect of mix variations on pavement life and to establish layer equivalencies for the rubber mixes. The laboratory and field data were also used to evaluate the economics of rubber-modified and conventional mixes. The chapter concludes with development of use guidelines.

The layer equivalencies were calculated for three different seasons. The ratio of conventional asphalt to rubber-modified thickness for winter, spring thaw, and spring/fall was ranged between 1.2 and 1.4 to 1.

The economic analysis shows rubber-modified asphalt mixes to be slightly less cost effective than conventional asphalt mixes. Additional study is recommended to quantify currently intangible benefits such as lower winter maintenance costs and reduced stopping distances. If these can be quantified, inclusion of these benefits could improve the cost effectiveness of rubber asphalt mixes and justify their increased use.

Finally, guidelines for use of rubber asphalt mixes in Alaska are developed. These guidelines are in the form of suggestions of types of mixes to be used by Alaska to reduce life cycle costs and potential short and long term raveling problems.

6.0 CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

This chapter summarizes the findings of a field performance questionnaire and a laboratory study. The goal was to optimize ingredients for rubber-modified asphalt pavement in terms of the selected mix properties of resilient modulus and diametral fatigue resistance at two different test temperatures. This has been done by developing mix design recommendations for rubber-modified asphalt mix for use in Alaska. Based on the results of this study, the following conclusions appear warranted:

1) The 1984 field survey indicated that most rubber-modified pavements placed to date have not failed in fatigue. Where problems have been reported, they have generally been early raveling and attributed to excessive voids resulting from poor compaction and/or low asphalt content. Intangible benefits, such as ice control and noise reduction, still need further quantification.
2) The laboratory mix design results show that the required asphalt content to reach a certain minimum voids level for rubber-modified mixes depends on rubber and aggregate gradation, and rubber content. The mixture with gap-graded aggregate and 3% coarse rubber* required the highest design asphalt content (9.3%). The mixture with 3% coarse rubber* and dense aggregate grading required 7.5%, and the conventional asphalt mix (no rubber) had the lowest design asphalt content (5.5%). The asphalt contents reported were for 2% air voids.
3) The resilient modulus for rubber mixes at +10° and -6°C was generally higher for dense-graded aggregates than for gap-graded aggregates.
4) The gap-graded mix had a higher (by 40%) fatigue life at +10°C than the dense-graded mix. However, at -6°C, the dense-graded mix had the highest fatigue life (by 300%).

*Based on dry aggregate weights.

Table 3.6. Rubber Properties*.

a) Gradation

Sieve Size	Coarse	Fine	80/20	60/40	0/100	All Seasons 80/20 Rubber (4) Specifications
1/4 inch	100		100	100		100
No. 4	97		97.6	98.2		76-92
No. 10	15	100	32	49	100	28-36
No. 20	4	86	20.4	36.8	86	10-24
No. 40	3	30	8.4	13.8	30	-
No. 50	2.9	20	6.3	9.7	20	-

b) Other Physical Properties*

Natural Rubber (%)	20
Synthetic Rubber (%)	80
Specific Gravity (lb/ft^3) (bulk)	30
<u>Mixture</u>	
Carbon black (%)	30
Acetone (%)	15
Hydrocarbon (%)	45
Fiber (%)	10

*Rubber Data Source: Rubber Granulators, Everett, WA (42).

Table 3.7. Tests Performed on Rubber Asphalt Mixtures*.

Type of Tests	Mix Properties
Mix Design Tests	• Stability
	• Flow
	• Voids*
Mix Property Tests	• Diametral Modulus
@ +10°C, -6°C	• Diametral Fatigue

*Based on Rice's theoretical maximum specific gravity (AASHTO T-209).

5) The resilient modulus values for gap-graded and dense-graded aggregates increased at +10° and -6°C as the rubber gradation became finer. The fatigue lives were reduced by about 20% as the rubber gradation got finer. These results correlate with values obtained by ADOTPF for modulus but not for fatigue.

6) As the percent rubber by dry weight of aggregate increased from 2 to 3% the modulus values generally decreased at +10°C and were unaffected at -6°C for gap-graded mixes. The fatigue life of gap-graded mixes was not significantly affected at +10°C by increasing the rubber content. At -6°C, the fatigue life of gap-graded mixes was greatly increased by reducing the rubber content.

7) Gap-graded aggregate mixtures with a blend of 80% coarse and 20% fine rubber had the lowest modulus and highest fatigue life at both testing temperatures.

8) A high mixing temperature slightly increased the modulus and the fatigue life for gap-graded mixes tested at +10°C. Dense-graded mixes tested at +10°C showed an increase in modulus, but a decrease in fatigue life with higher mixing temperatures. The high mixing temperature had little effect on the modulus but reduced the fatigue life of all mixes tested at -6°C.

9) The effect of cure time after mixing on resilient modulus and fatigue life at both testing temperatures was not significant.

10) The 5-pound surcharge weight, which was applied after compaction, increased the fatigue life and decreased the resilient modulus at +10°C. At -6°C, the fatigue life was slightly reduced and the modulus not significantly affected with the application of the surcharge.

11) The fatigue life generally increased as the air void content increased from 2 to 4%, regardless of the testing temperature. However, tests were not performed at higher voids (6-8%) which have often been reported in the field trials. This is contrary to the conventional relationship between air voids and fatigue life. The resilient modulus values at both tem-

peratures decreased as air voids increased as would be expected.

12) The effect of temperature on resilient modulus appears to be linear within the range tested. As the temperature decreases, the resilient modulus increases.

13) The effect of temperature on modulus of compacted rubber buffings was evaluated and the results show that the stiffness increases with decreasing temperature. However, the increase in stiffness from 18°C to 0°C and 0°C to -10°C are only 9% and 18% respectively.

14) The limited study of aging effects on resilient modulus, showed a small increase of modulus with age when tested at +10°C.

15) Based on the fatigue lives obtained for three different seasons, the layer equivalency for conventional to rubber-modified mixes for winter, spring thaw, and spring/fall ranged between 1.2 and 1.4 to 1.0.

6.2 Recommendations

Based on the findings of this study, the following recommendations appear warranted:

1) The incorporation of coarse rubber particles in a normal dense-graded paving mix shows considerable promise from laboratory trials and should be field tested. This approach would avoid the common problem of contractor resistance to produce the normally specified gap-graded aggregate.

2) Reduction of the 80:20 rubber content to 2% of dry aggregate and the use of a 60:40 blend of coarse to fine rubber also shows promise and should be field tested. These changes could result in cost savings and less chance of early raveling.

3) The rubber-modified mixes should continue to be placed in conjunction with a conventional surfacing for a control measure to evaluate long-term benefits and performance.

4) Alaska should develop a local supplier for rubber to reduce rubber costs.

6.3 Recommended Research

Items which need further study include:

1) Examine the need for including tests such as modulus and fatigue in the mix design process.
2) Evaluate dynamic properties of rubber-modified asphalt with higher air voids, such as 6%, 8%, and 10%.
3) Construct demonstration project(s) to compare the performance of dense-graded and gap-graded aggregate pavements with both coarse and fine rubber under field conditions.
4) Quantify the de-icing and noise benefits of rubber-modified asphalt pavements.
5) Quantify user cost differences between rubber-modified and conventional asphalt pavements.

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APPENDIX A

SUMMARY OF INITIAL (1983) AND FOLLOW-UP QUESTIONNAIRE SURVEY (1984)

Table A.1. Rubber-Modified Asphalt Project Information.

Project ID Agency	1983 Overlay Program City of Bellevue, Washington	FR 282 (71) Oklahoma Department of Transportation
	a) Initial Questionnaire	
General		
Date Constructed	9/14/82	8/17/82
Tons Mixed	220	2,570
Mix Thickness	1-1/2 inches min.	2 inches
Mix Design		
Rubber Content	3%	2.5-3.5%
Asphalt Content	7.5-9.5%	5.0-9.0%
Construction		
Mix Temp., °F	325-360	325
Mixing Time, Sec.	15	27
Compaction Temp., °F	280 min.	285
Voids in Mix, %	2-5 (Ave 4)	---
Problems	Mix was very stiff and hard to work by hand.	Introduction of volcanic ash in dryer, estimated 1% loss.
Mix Performance		
Types of Problems	Some segregation in first load placed	Areas would shove and pothole throughout the Plusride mix.
Causes of Problems	Poor mixing	
Reason for Use	Experimental - Placed to compare performance with fabric interlayer in delaying reflective cracking.	Experimental - Check Plusride formula's ability to stop reflected transverse cracking.
	b) Follow-up Questionnaire	
Present Condition		
Raveling	None	None
Bleeding	None	Moderate
Potholing	None	Moderate-None
Wheel Track Rutting	None	None
Cracking	None	None
Overall	---	Moderate-None
Effectivenss of Rubber Mix		
Ice Control	---	No
Noise Control	Yes	Yes
Reflective Crack Control	Yes	Yes
Skid Resistance	Yes	Yes
Fatigue Resistance	Yes	Yes
Comments	---	(1) The potholing occurred at the beginning of construction. The 0.2 mile potholed area was totally removed and patched. (2) The roadway exhibited transverse cracks as the major distress but the cracks close up in the summer.

Program for Economically Determining the Modified Pavement Life Versus Conventional Pavement Life

```
♦LBL "LIFECST"
"CALCULATION OF"
AVIEW
"LIFE FOR EQUAL"
AVIEW
"ANNUAL COST"
AVIEW
"COST CONV AC=?"
PROMPT
STO 01
"COST MOD.=?"
PROMPT
STO 02
"DISCOUNT RATE=?"
PROMPT
STO 03
♦LBL 15
"CONV AC LIFE=?"
PROMPT
STO 04
RCL 03
1
+
STO 05
RCL 04
Y↑X
1
-
STO 06
RCL 05
ENTER↑
RCL 04
Y↑X
RCL 03
*
ENTER↑
RCL 06
/
RCL 01
*
RCL 02
/
STO 07
ENTER↑
RCL 07
ENTER↑
RCL 03
-
/
LN
RCL 05
LN
/
"LIFE MOD="
ARCL X
AVIEW
BEEP
"PLACE X=0 IF"
AVIEW
"IF MORE MOD"
AVIEW
"LIFES ARE"
AVIEW
"REQUIRE: IF"
AVIEW
"CALCS ARE"
AVIEW
"COMPLETE, PLACE"
AVIEW
"ANY INTEGER"
AVIEW
"EQUAL TO X"
AVIEW
"X=?"
PROMPT
ENTER↑
X=0?
GTO 15
BEEP
"RUN COMPLETE"
AVIEW
"END"
END
```

System: HP41C

Required Registers = 43

Table A.3. Rubber-Modified Asphalt Project Information.

Project ID Agency	F8-2(22)28U-2 MDOH	02-189504 CALTRANS
	a) Initial Questionnaire	
General		
Date Constructed	September 1983	9/26/83 to 10/6/83
Tons Mixed	2885	7260
Mix Design		
Rubber Content	3%	3.28%
Asphalt Content	8.75%	9.41%
Construction		
Mix Temp., °F	377	350
Mixing Time, Sec.	15	20 dry/30 wet
Compaction Temp., °F	300 breakdown, 203 final	260
Voids in Mix	2	---
Problems	None	
Mix Performance		
Types of Problems	Too early to determine	Too early to determine
Causes of Problems	---	---
Reason for Use	Experimental, de-icing	Experimental
	b) Follow-up Questionnaire	
Present Condition		
Raveling	None	None
Bleeding	None	None
Potholing	None	None
Wheel Track Rutting	None	None
Cracking	None	None
Overall	None	None
Pavement Performance	**Effective**	
Ice Control	No	No
Noise Control	Yes	No
Reflective Crack Control	Yes	Yes (in less than a year)
Skid Resistance	---	No (same as conventional AC)
Fatigue Resistance	No	Yes
Comments	---	The 0.15' and 0.20' thick conventional AC control sections on the project have begun to crack heavily in places, whereas the rubberized AC, including the Plusride shows no signs of distress.

APPENDIX D

PROGRAM FOR ECONOMICALLY DETERMINING THE MODIFIED PAVEMENT LIFE VERSUS CONVENTIONAL PAVEMENT LIFE

Table A.5. Rubber-Modified Asphalt Project Information.

Project ID Agency	Upper Huffman Road Anchorage, AK / ADOTPF	Carnation Drive Fairbanks, AK / ADOTPF
	a) Initial Questionnaire	
General		
Date Constructed	1981	September 1979
Tons Mixed	---	---
Mix Thickness	3/4 inches	2 inches
Mix Design		
Rubber Content	3.0	3.0-3.5
Asphalt Content	9.5	7.5
Construction		
Mix Temp., °F	360	---
Mixing Time, Sec.	---	---
Compaction Temp., °F	---	240
Voids in Mix	up to 10%	4.6
Problems	Thin paving necessitated quick rolling	None
Mix Performance		
Types of Problems	None	None
Causes of Problems	---	---
Reason for Use	Experimental, de-icing and use very steep grade (up to 14%).	Experimental, de-icing
	b) Follow-Up Questionnaire	
Present Condition		
Raveling	None	Less than 1%
Bleeding	None	None
Potholing	None	Less than 1%
Wheel Track Rutting	None	None
Cracking	None	Similar to Conventional Asphalt
Overall	Acceptable	Acceptable
Effectiveness of Rubber Mix		
Ice Control	Not Evaluated	Yes
Noise Control	Not Evaluated	Not Evaluated
Reflective Crack Control	Not Evaluated	Not Evaluated
Skid Resistance	Not Evaluated	Yes
Fatigue Resistance	Not Evaluated	Not Evaluated
Comments		
	The pavement durability to date has been excellent.	

Table C.4. Summary of Resilient Modulus After Aging.

Sample Number	Test Condition Load (lb)	Strain (10^{-6})	Resilient Modulus (ksi)	Age (Days)
A-1	311	100	420	1
A-1	306	100	414	29
A-1	354	100	478	81
A-2	287	100	386	1
A-2	321	100	419	29
A-2	335	100	438	81
A-3	302	100	409	1
A-3	302	100	409	29
A-3	364	100	476	81
K-1	392	100	548	1
K-1	401	100	561	29
K-1	407	100	569	81
K-2	402	100	560	1
K-2	421	100	587	29
K-2	430	100	599	81
K-3	409	100	564	1
K-3	412	100	568	29
K-3	440	100	607	81

Table A.7. Rubber-Modified Asphalt Project Information.

Project ID Agency	Peger-Van Horn Intersection Fairbanks, AK / ADOTPF	Victoria Street City of Victoria, British Columbia
	a) Initial Questionnaire	
General		
Date Constructed	1981	1981
Tons Mixed	280	1,200
Mix Thickness	1-1/2 inches	---
Mix Design		
Rubber Content	3%	3%
Asphalt Content	8.0-8.5	7%
Construction		
Mix Temp., °F	310-345	---
Mixing Time, Sec.	---	---
Compaction Temp., °F	295	306
Voids in Mix	4.2	7-9%
Problems	None	---
Mix Performance		
Types of Problems	None	Raveling, confined to 1/2 of mat
Causes of Problems	---	Suspect that one-half of screen was not vibrating.
Reason for Use	Experimental, de-icing	Experimental - fatigue resistance.
	b) Follow-Up Questionnaire	
Present Condition		
Raveling	Less than 15%	No response received
Bleeding	None	
Potholing	Less than 15%	
Wheel Track Rutting	None	
Cracking	None	
Overall	Not Acceptable	
Effectiveness of Rubber Mix		
Ice Control	Yes	
Noise Control	Not Evaluated	
Reflective Crack Control	Not Evaluated	
Skid Resistance	Yes	
Fatigue Resistance	Not Evaluated	
Comments	The causes of the problems appear to be compounded by the lack of a stabilized layer beneath the rubber-modified mix	

Table C.3. Summary of Modulus and Fatigue Data at -6°C (Cont.).

Sample Number	Air Voids (%)	Test Condition Load (Lb)	Test Condition Strain (10^{-6})	Resilient Modulus (ksi)	Fatigue Life
H-11	1.97	1802	100	2499	47,743
H-12	2.12	1753	100	2409	48,254
I-5	2.32	1510	100	2049	34,151
I-6	2.31	1592	100	2177	43,256
I-7	2.12	1558	100	2145	47,116
I-8	2.22	1617	100	2225	40,252
J-5	4.02	1266	100	1657	42,764
J-6	3.85	1422	100	1861	48,123
J-7	4.18	1460	100	1842	38,926
K-12*	1.91	1851	100	2583	33,202
K-13	2.23	1695	100	2400	87,087
K-14	2.24	1646	100	2353	96,851
K-15	2.12	1604	100	2301	83,250
L-4	2.27	1826	100	2617	71,780
L-5	2.18	1665	100	2362	80,943
L-6	2.22	1753	100	2486	73,252
M-12*	2.37	1534	100	2183	80,329
M-13	2.33	1851	100	2613	40,321
M-14	2.33	1811	100	2564	43,256
N-12*	2.43	1924	100	2651	101,222
N-13	2.17	1704	100	2349	121,216
N-14	2.06	1656	100	2243	132,121
N-15	2.29	2167	130	2271	82,762
N-16	2.17	2118	130	2193	65,624
N-17	2.42	2215	130	2269	71,402
N-18	2.18	974	70	1884	191,262
N-19	2.32	1071	70	2094	221,202
N-20	2.05	1120	70	2183	185,216
O-5*	2.12	1802	100	2503	209,004
O-6	1.93	1705	100	2406	98,829
O-7	2.42	1870	100	2690	77,372
O-8	2.11	1924	100	2681	114,895
P-5	2.29	1558	100	2111	78,577

*The results were not included in the statistical analysis.

Table A.9. Rubber-Modified Asphalt Project Information.

Project ID Agency	Mordialloc Road Trial Country Roads Board of Victoria, Australia	Second Kingsway Trial Country Roads Board of Victoria, Australia
	a) Initial Questionnaire	
General		
Date Constructed	1977	3/26/77
Tons Mixed	---	---
Mix Thickness	1-1/4 inches	1-1/4 inches
Mix Design		
Rubber Content	3.0%	3.0%
Asphalt Content	7.5%	8.3%
Construction		
Mix Temp., °F	360-400	360-400
Mixing Time, Sec.	10-12 dry, 35 wet	10-12 dry, 35 wet
Compaction Temp., °F	---	---
Voids in Mix	9.4%	2.9%
Problems	---	---
Mix Performance		
Types of Problems	Raveling	None, after 7 months
Causes of Problems	---	---
Reason for Use	Experimental to Determine Reflective Cracking Control.	Experimental
	b) Follow-Up Questionnaire	
	No response received.	

Table C.2. Summary of Modulus and Fatigue Data at +10° C (Cont.).

Sample Number	Air Voids (%)	Test Condition Load (Lb)	Test Condition Strain (10^{-6})	Resilient Modulus (ksi)	Fatigue Life
Q-5	1.90	475	100	662	9,284
Q-6	2.02	741	100	1028	6,464
R-1	1.81	514	100	706	21,312
R-2	2.06	494	100	681	17,153
R-3	2.02	497	100	675	164,582
R-4	2.23	526	100	720	13,424
S-1	3.28	397	100	531	9,019
S-2	4.59	254	100	332	13,722
S-3	5.55	268	100	347	16,498
S-4	3.62	282	100	376	9,121
T-1	2.16	465	75	869	96,461
T-2	2.22	631	75	1174	12,030
T-3	2.63	679	75	1253	19,253
T-4	2.66	574	85	1009	10,641
T-5	2.96	545	85	952	17,487
T-6	2.82	612	85	999	8,924
T-7	1.82	885	100	1250	10,144
T-8	2.33	670	100	963	5,560
T-9	1.94	670	100	940	10,721
T-10	2.17	586	100	815	7,599
T-11	2.11	727	100	1030	19,253
T-12	2.41	775	100	1109	12,592
T-13	2.64	602	100	906	17,417
T-14	2.88	603	100	892	25,321
T-15	2.61	794	150	779	6,638
T-16	2.09	794	150	974	2,592
T-18	2.29	768	150	707	2,250

* Information on Rubber Materials *

Name of Supplier:________________________________ Location:________________

Form Completed By:____________________ Phone #: (   ) ________________

Address: ____

Coarse Rubber (1/4" to No. 10 sieve):

Source of Tires Used: Auto ________ Heavy Truck & Bus ________

Heavy Offroad Equipment______ Light Truck _____

Type of Tire: Fabric ________, Steel Belted ________, Studded_____,

Buffings from Recapping _____, Other ______________

Portion of Tire Used: All __________, Tread Rubber Only __________.

Method of Processing: Ground at ambient temperature __________

Cryogenically ground ____________, Other ________________________

Tests Run on Rubber:

Gradation ______, Shape ______, Specific Gravity ______, Absorption _____,

Percent Synthetic/Natural ______, Percent Carbon Black _______,

Other ____

Fine Rubber (Minus #10 sieve):

Source of Tires Used: Auto ________ Heavy Truck & Bus __________

Heavy Offroad Equipment ____ Light Truck ________

Type of Tire: Fabric ________, Steel Belted ________, Studded_____,

Buffings from Recapping _____, Other ______________

Portion of Tire Used: All __________, Tread Rubber Only __________.

Method of Processing: Ground at ambient temperature __________

Cryogenically ground ____________, Other ________________________

Tests Run on Rubber:

Gradation ______, Shape ______, Specific Gravity ______, Absorption _____,

Percent Synthetic/Natural ______, Percent Carbon Black _______,

Bulk Density _______, Other ___________________________________.

Figure A.1 Initial Questionnaire Form

Table C.2. Summary of Modulus and Fatigue Data at +10°C (Cont.).

Sample Number	Air Voids (%)	Test Condition Load (Lb)	Test Condition Strain (10^{-6})	Resilient Modulus (ksi)	Fatigue Life
F-1	2.26	239	100	324	88,226
F-2	1.92	364	100	501	80,082
F-3	1.84	220	100	304	81,942
F-4	2.14	239	100	326	89,846
F-5	1.66	373	100	511	71,704
F-6	1.75	268	100	365	116,268
G-1	4.46	297	100	394	39,426
G-2	3.96	278	100	370	41,356
G-3	4.60	268	100	360	47,349
H-1	2.14	511	100	710	12,420
H-2	2.16	808	100	1122	6,016
H-3	2.24	814	100	1045	7,250
H-4	2.25	823	100	1071	4,924
H-5	2.14	450	100	615	9,536
H-6	2.22	421	100	580	12,158
H-7	2.02	379	100	515	20,398
H-8	2.48	473	100	650	11,265
I-1	2.67	325	100	445	18,270
I-2	2.33	440	100	614	13,804
I-3	2.62	335	100	462	16,785
I-4	2.12	430	100	592	17,791
J-1	4.06	277	100	373	21,348
J-2	4.06	296	100	393	15,486
J-3	4.60	277	100	367	28,556
J-4	3.90	268	100	363	23,410
K-1	2.39	239	85	398	68,876
K-2	2.58	253	85	415	27,965
K-3	1.98	230	85	376	78,324
K-4	1.99	246	85	399	70,339
K-5	2.29	330	100	482	26,049
K-6	2.08	344	100	486	34,265
K-7	2.41	311	100	446	26,262
K-8	2.57	516	150	440	1,061
K-9	2.70	440	150	374	6,430
K-10	2.78	497	150	426	5,548
K-11	2.41	468	150	433	9,201

APPENDIX B

DESCRIPTION OF LEMON ROAD PROJECT (RS-0955(1))

Table C.1. Specimen Identification.

Sample Symbol	Rubber Content (%)	Rubber Blend (% Fine/% Coarse)	Mixing/Compaction Temperature (°F)	Asphalt Content (%)	Aggregate Gradation	Cure Time (hrs)	Surcharge (lbs)
A	3	80/20	375/265	9.3	Gap	0	0
B	3	80/20	375/265	9.3	Gap	2	0
C	3	80/20	375/265	9.3	Gap	0	5
D	3	80/20	425/265	9.3	Gap	0	0
E	3	80/20	425/265	9.3	Gap	2	0
F	3	80/20	425/265	9.3	Gap	0	5
G	3	80/20	375/210	9.3	Gap	0	0
H	3	60/40	375/265	7.5	Gap	0	0
I	3	0/100	375/265	7.5	Gap	0	0
J	3	80/20	425/210	9.3	Gap	0	0
K	2	80/20	375/265	8.0	Gap	0	0
L	2	60/40	375/265	7.2	Gap	0	0
M	2	60/40	375/265	7.0	Gap	0	0
N	3	80/20	375/265	7.5	Dense	0	0
O	3	80/20	375/265	7.5	Dense	2	0
P	3	80/20	375/265	7.5	Dense	0	5
Q	3	80/20	425/265	7.5	Dense	0	0
R	3	80/20	425/265	7.5	Dense	0	0
S	3	80/20	375/210	7.5	Dense	0	0
T	0	0	375/265	5.5	Dense	0	0

1.0 WORK PLAN

1.1 Objective

The objective of this project is to evaluate the performance of an asphalt concrete pavement constructed with the addition of 3% of 1/4-inch minus-sized rubber particles produced from ground-up waste tires. The addition of the rubber particles is expected to provide: 1) a benefit from reduced roadway surface ice deposits as a result of flexure and ice bonding action, 2) improved skid resistance, and 3) increased pavement life as a result of improved fatigue failure resistance.

1.2 Project Description

The Lemon Road project is located approximately 5-1/2 miles northwest of Juneau within the flood plain of Lemon Creek. A quantity of 2,279 tons of rubberized asphalt pavement was incorporated into the project as a 48-foot wide interim finish course pavement between stations "L" 260+75 and "L" 311+50. The approximate mat thickness was 1-1/2 inches. Testing, evaluation, and reporting was performed by personnel from the Southeast Region Materials Section with the assistance of mix design and evaluation by staff of the Central Region Materials Laboratory.

1.3 Observations

The performance of the rubber section is compared to the adjacent new conventional asphalt concrete pavement placed under the general paving project. Observation includes skid testing with a "Tapley" decelerometer mounted in a light passenger vehicle, Benkleman Beam deflection testing, laboratory testing of cored samples for density and resilient properties, and repeated visual observation for surface de-icing characteristics.

Information derived from this project is reported along with updated data on previously constructed rubberized asphalt concrete projects within the State. Expected construction staging and a minimum of one winter's observations delayed completion of this appendix until January 1985. Final recommendations for the future use of rubberized asphalt concrete in Alaska will be presented in a follow-up report.

APPENDIX C

TEST DATA

Mix design information for the target value asphalt content of 8.6% was:

Characteristic	Value
Unit weight (pcf)	144.1
Stability (lbs)	820
Flow (1/100 inch)	19
Voids filled (%)	94
Voids total mix (%)	1.1
Aggregate blend specific gravity	2.757
Mixing Temperature	350° to 375°F

3.0 CONSTRUCTION OPERATIONS AND JOB CONTROL

3.1 Construction Operations

The contract for the project was awarded to:

TRI State Construction
Box 3-600, Suite 34
Juneau, Alaska 99807

A project meeting was held on August 10, 1983 between the ADOTPF, the contractor, and representatives from All Seasons Surfacing Corporation. Items discussed included:

1) Mix Temperatures. The mix temperature at the paver should be 300°F.
2) Compaction Procedures. The contractor should use vibratory compactors for breakdown and not use rubber-tired rollers.
3) Test Strip. The contractor believes his gradation will be within specifications after a run through the plant. Specific questions raised were:
    a) What happens if the test strip is out of specifications?
    b) What happens if the rubber shows up as oil in the nuclear gauge?
    c) The rubber asphalt portion of the project should be completed as early as possible before the cutoff date.

A 100-ton test strip was placed on August 19, 1983. The first truckload looked dry; hence, the oil content was increased 0.2%. The laydown went

Table B.5. Life Cycle Cost Comparisons for Lemon Road, Juneau, Alaska.

Assumptions: Discount Rate = 4.0%
Crack Seal Maintenance Cost = \$0.10/s.y.
Chip Seal Maintenance Cost = \$0.40/s.y.
Conventional Mix Cost Without Binder = \$33.40/ton
Binder Cost = \$293/ton
Rubber Cost = \$400/ton
A-R Mix Without Binder and Rubber Cost = \$57.50/ton
Salvage Value = \$0.00 at the end of economic life
Unit Weight = 141 pcf

Alternative No. 1: Conventional Asphaltic Concrete with 6.5% Asphaltic Concrete Binder

Year	\$ Cost/s.y.	Description
0	4.16	1-1/2" surfacing
4	0.10	Crack seal
8	0.40	Chip seal
12	0.10	Crack seal
15	-	End of economic life

$AE_1(4)$ = + 4.16 (A/P, 4, 15) + 0.10 (P/F, 4, 4)(A/P, 4, 15) + 0.40 (P/F, 4, 8)(A/P, 4, 15) + 0.10 (P/F, 4,12) (A/P, 4, 15)

$AE_1(4)$ = \$0.42./s.y.

Alternative No. 2: Plusride, Asphalt Binder Average of 9.1%, 3% Coarse Rubber, Gap-Graded, and 8% Unit Weight Reduction as Compared to Conventional Mix

Year	\$ Cost/s.y	Description
0	6.90	1-1/2" Surfacing
10	0.10	Crack seal
20	0.40	Chip seal
30	0.10	Crack seal
40	-	End of economic life

$AE_2(4)$ = + 6.90 (A/P, 4, 40) + 0.10 (P/F, 4, 10)(A/P, 4, 40) + 0.40 (P/F, 4, 20)(A/P, 4, 40) + 0.10 (P/F, 4, 30) (A/P, 4, 40)

$AE_2(4)$ = \$0.36/s.y.

6) Mat shoving was most noticeable when the base was primed and was not strengthened by chips or sand.
7) The contractor must be required to use a wetting agent on roller drums.

3.3 Project Control

Tables B.1 and B.2 summarize results of ADOT/PF tests taken from the project. Note the circled sample properties indicate the value does not meet the project specifications. Both samples exhibited low voids.

4.0 PERFORMANCE

The Lemon Road performance evaluation consists of "Tapley" skid testing, Benkleman Beam deflection testing, visual observation of surface de-icing characteristics, and laboratory testing of control and rubber-modified core samples for bulk specific gravity and resilient properties. Part of the laboratory testing (resilient properties) was to be performed at Oregon State University. The sections which follow in this appendix summarize the results of those tests.

Upon receipt at OSU, the Lemon Road cores were measured for overall dimensions and top lift thickness. The measurements are summarized in Table B.3.

4.1 Test Summary and Economic Analysis of Fatigue Results

Table B.4 presents the average resilient modulus and fatigue test results from the Lemon Road cores. The fatigue life versus tensile strain is shown in Figure B.1. Evaluating the curves at 100 and 200 microstrain values gives fatigue lives for the rubber asphalt mixes 3 times and 2 times (respectively) greater than the conventional asphalt pavement.

The economic impact of the increased fatigue life and the 8% reduction in bulk specific gravity is approximated in Table B.5. This table was constructed using the same assumptions as section 5.2.1 in the report. No

Table B.3. Lemon Road Core Sample Identification.

Sample Identification	Sample Number	Core Diameter (inches)	Core Length (inches)	Top Lift Thickness (inches)
R-C (rubber asphalt from the center of lane)	1	3-1/2	5-1/2	1-3/4
	2	3-1/2	10	1-3/4
	3	3-1/2	5	1-3/4
	4	3-1/2	5	1-3/4
R-W (rubber asphalt from the wheel path)	5	3-1/2	5-3/4	1-1/2
	6	3-1/2	1-1/2	1-1/2
	7	3-1/2	3-1/4	1-1/2
	8	3-1/2	10	1-3/4
W-R Control (Class II asphalt from the wheel path)	9	3-1/2	6-1/2	1-3/4
	10	3-1/2	6-1/2	2
	11	3-1/2	6-3/4	1-3/4
	12	3-1/2	6-1/2	1-3/4
C Control (Class II asphalt from the center of the lane)	13	3-1/2	6-1/2	2
	14	3-1/2	6-1/2	2
	15	3-1/2	6-1/2	1-1/2
	16	3-1/2	6-1/2	1-3/4

Note: Testing by OSU was performed on the top lift of each core sample.

Table B.4. Bulk Specific Gravity, Modulus, and Fatigue Test Results of Lemon Road Cores.

Sample Identification	Strain (μs)	Bulk Specific Gravity	Resilient* Modulus (ksi)	Fatigue* Life
Class II asphalt	100	2.451	922	8,345
	150	2.447	817	2,939
	200	2.454	919	1,589
Rubberized asphalt	100	2.293	357	15,556
	150	2.283	328	7,750
	200	2.262	402	3,752

*Test Temperature = 10°C
Load Duration = 0.1 s
Load Frequency = 1 Hz

Table B.3. Lemon Road Core Sample Identification.

Sample Identification	Sample Number	Core Diameter (inches)	Core Length (inches)	Top Lift Thickness (inches)
R-C (rubber asphalt from the center of lane)	1	3-1/2	5-1/2	1-3/4
	2	3-1/2	10	1-3/4
	3	3-1/2	5	1-3/4
	4	3-1/2	5	1-3/4
R-W (rubber asphalt from the wheel path)	5	3-1/2	5-3/4	1-1/2
	6	3-1/2	1-1/2	1-1/2
	7	3-1/2	3-1/4	1-1/2
	8	3-1/2	10	1-3/4
W-R Control (Class II asphalt from the wheel path)	9	3-1/2	6-1/2	1-3/4
	10	3-1/2	6-1/2	2
	11	3-1/2	6-3/4	1-3/4
	12	3-1/2	6-1/2	1-3/4
C Control (Class II asphalt from the center of the lane)	13	3-1/2	6-1/2	2
	14	3-1/2	6-1/2	2
	15	3-1/2	6-1/2	1-1/2
	16	3-1/2	6-1/2	1-3/4

Note: Testing by OSU was performed on the top lift of each core sample.

Table B.4. Bulk Specific Gravity, Modulus, and Fatigue Test Results of Lemon Road Cores.

Sample Identification	Strain (μs)	Bulk Specific Gravity	Resilient* Modulus (ksi)	Fatigue* Life
Class II asphalt	100	2.451	922	8,345
	150	2.447	817	2,939
	200	2.454	919	1,589
Rubberized asphalt	100	2.293	357	15,556
	150	2.283	328	7,750
	200	2.262	402	3,752

*Test Temperature = $10^{\circ}C$
Load Duration = 0.1 s
Load Frequency = 1 Hz

6) Mat shoving was most noticeable when the base was primed and was not strengthened by chips or sand.

7) The contractor must be required to use a wetting agent on roller drums.

3.3 Project Control

Tables B.1 and B.2 summarize results of ADOT/PF tests taken from the project. Note the circled sample properties indicate the value does not meet the project specifications. Both samples exhibited low voids.

4.0 PERFORMANCE

The Lemon Road performance evaluation consists of "Tapley" skid testing, Benkleman Beam deflection testing, visual observation of surface de-icing characteristics, and laboratory testing of control and rubber-modified core samples for bulk specific gravity and resilient properties. Part of the laboratory testing (resilient properties) was to be performed at Oregon State University. The sections which follow in this appendix summarize the results of those tests.

Upon receipt at OSU, the Lemon Road cores were measured for overall dimensions and top lift thickness. The measurements are summarized in Table B.3.

4.1 Test Summary and Economic Analysis of Fatigue Results

Table B.4 presents the average resilient modulus and fatigue test results from the Lemon Road cores. The fatigue life versus tensile strain is shown in Figure B.1. Evaluating the curves at 100 and 200 microstrain values gives fatigue lives for the rubber asphalt mixes 3 times and 2 times (respectively) greater than the conventional asphalt pavement.

The economic impact of the increased fatigue life and the 8% reduction in bulk specific gravity is approximated in Table B.5. This table was constructed using the same assumptions as section 5.2.1 in the report. No

Table B.5. Life Cycle Cost Comparisons for Lemon Road, Juneau, Alaska.

Assumptions: Discount Rate = 4.0%
Crack Seal Maintenance Cost = \$0.10/s.y.
Chip Seal Maintenance Cost = \$0.40/s.y.
Conventional Mix Cost Without Binder = \$33.40/ton
Binder Cost = \$293/ton
Rubber Cost = \$400/ton
A-R Mix Without Binder and Rubber Cost = \$57.50/ton
Salvage Value = \$0.00 at the end of economic life
Unit Weight = 141 pcf

Alternative No. 1: Conventional Asphaltic Concrete with 6.5% Asphaltic Concrete Binder

Year	\$ Cost/s.y.	Description
0	4.16	1-1/2" surfacing
4	0.10	Crack seal
8	0.40	Chip seal
12	0.10	Crack seal
15	-	End of economic life

$AE_1(4)$ = + 4.16 (A/P, 4, 15) + 0.10 (P/F, 4, 4)(A/P, 4, 15) + 0.40 (P/F, 4, 8)(A/P, 4, 15) + 0.10 (P/F, 4,12) (A/P, 4, 15)

$AE_1(4)$ = \$0.42./s.y.

Alternative No. 2: Plusride, Asphalt Binder Average of 9.1%, 3% Coarse Rubber, Gap-Graded, and 8% Unit Weight Reduction as Compared to Conventional Mix

Year	\$ Cost/s.y	Description
0	6.90	1-1/2" Surfacing
10	0.10	Crack seal
20	0.40	Chip seal
30	0.10	Crack seal
40	-	End of economic life

$AE_2(4)$ = + 6.90 (A/P, 4, 40) + 0.10 (P/F, 4, 10)(A/P, 4, 40) + 0.40 (P/F, 4, 20)(A/P, 4, 40) + 0.10 (P/F, 4, 30) (A/P, 4, 40)

$AE_2(4)$ = \$0.36/s.y.

Mix design information for the target value asphalt content of 8.6% was:

Characteristic	Value
Unit weight (pcf)	144.1
Stability (lbs)	820
Flow (1/100 inch)	19
Voids filled (%)	94
Voids total mix (%)	1.1
Aggregate blend specific gravity	2.757
Mixing Temperature	350° to 375°F

3.0 CONSTRUCTION OPERATIONS AND JOB CONTROL

3.1 Construction Operations

The contract for the project was awarded to:

TRI State Construction
Box 3-600, Suite 34
Juneau, Alaska 99807

A project meeting was held on August 10, 1983 between the ADOTPF, the contractor, and representatives from All Seasons Surfacing Corporation. Items discussed included:

1) Mix Temperatures. The mix temperature at the paver should be 300°F.
2) Compaction Procedures. The contractor should use vibratory compactors for breakdown and not use rubber-tired rollers.
3) Test Strip. The contractor believes his gradation will be within specifications after a run through the plant. Specific questions raised were:
   a) What happens if the test strip is out of specifications?
   b) What happens if the rubber shows up as oil in the nuclear gauge?
   c) The rubber asphalt portion of the project should be completed as early as possible before the cutoff date.

A 100-ton test strip was placed on August 19, 1983. The first truckload looked dry; hence, the oil content was increased 0.2%. The laydown went

APPENDIX C

TEST DATA

1.0 WORK PLAN

1.1 Objective

The objective of this project is to evaluate the performance of an asphalt concrete pavement constructed with the addition of 3% of 1/4-inch minus-sized rubber particles produced from ground-up waste tires. The addition of the rubber particles is expected to provide: 1) a benefit from reduced roadway surface ice deposits as a result of flexure and ice bonding action, 2) improved skid resistance, and 3) increased pavement life as a result of improved fatigue failure resistance.

1.2 Project Description

The Lemon Road project is located approximately 5-1/2 miles northwest of Juneau within the flood plain of Lemon Creek. A quantity of 2,279 tons of rubberized asphalt pavement was incorporated into the project as a 48-foot wide interim finish course pavement between stations "L" 260+75 and "L" 311+50. The approximate mat thickness was 1-1/2 inches. Testing, evaluation, and reporting was performed by personnel from the Southeast Region Materials Section with the assistance of mix design and evaluation by staff of the Central Region Materials Laboratory.

1.3 Observations

The performance of the rubber section is compared to the adjacent new conventional asphalt concrete pavement placed under the general paving project. Observation includes skid testing with a "Tapley" decelerometer mounted in a light passenger vehicle, Benkleman Beam deflection testing, laboratory testing of cored samples for density and resilient properties, and repeated visual observation for surface de-icing characteristics.

Information derived from this project is reported along with updated data on previously constructed rubberized asphalt concrete projects within the State. Expected construction staging and a minimum of one winter's observations delayed completion of this appendix until January 1985. Final recommendations for the future use of rubberized asphalt concrete in Alaska will be presented in a follow-up report.

Table C.1. Specimen Identification.

Sample Symbol	Rubber Content (%)	Rubber Blend (% Fine/% Coarse)	Mixing/Compaction Temperature (°F)	Asphalt Content (%)	Aggregate Gradation	Cure Time (hrs)	Surcharge (lbs)
A	3	80/20	375/265	9.3	Gap	0	0
B	3	80/20	375/265	9.3	Gap	2	0
C	3	80/20	375/265	9.3	Gap	0	5
D	3	80/20	425/265	9.3	Gap	0	0
E	3	80/20	425/265	9.3	Gap	2	0
F	3	80/20	425/265	9.3	Gap	0	5
G	3	80/20	375/210	9.3	Gap	0	0
H	3	60/40	375/265	7.5	Gap	0	0
I	3	0/100	375/265	7.5	Gap	0	0
J	3	80/20	425/210	9.3	Gap	0	0
K	2	80/20	375/265	8.0	Gap	0	0
L	2	60/40	375/265	7.2	Gap	0	0
M	2	60/40	375/265	7.0	Gap	0	0
N	3	80/20	375/265	7.5	Dense	0	0
O	3	80/20	375/265	7.5	Dense	2	0
P	3	80/20	375/265	7.5	Dense	0	5
Q	3	80/20	425/265	7.5	Dense	0	0
R	3	80/20	425/265	7.5	Dense	0	0
S	3	80/20	375/210	7.5	Dense	0	0
T	0	0	375/265	5.5	Dense	0	0

APPENDIX B

DESCRIPTION OF LEMON ROAD PROJECT (RS-0955(1))

Table C.2. Summary of Modulus and Fatigue Data at +10°C (Cont.).

Sample Number	Air Voids (%)	Test Condition Load (Lb)	Test Condition Strain (10^{-6})	Resilient Modulus (ksi)	Fatigue Life
F-1	2.26	239	100	324	88,226
F-2	1.92	364	100	501	80,082
F-3	1.84	220	100	304	81,942
F-4	2.14	239	100	326	89,846
F-5	1.66	373	100	511	71,704
F-6	1.75	268	100	365	116,268
G-1	4.46	297	100	394	39,426
G-2	3.96	278	100	370	41,356
G-3	4.60	268	100	360	47,349
H-1	2.14	511	100	710	12,420
H-2	2.16	808	100	1122	6,016
H-3	2.24	814	100	1045	7,250
H-4	2.25	823	100	1071	4,924
H-5	2.14	450	100	615	9,536
H-6	2.22	421	100	580	12,158
H-7	2.02	379	100	515	20,398
H-8	2.48	473	100	650	11,265
I-1	2.67	325	100	445	18,270
I-2	2.33	440	100	614	13,804
I-3	2.62	335	100	462	16,785
I-4	2.12	430	100	592	17,791
J-1	4.06	277	100	373	21,348
J-2	4.06	296	100	393	15,486
J-3	4.60	277	100	367	28,556
J-4	3.90	268	100	363	23,410
K-1	2.39	239	85	398	68,876
K-2	2.58	253	85	415	27,965
K-3	1.98	230	85	376	78,324
K-4	1.99	246	85	399	70,339
K-5	2.29	330	100	482	26,049
K-6	2.08	344	100	486	34,265
K-7	2.41	311	100	446	26,262
K-8	2.57	516	150	440	1,061
K-9	2.70	440	150	374	6,430
K-10	2.78	497	150	426	5,548
K-11	2.41	468	150	433	9,201

* Information on Rubber Materials *

Name of Supplier:______________________________ Location:________________

Form Completed By:____________________ Phone #: (   ) ________________

Address: ____

Coarse Rubber (1/4" to No. 10 sieve):

Source of Tires Used: Auto _________ Heavy Truck & Bus _______

Heavy Offroad Equipment______ Light Truck _____

Type of Tire: Fabric _________, Steel Belted _______, Studded_____,

Buffings from Recapping _____, Other ________________

Portion of Tire Used: All ___________, Tread Rubber Only __________.

Method of Processing: Ground at ambient temperature __________

Cryogenically ground _____________, Other _________________________

Tests Run on Rubber:

Gradation ______, Shape ______, Specific Gravity ______, Absorption _____,

Percent Synthetic/Natural ______, Percent Carbon Black _______,

Other ____

Fine Rubber (Minus #10 sieve):

Source of Tires Used: Auto __________ Heavy Truck & Bus ___________

Heavy Offroad Equipment ____ Light Truck _________

Type of Tire: Fabric _________, Steel Belted _______, Studded_____,

Buffings from Recapping _____, Other ________________

Portion of Tire Used: All ___________, Tread Rubber Only __________.

Method of Processing: Ground at ambient temperature __________

Cryogenically ground _____________, Other _________________________

Tests Run on Rubber:

Gradation ______, Shape ______, Specific Gravity ______, Absorption _____,

Percent Synthetic/Natural ______, Percent Carbon Black _______,

Bulk Density _______, Other ____.

Figure A.1 Initial Questionnaire Form

Table C.2. Summary of Modulus and Fatigue Data at +10°C (Cont.).

Sample Number	Air Voids (%)	Test Condition Load (Lb)	Test Condition Strain (10^{-6})	Resilient Modulus (ksi)	Fatigue Life
Q-5	1.90	475	100	662	9,284
Q-6	2.02	741	100	1028	6,464
R-1	1.81	514	100	706	21,312
R-2	2.06	494	100	681	17,153
R-3	2.02	497	100	675	164,582
R-4	2.23	526	100	720	13,424
S-1	3.28	397	100	531	9,019
S-2	4.59	254	100	332	13,722
S-3	5.55	268	100	347	16,498
S-4	3.62	282	100	376	9,121
T-1	2.16	465	75	869	96,461
T-2	2.22	631	75	1174	12,030
T-3	2.63	679	75	1253	19,253
T-4	2.66	574	85	1009	10,641
T-5	2.96	545	85	952	17,487
T-6	2.82	612	85	999	8,924
T-7	1.82	885	100	1250	10,144
T-8	2.33	670	100	963	5,560
T-9	1.94	670	100	940	10,721
T-10	2.17	586	100	815	7,599
T-11	2.11	727	100	1030	19,253
T-12	2.41	775	100	1109	12,592
T-13	2.64	602	100	906	17,417
T-14	2.88	603	100	892	25,321
T-15	2.61	794	150	779	6,638
T-16	2.09	794	150	974	2,592
T-18	2.29	768	150	707	2,250

Table A.9. Rubber-Modified Asphalt Project Information.

Project ID Agency	Mordialloc Road Trial Country Roads Board of Victoria, Australia	Second Kingsway Trial Country Roads Board of Victoria, Australia
	a) Initial Questionnaire	
General		
Date Constructed	1977	3/26/77
Tons Mixed	---	---
Mix Thickness	1-1/4 inches	1-1/4 inches
Mix Design		
Rubber Content	3.0%	3.0%
Asphalt Content	7.5%	8.3%
Construction		
Mix Temp., °F	360-400	360-400
Mixing Time, Sec.	10-12 dry, 35 wet	10-12 dry, 35 wet
Compaction Temp., °F	---	---
Voids in Mix	9.4%	2.9%
Problems	---	---
Mix Performance		
Types of Problems	Raveling	None, after 7 months
Causes of Problems	---	---
Reason for Use	Experimental to Determine Reflective Cracking Control.	Experimental
	b) Follow-Up Questionnaire	
	No response received.	

Table C.3. Summary of Modulus and Fatigue Data at -6°C (Cont.).

Sample Number	Air Voids (%)	Test Condition Load (Lb)	Test Condition Strain (10^{-6})	Resilient Modulus (ksi)	Fatigue Life
H-11	1.97	1802	100	2499	47,743
H-12	2.12	1753	100	2409	48,254
I-5	2.32	1510	100	2049	34,151
I-6	2.31	1592	100	2177	43,256
I-7	2.12	1558	100	2145	47,116
I-8	2.22	1617	100	2225	40,252
J-5	4.02	1266	100	1657	42,764
J-6	3.85	1422	100	1861	48,123
J-7	4.18	1460	100	1842	38,926
K-12*	1.91	1851	100	2583	33,202
K-13	2.23	1695	100	2400	87,087
K-14	2.24	1646	100	2353	96,851
K-15	2.12	1604	100	2301	83,250
L-4	2.27	1826	100	2617	71,780
L-5	2.18	1665	100	2362	80,943
L-6	2.22	1753	100	2486	73,252
M-12*	2.37	1534	100	2183	80,329
M-13	2.33	1851	100	2613	40,321
M-14	2.33	1811	100	2564	43,256
N-12*	2.43	1924	100	2651	101,222
N-13	2.17	1704	100	2349	121,216
N-14	2.06	1656	100	2243	132,121
N-15	2.29	2167	130	2271	82,762
N-16	2.17	2118	130	2193	65,624
N-17	2.42	2215	130	2269	71,402
N-18	2.18	974	70	1884	191,262
N-19	2.32	1071	70	2094	221,202
N-20	2.05	1120	70	2183	185,216
O-5*	2.12	1802	100	2503	209,004
O-6	1.93	1705	100	2406	98,829
O-7	2.42	1870	100	2690	77,372
O-8	2.11	1924	100	2681	114,895
P-5	2.29	1558	100	2111	78,577

*The results were not included in the statistical analysis.

Table A.7. Rubber-Modified Asphalt Project Information.

Project ID Agency	Peger-Van Horn Intersection Fairbanks, AK / ADOTPF	Victoria Street City of Victoria, British Columbia
	a) Initial Questionnaire	
General		
Date Constructed	1981	1981
Tons Mixed	280	1,200
Mix Thickness	1-1/2 inches	---
Mix Design		
Rubber Content	3%	3%
Asphalt Content	8.0-8.5	7%
Construction		
Mix Temp., °F	310-345	---
Mixing Time, Sec.	---	---
Compaction Temp., °F	295	306
Voids in Mix	4.2	7-9%
Problems	None	---
Mix Performance		
Types of Problems	None	Raveling, confined to 1/2 of mat
Causes of Problems	---	Suspect that one-half of screen was not vibrating.
Reason for Use	Experimental, de-icing	Experimental - fatigue resistance.
	b) Follow-Up Questionnaire	
Present Condition		
Raveling	Less than 15%	No response received
Bleeding	None	
Potholing	Less than 15%	
Wheel Track Rutting	None	
Cracking	None	
Overall	Not Acceptable	
Effectiveness of Rubber Mix		
Ice Control	Yes	
Noise Control	Not Evaluated	
Reflective Crack Control	Not Evaluated	
Skid Resistance	Yes	
Fatigue Resistance	Not Evaluated	
Comments	The causes of the problems appear to be compounded by the lack of a stabilized layer beneath the rubber-modified mix	

Table C.4. Summary of Resilient Modulus After Aging.

Sample Number	Test Condition Load (lb)	Strain (10^{-6})	Resilient Modulus (ksi)	Age (Days)
A-1	311	100	420	1
A-1	306	100	414	29
A-1	354	100	478	81
A-2	287	100	386	1
A-2	321	100	419	29
A-2	335	100	438	81
A-3	302	100	409	1
A-3	302	100	409	29
A-3	364	100	476	81
K-1	392	100	548	1
K-1	401	100	561	29
K-1	407	100	569	81
K-2	402	100	560	1
K-2	421	100	587	29
K-2	430	100	599	81
K-3	409	100	564	1
K-3	412	100	568	29
K-3	440	100	607	81

Table A.5. Rubber-Modified Asphalt Project Information.

Project ID Agency	Upper Huffman Road Anchorage, AK / ADOTPF	Carnation Drive Fairbanks, AK / ADOTPF
	a) Initial Questionnaire	
General		
Date Constructed	1981	September 1979
Tons Mixed	---	---
Mix Thickness	3/4 inches	2 inches
Mix Design		
Rubber Content	3.0	3.0-3.5
Asphalt Content	9.5	7.5
Construction		
Mix Temp., °F	360	---
Mixing Time, Sec.	---	---
Compaction Temp., °F	---	240
Voids in Mix	up to 10%	4.6
Problems	Thin paving necessitated quick rolling	None
Mix Performance		
Types of Problems	None	None
Causes of Problems	---	---
Reason for Use	Experimental, de-icing and use very steep grade (up to 14%).	Experimental, de-icing
	b) Follow-Up Questionnaire	
Present Condition		
Raveling	None	Less than 1%
Bleeding	None	None
Potholing	None	Less than 1%
Wheel Track Rutting	None	None
Cracking	None	Similar to Conventional Asphalt
Overall	Acceptable	Acceptable
Effectiveness of Rubber Mix		
Ice Control	Not Evaluated	Yes
Noise Control	Not Evaluated	Not Evaluated
Reflective Crack Control	Not Evaluated	Not Evaluated
Skid Resistance	Not Evaluated	Yes
Fatigue Resistance	Not Evaluated	Not Evaluated
Comments		
	The pavement durability to date has been excellent.	

APPENDIX D

PROGRAM FOR ECONOMICALLY DETERMINING THE MODIFIED PAVEMENT LIFE VERSUS CONVENTIONAL PAVEMENT LIFE

Table A.3. Rubber-Modified Asphalt Project Information.

Project ID Agency	F8-2(22)28U-2 MDOH	02-189504 CALTRANS
	a) Initial Questionnaire	
General		
Date Constructed	September 1983	9/26/83 to 10/6/83
Tons Mixed	2885	7260
Mix Design		
Rubber Content	3%	3.28%
Asphalt Content	8.75%	9.41%
Construction		
Mix Temp., °F	377	350
Mixing Time, Sec.	15	20 dry/30 wet
Compaction Temp., °F	300 breakdown, 203 final	260
Voids in Mix	2	---
Problems	None	
Mix Performance		
Types of Problems	Too early to determine	Too early to determine
Causes of Problems	---	---
Reason for Use	Experimental, de-icing	Experimental
	b) Follow-up Questionnaire	
Present Condition		
Raveling	None	None
Bleeding	None	None
Potholing	None	None
Wheel Track Rutting	None	None
Cracking	None	None
Overall	None	None
Pavement Performance	**Effective**	
Ice Control	No	No
Noise Control	Yes	No
Reflective Crack Control	Yes	Yes (in less than a year)
Skid Resistance	---	No (same as conventional AC)
Fatigue Resistance	No	Yes
Comments	---	The 0.15' and 0.20' thick conventional AC control sections on the project have begun to crack heavily in places, whereas the rubberized AC, including the Plusride shows no signs of distress.

Program for Economically Determining the Modified Pavement Life Versus Conventional Pavement Life

```
♦LBL "LIFECST"
"CALCULATION OF"
AVIEW
"LIFE FOR EQUAL"
AVIEW
"ANNUAL COST"
AVIEW
"COST CONV AC=?"
PROMPT
STO 01
"COST MOD,=?"
PROMPT
STO 02
"DISCOUNT RATE=?"
PROMPT
STO 03
♦LBL 15
"CONV AC LIFE=?"
PROMPT
STO 04
RCL 03
1
+
STO 05
RCL 04
Y↑X
1
-
STO 06
RCL 05
ENTER↑
RCL 04
Y↑X
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ENTER↑
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RCL 01
*
RCL 02
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STO 07
ENTER↑
RCL 07
ENTER↑
RCL 03
-
/
LN
RCL 05
LN
/
"LIFE MOD="
ARCL X
AVIEW
BEEP
"PLACE X=0 IF"
AVIEW
"IF MORE MOD"
AVIEW
"LIFES ARE"
AVIEW
"REQUIRE: IF"
AVIEW
"CALCS ARE"
AVIEW
"COMPLETE, PLACE"
AVIEW
"ANY INTEGER"
AVIEW
"EQUAL TO X"
AVIEW
"X=?"
PROMPT
ENTER↑
X=0?
GTO 15
BEEP
"RUN COMPLETE"
AVIEW
"END"
END
```

System: HP41C

Required Registers = 43

Table A.1. Rubber-Modified Asphalt Project Information.

Project ID Agency	1983 Overlay Program City of Bellevue, Washington	FR 282 (71) Oklahoma Department of Transportation
	a) Initial Questionnaire	
General		
Date Constructed	9/14/82	8/17/82
Tons Mixed	220	2,570
Mix Thickness	1-1/2 inches min.	2 inches
Mix Design		
Rubber Content	3%	2.5-3.5%
Asphalt Content	7.5-9.5%	5.0-9.0%
Construction		
Mix Temp., ^{o}F	325-360	325
Mixing Time, Sec.	15	27
Compaction Temp., ^{o}F	280 min.	285
Voids in Mix, %	2-5 (Ave 4)	---
Problems	Mix was very stiff and hard to work by hand.	Introduction of volcanic ash in dryer, estimated 1% loss.
Mix Performance		
Types of Problems	Some segregation in first load placed	Areas would shove and pothole throughout the Plusride mix.
Causes of Problems	Poor mixing	
Reason for Use	Experimental - Placed to compare performance with fabric interlayer in delaying reflective cracking.	Experimental - Check Plusride formula's ability to stop reflected transverse cracking.
	b) Follow-up Questionnaire	
Present Condition		
Raveling	None	None
Bleeding	None	Moderate
Potholing	None	Moderate-None
Wheel Track Rutting	None	None
Cracking	None	None
Overall	---	Moderate-None
Effectivenss of Rubber Mix		
Ice Control	---	No
Noise Control	Yes	Yes
Reflective Crack Control	Yes	Yes
Skid Resistance	Yes	Yes
Fatigue Resistance	Yes	Yes
Comments	---	(1) The potholing occurred at the beginning of construction. The 0.2 mile potholed area was totally removed and patched. (2) The roadway exhibited transverse cracks as the major distress but the cracks close up in the summer.