AN ABSTRACT OF THE THESIS OF

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Title: Evaluation of Mix Ingredients on the Performance of Rubber Modified Asphalt Mixtures.

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R. G. Hicks

Rubber-modified asphalt pavements have been used in Sweden and the United States since the 1970's. In these applications ground recycled tire particles (1/4 inch minus) are added to a gap-graded aggregate and then mixed with hot asphalt cement. The benefits of adding rubber to the mix include increased skid resistance under icy conditions, improved flexibility and crack resistance, elimination of solid waste, and reduced traffic noise. The major disadvantage of these rubber-modified mixes is their high cost in relation to conventional asphaltic concrete pavements.

This research project consisted 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). Also, five different mix combinations were evaluated for static creep and permanent deformation. Layered theory was used to

evaluate the effects of mixture variations on pavement life. The resulting information was used to develop guidelines for use of rubber asphalt mixes in United States road systems.

The findings of the field survey indicate that the rubber-modified asphalt mixture is more susceptible than the conventional mixtures to preparation and compaction problems when adverse weather or equipment problems occur. However, with adequate equipment and favorable weather conditions, the rubber-modified asphalt mixture placement is similar to conventional mixture placement. The field study also indicates that stopping distances can be reduced 20 percent for the rubber-modified pavements in icy conditions. In view of the significant reductions in wintertime stopping distances under icy or frosty road surface conditions, the use of coarse rubber in asphalt pavements should be seriously considered. This is particularly true for areas such as bridge decks, on and off freeway ramps or insulated roadway sections.

The findings of the laboratory 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. The results of static creep and permanent deformation tests indicate that the rubber asphalt mixes had low stability and high elasticity. 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 1.4 to 1.0.

Evaluation of Mix Ingredients on the Performance of Rubber-Modified Asphalt Mixtures

by

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This report is dedicated to the memories of my late father and brother. On October 29, 1986, I lost a wonderful brother and the world lost one of its best surgeons. Mahmood, you are not around us but you always live in my heart; while I have missed you, I have tried hard to achieve the goals that we had planned together.

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1.0 INTRODUCTION

1.1 Problem Definition

Ground tire rubber has been used as an additive in various types of asphalt construction in recent years (1). The use of rubber is of interest to the paving industry because of the additional elasticity imparted to the binder. However, additional benefits such as resource recovery have also been observed by creating a use for waste tires. Each year the United States disposes of about 200,000,000 passenger tires and 40,000,000 truck tires (2). This represents about 2.1 million tons of scrap passenger tires and roughly 1.9 million tons of scrap truck tires, a total of 4 million tons. While a limited number of these 4 million tons of tires are used for resources and energy recovery, the vast majority go to landfills or are disposed of in an environmentally unacceptable manner. This presents a series of problems including the loss of a scarce resource and a potential health problem, since the tires serve as shelters and habitats for insects which often carry disease (2).

In recent years, the most overlooked aspect of rubber-modified asphalt is the attention it has received by Congress as it relates to the ecological problems of disposing of discarded tires. Congress, in order to stimulate the use of recycled materials, has requested the Environmental Protection Agency and the Federal Highway Administration to issue procurement guidelines. The response to this request is in the ruling by the Environmental Protection Agency for "Federal Procurement of Asphalt Materials Containing Ground Tire Rubber for Construction and Rehabilitation of Paved Surfaces" (3).

The impact of this proposed guideline remains to be seen. However, public road agencies are currently evaluating the use of recycled rubber to modify hot mix asphalts for road surfacing (4,5,6, 7,8) where the recycled rubber is placed into the mix in several ways. One method patented under the trade-name PlusRide^{TM} is marketed in the United States by PaveTech Corporation. The PlusRide^{TM} process typically uses 3 percent by weight of granulated coarse and fine rubber particles to replace some of the mix aggregates (Figure 1.1). This rubber is obtained from old passenger and truck tires. The rubber particles are cold fed into the mix in a manner similar to the aggregate. The reported advantages of using the PlusRide^{TM} paving system in hot mix applications are (10):

1. high fatigue resistance,
2. high durability,
3. reduced reflective and thermal pavement cracking,
4. improved skid resistance during dry, wet, and icy conditions,
5. improved ice removal by elastic deformation of the rubber granules under traffic loading,
6. noise reduction,
7. environmental soundness,
8. reduced hydroplaning and water spray, and
9. reduced need for sanding and salting.

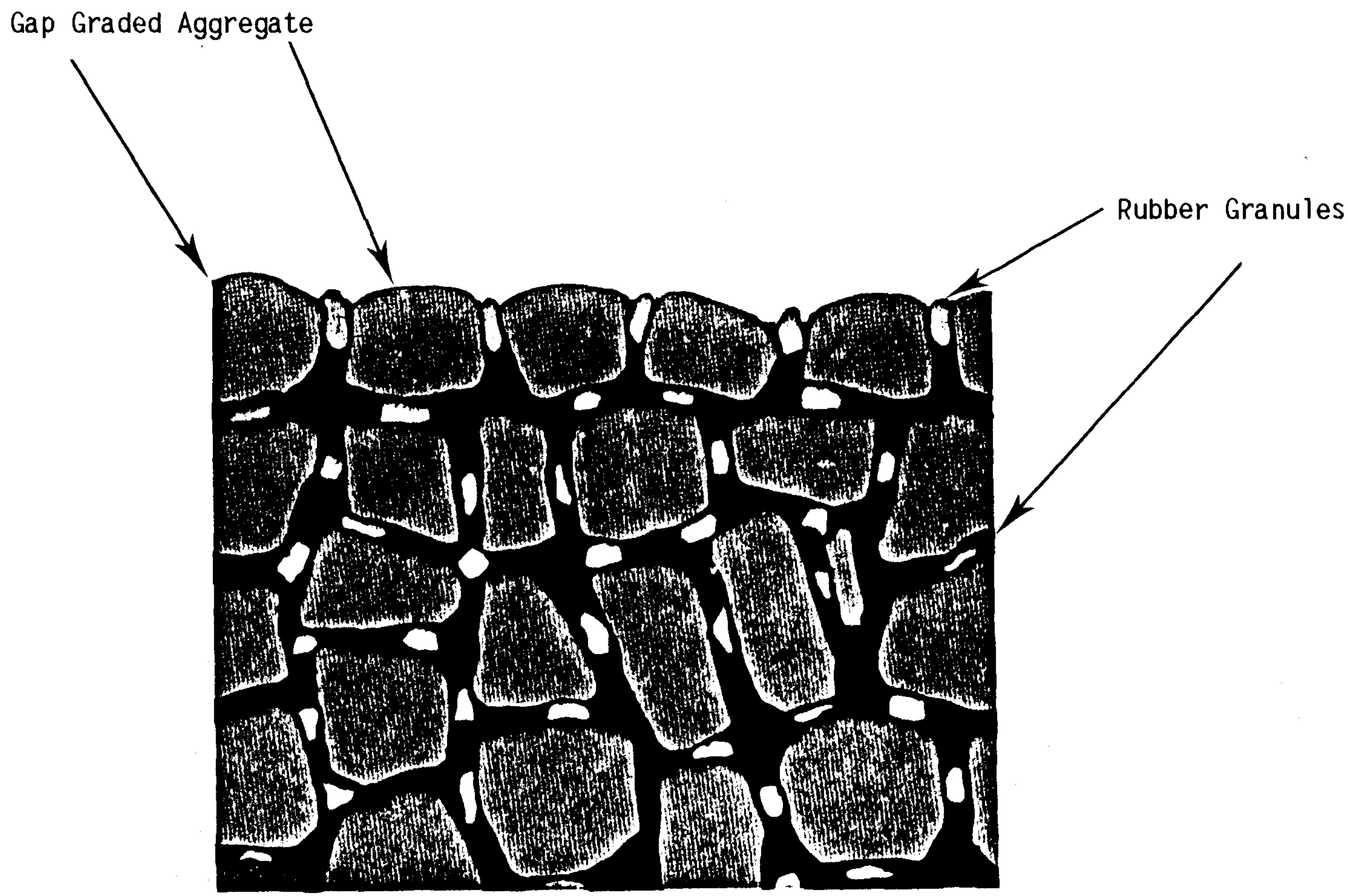


Figure 1.1. Illustration of rubber-modified asphalt (PlusRide process). Rubber granules depicted in light color (10).

Another method for introducing the rubber into the mix is by directly modifying the asphalt binder. This process, called Arm-R-Shield^{TM} (A-R-S), was patented by Union Oil Company and currently is marketed by Arizona Refining Company (ARCO). The ARCO product incorporates extender oils and recycled rubber from scrap tires directly in the hot liquid asphalt (11). The mix production proceeds normally with modified liquid asphalt being used in place of conventional asphalt. The reported benefits of using the A-R-S modified hot mix surfacing include (11):

1. flexibility down to -15°F,
2. tougher (in relation to surface wear from studs) and a more elastic surface,
3. higher viscosity than conventional asphalt at high temperatures (140°F),
4. greater resistance to aging, and
5. recycling of used rubber tires.

There are primarily two reasons why these types of rubber-modified asphalt mixes are not in widespread use. First, the capital cost for these surfacing alternatives is higher than conventional asphalt by 30 to 50 percent. Secondly, there is a lack of information regarding properties and performance of these surfacing alternatives.

Because of this lack of information, a need exists to evaluate the effect of mix ingredients in terms of critical mix properties. Assessment of applicability of the first method (PlusRide^{TM}) is the main purpose of this research.

1.2 Objectives

The overall purpose of this thesis was to evaluate the use of rubber-modified asphalt in road construction. Moreover, it was to evaluate the engineering properties of rubber-modified asphalt mixes and to develop suitable recommendations for their use. Specifically the objectives were to:

1. develop mix design recommendations for rubber-modified asphalt mixes,
2. evaluate mix properties including resilient modulus, fatigue and creep,
3. analyze the economics of rubber-modified asphalt mixes,
4. improve the constructability of the rubber-modified mixes, and
5. formulate guidelines indicating how these mixes can best be utilized in the United States road systems.

1.3 Study Approach

This research (Figure 1.2) consisted mainly of a laboratory study of mix properties as a function of variables such as aggregate gradation, rubber content and gradation, void content, mix temperature, mix curing periods, and use of surcharge. The influence of these variables on stability and stiffness was evaluated as well as the influence of temperature on resilient modulus and fatigue life. To satisfy the research objectives, it was necessary to undertake the four following tasks.

Task 1. Evaluate Use of Rubber in Asphalt Mixtures. In this task, rubber modified asphalt usage in the United States was reviewed

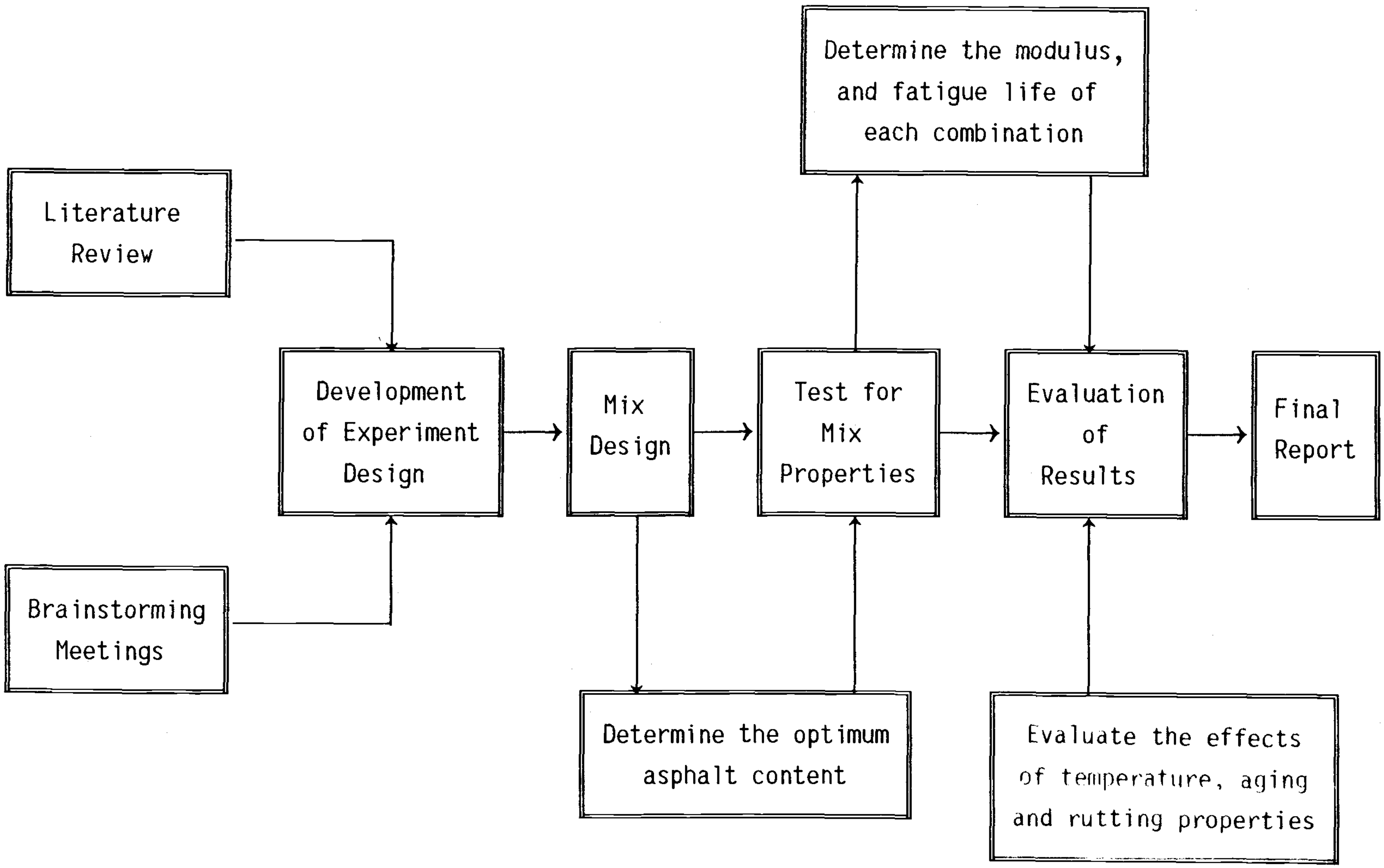


Figure 1.2 Study Approach.

to establish its usage feasibility and to identify potential problems and benefits. This consisted mainly of a review of available literature and interviews with asphalt and rubber suppliers, PlusRide^{TM} Company technical staff, asphalt chemistry experts and personnel from various State DOT's in order to:

1. identify effects of rubber particle shape, type, and gradation upon the properties of rubber-modified mixes,
2. evaluate the current mix design procedures and guidelines for rubber-modified mixes,
3. evaluate the effects of varying the rubber content, rubber source, rubber and aggregate gradations, and mixing temperature on mix properties,
4. survey the rubber suppliers to collect information on the type of portion of tire used, the method of processing, and test methods used to evaluate the rubber,
5. evaluate the rubber-asphalt interaction,
6. evaluate the performance of selected field projects placed in the United States, and
7. evaluate the construction problem and guidelines for improving the constructability of rubber modified mixes.

Results of this task are presented in Chapter 2.

Task 2. Development of Experimental Design. In this task, the test program used to evaluate the effect of mix variations on properties of rubber-asphalt mixes was determined. 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.

Chapter 3 presents the results of this task.

Task 3. Mix Design and Mix Properties Evaluation. Mix designs were prepared for twenty different combinations to evaluate the optimum asphalt content for various mix combinations. Standard Marshall samples were tested for flow, stability, void content, and diametral modulus. The major mix material variables used in the mix design study were as follows:

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

The optimum asphalt content for each mix was used to test for mix properties including resilient modulus, fatigue resistance, and rutting properties. The fatigue life test was conducted at two different temperatures (+10°C and -6°C). Also, the effects of temperature and aging on the rubber-modified asphalt mixes were evaluated. Finally, to determine characteristics for use with viscoelastic theory to predict rutting, five different mix combinations were tested for static creep and permanent deformation. The results of this task are presented in Chapter 4.

Task 4. Data Analysis and Final Report. This task brings together all test data and project information to:

1. estimate the effects of the mixture variables on mix design and mix properties, and
2. estimate the effects of the variables on pavement life.

The results were utilized to develop layer equivalency factors. These factors were used in the life cycle cost analysis of rubber-modified asphalt in comparison to conventional asphalt. Finally, by using the mix design results, mix properties results, and field surveys, guidelines were developed for selecting the best uses for rubber-modified asphalt mixes as presented in Chapter 5.0.

The final report summarizes the work done. It includes the results of the previous tasks. It presents the advantages, disadvantages, data analysis and interpretation, and recommendations for use of the rubber-modified asphalt and further research.

2.0 LITERATURE REVIEW

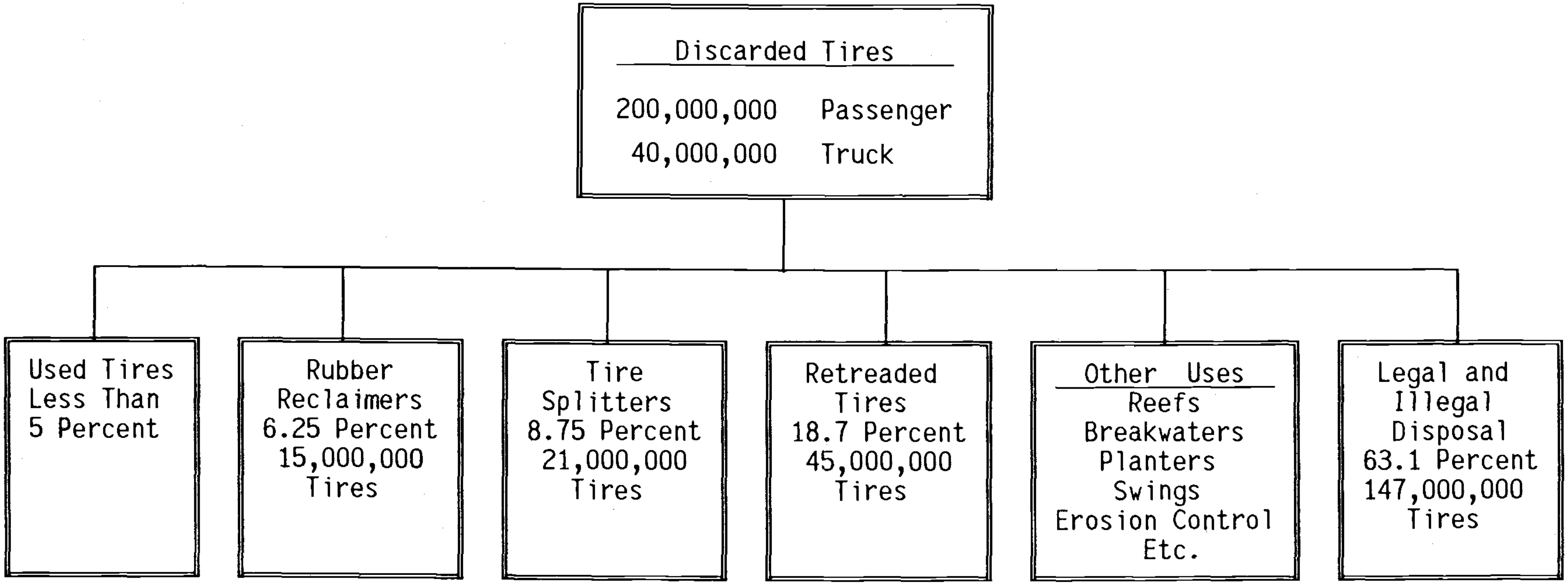
Rubber, in the form of vulcanized scrap, has long been used as an additive to improve toughness of asphaltic road surfacing materials. Charles H. McDonald, considered to be the father of the asphalt-granulated rubber system developed in the United States, initiated work in 1963 which was based on concepts developed as early as the 1930's in the United States (7). Also, in the late 1960's, experimentation was done in Sweden on the effect of mixing rubber particles in asphaltic pavements.

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 in the United States is 4 million tons (2). This is adequate to pave 40,000 lane miles of rubber asphalt pavement. 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 rubber-asphalt interaction,
4. 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),

Table 2.1. Uses of Discarded Tires in the United States (2).



5. evaluation of the performance of selected field projects placed in the United States, and
6. evaluation of current construction rubber-modified asphalt practices and guidelines for construction of rubber-modified asphalt pavements.

2.1 Use of Rubber in Asphalt Mixtures

Recommendations for use of rubber to improve asphalt pavements date back more than a century (7). This section briefly reviews the history of the rubber industry, important properties of rubber, 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 were taken back to Europe by the Spaniards and Portuguese. However, their discovery had no impact on civilization at that time (12).

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. With further compound development, vulcanization 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 (12).

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 (12). This group was successful in producing several grades of GRS (Government Rubber-Styrene) rubber. The government later sold the synthetic rubber plants to industry. This move led to the rapid development of numerous specialty polymers. There are presently (1983) over 20 major types of synthetic rubber produced in this country with over 700 individual specialty grades (12). For the past several years, synthetic rubber has constituted approximately 78 percent of the new rubber used in this country (12).

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 (12). 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 pickups.
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 percent 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

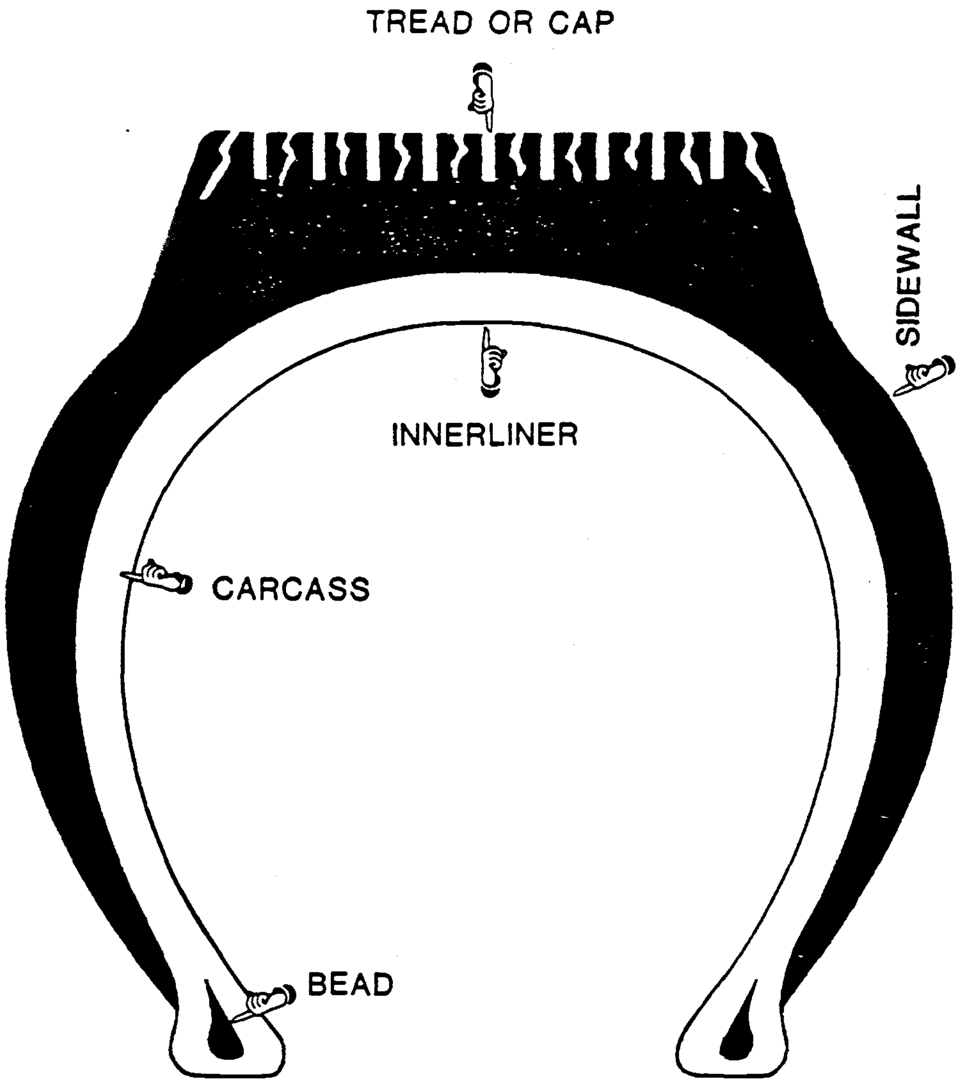


Figure 2.1 Cross Section of a Passenger Tire (23)

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.

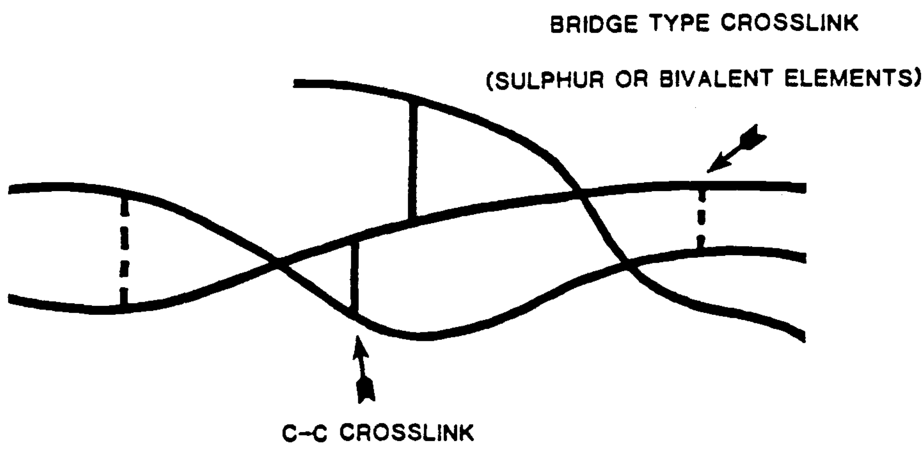
2.1.3 Rubber Concentration

As the cost of rubber is so much greater than that of bitumen the minimum quantity to effect an "improvement" is used. Consideration of the compatibility of the bitumen/rubber blends also limits the quantity of rubber that can be dispersed.

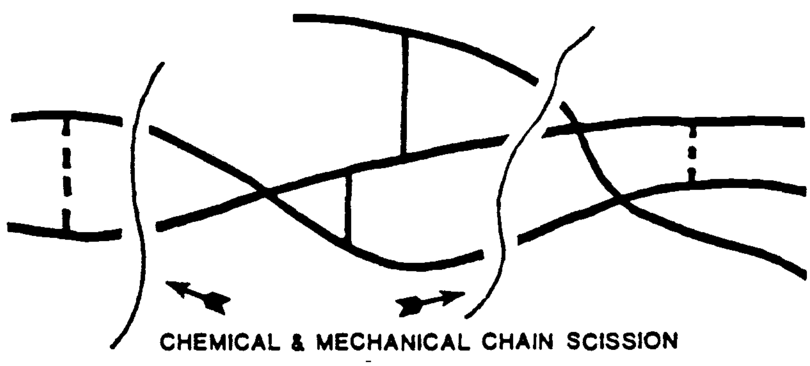
In laboratory trials, rubber concentrations of from 0.5 to 10 percent (normally specified by weight) of the bitumen have been used. For field applications the percentage of rubber has been from 0.5 to 6 percent of the bitumen. The low (0.5 to 1.0%) rubber contents have normally been used for chip seals, although 3 to 4 percent has been used in Australia. The higher rubber contents (2 to 6%) have normally been used in asphaltic concrete.

A special case is the scrap rubber/bitumen blends, with rubber concentrations of between 15 and 25 percent which were originally developed by C. H. McDonald (7). These have been used principally in Arizona, but also in other American states as well as Australia (13).

Finally, the PlusRide^{TM} process is prepared by a process which typically uses 3 percent by weight of granulated coarse and fine rubber particles to replace some of the aggregate in the mixture.



a) Vulcanized Rubber



b) Devulcanized Rubber

Figure 2.2 Chemical Mechanism of Vulcanization and Devulcanization (12).

2.1.4 Methods of Rubber Addition

The form of rubber and the final use of the blend influences the method of addition and dispersion. The following methods have been used successfully (15):

1. Addition to hot bitumen. The dispersion of rubber powder into hot bitumen with plenty of agitation is straightforward. The addition of latex to hot bitumen is more difficult, due to the danger of foaming as water evaporates. It is normally recommended (14) that the bitumen be heated to at least 150°C. The latex must be added slowly, so that it sits on the top of the bitumen for about 20 seconds, and is then sucked in by a powerful stirrer. The speed of addition, however, should be as fast as possible, consistent with controlling foaming. If mixing is not fast enough or the latex sits on top of the bitumen for too long, coagulation occurs and a lumpy mixture results. The McDonald process for scrap rubber calls for holding the bitumen/rubber blend at 200°C for a period of 30 minutes (15).
2. Master batch. This system is traditionally recommended for cutbacks, but it is currently being used in the marketing of a thermoplastic rubber (15). In the case of cutbacks using latex, the total kerosene content required for the blend is mixed with the same quantity of bitumen (giving a 50% cutback). The temperature of this blend is controlled so that the viscosity is such that a vortex forms when mixed with a propeller stirrer. Latex is added slowly so that a fine dispersion of the binder is obtained. The temperature is

then slowly raised and the water starts to evaporate at about 95°C. The mixture remains at about 100°C until hardly any water remains, at which point the temperature starts to rise rapidly. The final mix, the "master batch," is therefore a concentrate of rubber, bitumen and kerosene (15). This "master batch" can then be blended with the rest of the bitumen required for the job, taking care that there is sufficient mixing to ensure adequate dispersion of the rubber through the blend.

3. Direct into Pugmill. When using latex in hot mixed asphalt, the rubber bitumen can be mixed and sprayed directly into the pugmill. Alternatively, a separate spray bar for the latex can be installed. Tests performed in Italy (16) indicated that when spraying the latex separately from the bitumen, best results were obtained when the latex spray started 3 to 4 seconds after that of the bitumen. This practice of initially coating the stones before addition of the latex is also recommended by Thompson (17). Addition of scrap rubber directly into the pugmill has been used in New Zealand on a proprietary recreational asphalt surface. In Canada, road trials (18) have been performed with scrap rubber which has been pre-blended with the bitumen for 30 minutes at 200°C, and added directly to the pugmill. This process in the United States is known as the McDonald process.

4. In Place. A different approach to the problem of incorporating rubber into bitumen is reported by Rostler and White

(19), where a special rubber emulsion is sprayed on to the completed pavement. This emulsion carries the rubber into the voids of the mix, where it is deposited on, and absorbed by, the bitumen. Laboratory trials carried out in New Zealand (20) indicated that in order for the emulsion to penetrate the bitumen, the void content of the asphalt needed to be greater than 8 percent. Most structural asphalt in New Zealand would be below this figure, thus adequate penetration would not be obtained.

5. Emulsion. Since rubber latex is an emulsion of rubber particles in water, it can be blended with an appropriate bitumen emulsion. Natural rubber latex has been used in N.Z. up to a concentration of 20 percent of an anionic emulsion. Although phase separation occurs during storage, the components are easily remixed.

2.1.5 Important Properties of Recycled Rubber

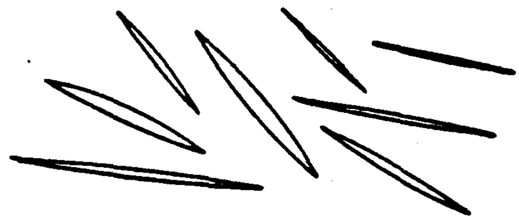
The important characteristics of recycled rubber affecting the various properties of asphalt rubber mixes include particle shape, rubber type, and rubber gradation. Studies conducted by Oliver (21) indicate that particle structure is the most important factor affecting the elastic properties of the mix. Tests performed for Environment Canada also indicate rubber particle size is an important factor in resistance to crack growth at low temperatures (22). The chemical constituents of bitumen and rubber also display a vital role in asphalt rubber properties (21,22).

2.1.5.1 Particle Shape. Various processing methods result in different morphology (i.e., 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 methods 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 (23).

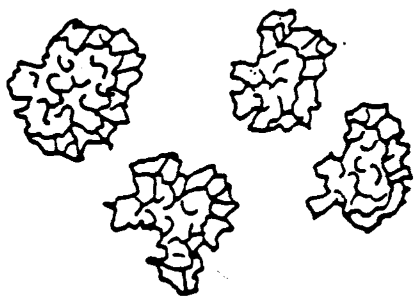
Oliver (21) found surface particles, similar to those in Figure 2.3b, produced a bitumen/rubber blend with highest elastic recovery. The large surface area of these particles offered a reactive surface for the bitumen. Cryogenically produced particles (Fig. 2.3c) with less surface area produced lowest elastic recovery.

2.1.5.2 Rubber by Chemical Type. Interest in the past has been directed toward the addition of specially prepared rubbers to the bitumen. The cost of these additives has been high in relation to the bitumen cost; to keep costs low, relatively small amount (less than 5% by weight of bitumen) have been used. The major types of additives are outlined below (15):

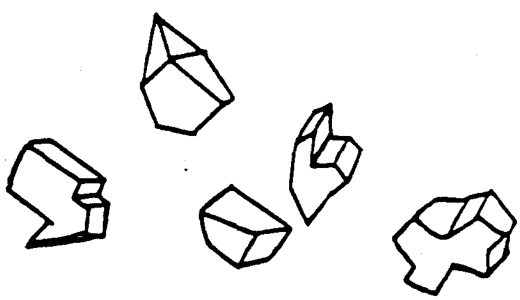
1. Natural Rubber. Chemically a polyisoprene, natural rubber is extracted from rubber trees. It is available as the natural latex, as a powder, or as a solution in kerosene.
2. Styrene Butadiene (SBR). A random copolymer of styrene and butadiene, (SBR) is marketed depending on the degree of polymerization, ratio of styrene to butadiene, and the presence of additives.



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 (23).

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.
5. Vulcanized Rubber (or Recycled Rubber). Vulcanized natural rubber is formed by heating a mixture of natural rubber with sulphur, sulphur compounds or other chemicals, to produce cross-linking of the rubber molecules. The degree of cross-linking (vulcanization) can be controlled.
6. Devulcanized Rubber (or Reclaimed Rubber). This is previously used rubber which has been ground and then undergone some reprocessing. The processing depolymerizes the rubber.
7. Scrap Rubber. This is often called waste rubber or crumb rubber. It is ground or pulverized rubber that has been screened into specified size fractions. The main source is normally vehicle tires. Passenger car tire treads are usually SBR, while more heavily stressed tires are made from natural rubber.

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 composed of synthetic rubbers (Table 2.2).

Table 2.2. Typical Composition of Recycled Rubber Used in Asphalt Rubber (12)

	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

2.1.5.3 **Rubber by Physical Form**. Rubber has been dispersed into bitumen in various forms (15):

1. Latex. This is, in effect, an emulsion of the rubber in water. Natural rubber obtained from the tree is in a latex form, which is then concentrated to between 60 and 70 percent rubber.
2. Powders. Fine and coarse rubber powders are available. The majority of work has used vulcanized or lightly vulcanized rubbers. Unvulcanized rubber is sticky and can only be easily handled when mixed with a mineral carrier. S.B.S. rubbers can be handled in powder form, as they are cross-linked at ambient temperatures. Scrap rubber is a comparatively coarser powder. The most commonly used is a material retained between 1.18 mm and 0.60 mm screens.
3. Liquid. Natural rubber and some synthetic rubbers can be taken up by a solvent and added to bitumen in this form. The solvent is regarded as part of the flux for sealing binders. This form has been used, mainly in Australia, for chip seals. Reclaimed rubber can also be obtained in the United States in liquid form.

2.1.5.4 **Rubber Gradation**. The improvement of pavement properties via the effects of rubber gradation depends on the pavement application. PlusRide^{TM} 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

Table 2.3. Rubber Gradation for PlusRide (10).

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.

viscosity. This thickening results in good stability at low surface temperatures. Oliver (21) 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 (22). Also, the repeated flexing of protruding large rubber particles due to traffic loading, has been suggested as causing breakdown of surface ice deposits (24).

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 (25).

2.1.6 Survey of Rubber Suppliers

In May 1987, 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 Avenue
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 temperatures. The majority ground the whole tire using fabric-type automobile or light truck tires, producing a heterogenous 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.

2.1.7 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.

2.1.7.1 Patent Types. Three 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 Number 4,166,049 describes processes in which the asphalt rubber is used as a binder in asphaltic mixtures. Finally, U.S. Patent Number 4,086,241 describes a process in which the rubber works as elastic aggregate in the mixture.

2.1.7.2 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

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 and % 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.

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 (26).

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" (27). 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 (27). 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).
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.

Table 2.5. Asphalt and Rubber Composition Claimed for U.S. Patent No. 4,166,049 (26).

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

The amount of materials is as follows:

1. Aggregates - at least 65 percent by weight (defined as particles larger than 8 mm).
2. Coarse rubber (1 to 8 mm in the greatest dimension) - 1.35 percent by weight.
3. Fine rubber (less than 1 mm in the greatest dimension)- 1.65 percent by weight.
4. Asphalt cement - 8.5 percent by weight of total mix.
5. Filler material (which may include lime) - 6-10 percent by weight.

2.2 Rubber-Asphalt Interaction

Most investigators in the area of rubberized asphalt believe that some type of reaction or exchange takes place between rubber and asphalt. This is manifested by observing the swelling of rubber in hot asphalt (1,28). Shuler et al (29) have used the term asphalt-rubber to emphasize that a chemical and physical interaction has occurred and make a distinction between asphalt and rubber.

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.

2.2.1 Theories

The condition in which the rubber exists in the bitumen has a pronounced effect on the behavior of the blend. Rubber can be dispersed in bitumen in one or more of the following forms:

1. as an integral part of the binder (ture solution, not discernible under the optical microscope as separate particles),
2. as a network through the binder, visible under moderate magnification, and
3. as an elastic aggregate, visible with the naked eye as discrete, individual particles dispersed through the bitumen.

According to Patrick (15), 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.

Rostler (30) provided an explanation of the rubber-bitumen interaction mechanism based on the solubility of the rubber and the composition of the bitumen as described below. Figure 2.4 shows the composition of asphalt in terms of the three functional components affecting compatibility. Bitumen is composed of a bodying agent (asphaltenes) dissolved in a solvent (the chemically active portion of the maltenes), and a gelling agent (paraffins, the chemically inactive portion of the maltenes) which affects the compatibility of the solvent and bodying agent. The center point of this triangular graph (Figure 2.4) represents the composition of an asphalt containing one third of each of three components. Incorporation of rubber into asphalt in a manner that results in a homogenous solution produces a

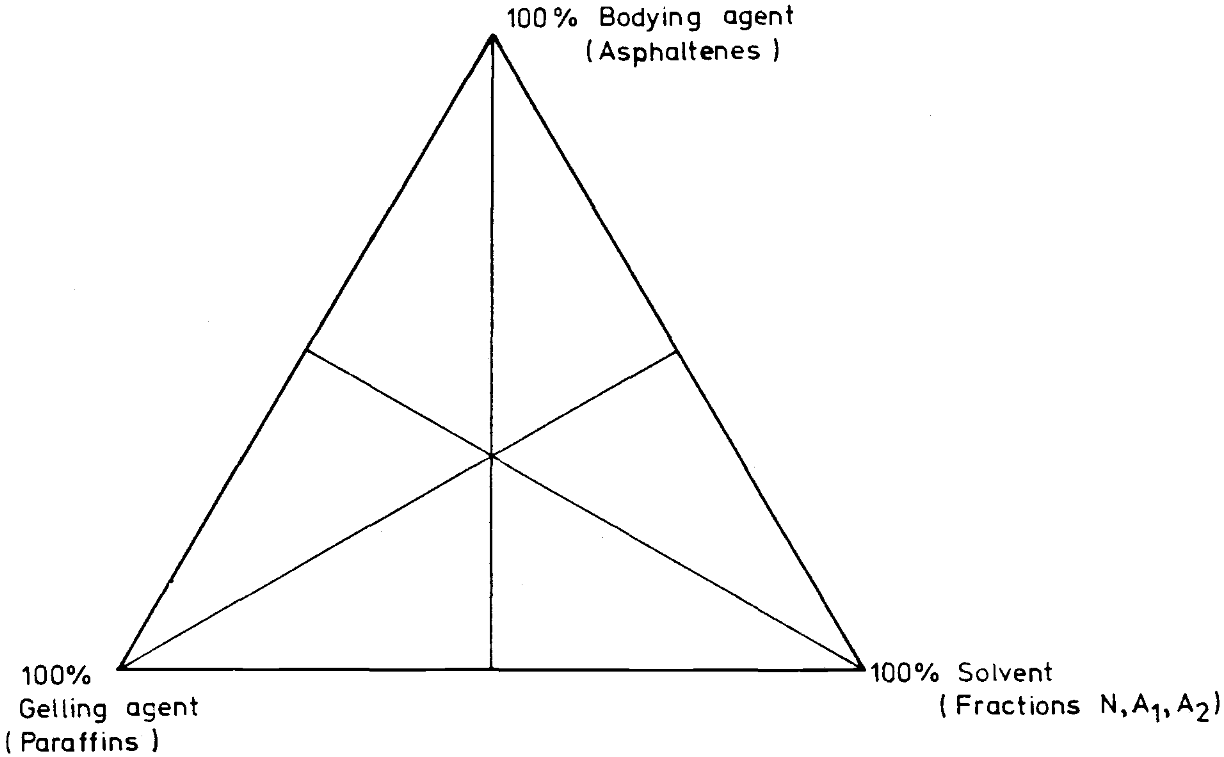


Figure 2.4. Compatibility Relationship (30).

new type of asphalt cement which is an asphalt modified by rubber, containing the rubber either as part of the bodying agent or the solvent.

In rubberizing asphalt the rubber, which becomes part of the bodying agent, shows up analytically as part of the asphaltenes, the rubber which is not determined as asphaltenes and is consequently not affected by the amount of gelling agent present, for example, the paraffins, becomes part of the solvent. The chemical nature of the rubber determines where the rubber ends up in the system. In terms of the chemical analysis employed, a rubber insoluble in n-pentane will become part of the asphaltenes fraction while a rubber soluble in n-pentane will become part of the solvent. This interrelation of the three portions of asphalt as defined in the triangle permits the modification of an asphalt at will by use of the proper rubber. For example, natural rubber which is an unsaturated hydrocarbon, soluble in n-pentane, functions as a modifier of the maltenes, affecting primarily the maltenes viscosity. The same is true of SBR rubbers, while an SBS rubber is insoluble in n-pentane and will act as a modifier of the asphaltene fraction. Vulcanized rubber is less soluble in solvents than devulcanized rubber. This is shown in the recommended blending times for the two materials - 15 minutes for devulcanized rubber, 150°C, compared with three to four hours for vulcanized rubber (14). The triangular picture shown (Figure 2.4) is not only of theoretical interest and an aid to visualizing what is happening in rubberizing, but fully depicts the internal compositional occurrences in rubberizing. As with any solution there is a point when the solubility is disturbed simply because there is too much of a component present. The result is then, as in supersaturated solutions of highly compatible ingredients, that the surplus is precipitated or flocculated out.

Rostler (30) also reports the photomicrography of rubber in asphalt (Fig. 2.5 - 2.7). Figure 2.5 shows the surplus of rubber, Figure 2.6 the surplus of rubber and asphalt, and Figure 2.7 shows a truly modified asphalt.

Work done by Huff (26) suggests that asphalts having less than 30 percent second acidaffin (part of the solvent portion) do not produce the adhesive properties required with rubber. Those asphalts that contain more than 40 percent second acidaffins become soft at summer pavement temperatures.

From the above stated theories, it is evident that solubility and compatibility conditions prevailing in a rubberized asphalt are contingent on the type of rubber and the proportions in which the components exist in the system.

2.2.2 Results of Laboratory Studies

Van Beem and Brasser (31) 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

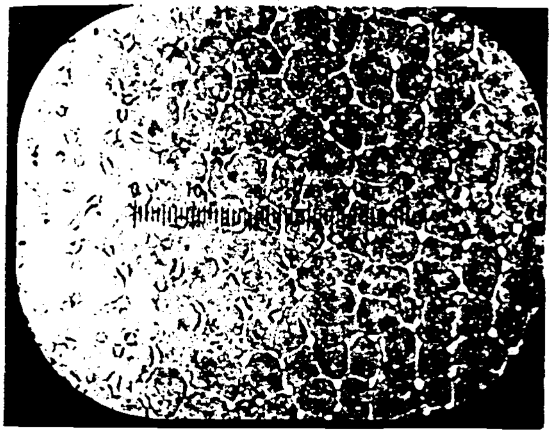


Figure 2.5 Surplus Rubber (30)

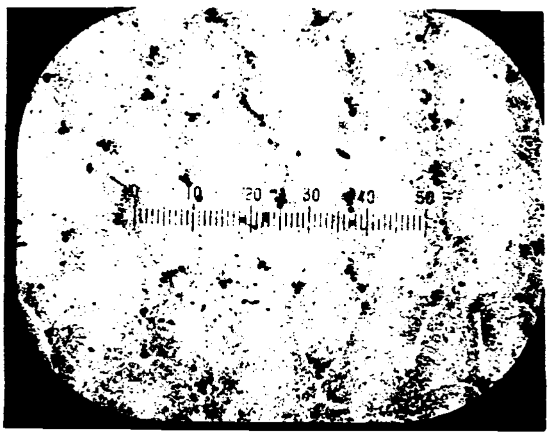


Figure 2.6 Surplus Asphaltenes and Rubber (30)

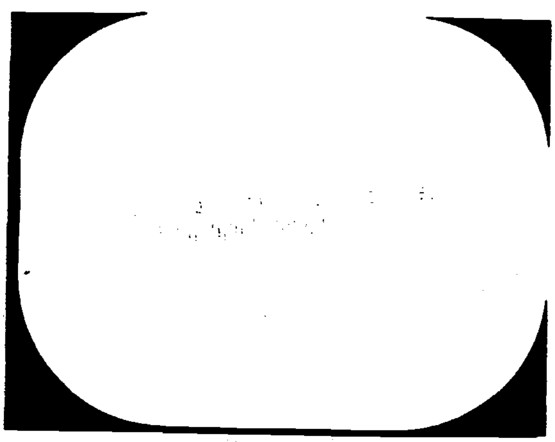


Figure 2.7 Rubberized Asphalt Cement (30)

improved bitumen properties; the rubber was visible as a "single phase" system under a microscope.

Studies conducted by Patrick indicate that the addition of Samrubba^{TM}, another thermoplastic rubber, decreases the penetration of the blend at low temperatures (15). The addition of natural rubber produced no significant effect on penetration at low temperatures (15).

Oliver found that natural rubber blends exhibited superior elastic properties as compared to those of SBR blends (21). However, synthetic rubbers were found to be more thermally stable than natural rubbers, as shown by Figures 2.8 and 2.9. 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.

2.3 Commercial Rubber-Asphalt Systems

Since the work by McDonald, engineers and researchers have been adding rubber, or rubber-like, materials in one form or another to asphalt. In recent years, adding ground tires to asphalt has been practiced on a routine basis by several companies, each of which supplies a proprietary product based on variations of the original concept by McDonald. However, the two main systems of rubber-modified asphalt which have been used in practice are Asphalt Rubber Binder System (Arm-R-Shield^{TM}), and rubber-modified asphalt pavements (PlusRide^{TM}). These systems are described below.

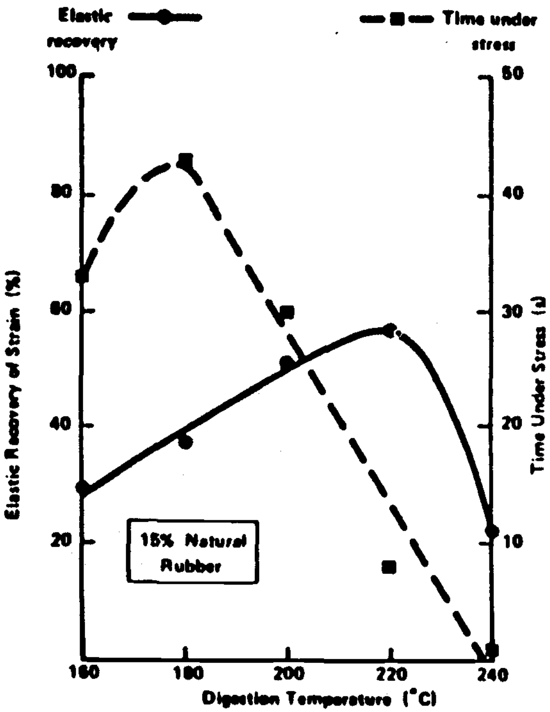


Figure 2.8. Effect of Digestion Temperature on Properties of an Asphalt Natural Rubber (21).

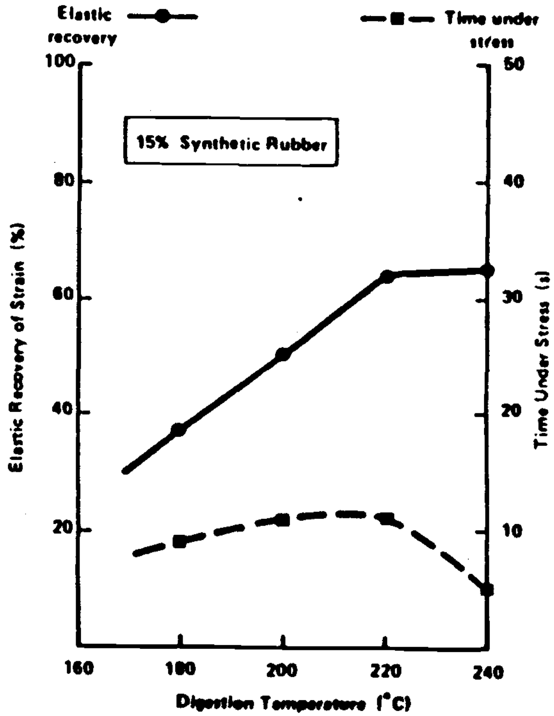


Figure 2.9. Effect of Digestion Temperature on Properties of an Asphalt Synthetic Rubber (21).

2.3.1 Asphalt/Rubber Binder System (Arm-R-Shield^{TM})

This concept was developed primarily to overcome the problem of the early reflection of fatigue cracking in resurfaced asphalt pavements. The concept is based primarily on a composite material of asphalt cement and a high percentage of granulated rubber (at least 15% by weight, of total binder) from recycled tires. When granulated rubber is mixed with hot asphalt, it forms a tough and elastic binder with less susceptibility to temperature change. In addition to its initial use as a reflection crack control membrane and waterproofing for pavements, it is also being used for crack and joint sealing and for control of swelling in expansive clays (1).

Considerable experimental work and field trials have been performed in the United States, particularly in Arizona, California and Colorado, on rubberized asphalt seal coats. These installations have utilized finely ground crumb rubber (#16 to #25) reacted with various grades of asphalt (60/70, 85/100, 120/150, 200/300). At elevated temperatures (300° - 400°F) for periods of one-half hour to one hour this forms a thick elastic type material which is then diluted with 5 percent kerosene to aid in application (32). The exact nature of this reaction has not been determined, but it is believed that only a limited portion of the rubber goes into solution with the asphalt. The net result of the reaction is a marked thickening of the mixture to a consistency similar to that of a very thick slurry with discernible rubber particles throughout the mass. At room temperature this asphalt-rubber composition is a tough rubbery and elastic binder material. The elastic quality of this mixture is most probably caused by the mechanical action of the undissolved rubber particles performing as a completely elastic aggregate within the asphalt, which is modified by the dissolved rubber (33).

Using rubber-asphalt binder for seal coat construction of fatigue-cracked bituminous concrete pavements prevents reflection cracking from the substrate pavement because of its flexibility. The interlaced particles of rubber discourage the propagation of cracks. The undissolved rubber particles serve as units of elastic interference to the propagation of cracking. Should a crack begin to propagate through the membrane, it encounters an elastic rubber particle and is stopped, or is redirected, whereupon it will encounter another elastic rubber particle, and so on. Since asphalt-rubber composition is waterproof, the moisture in the subgrade becomes stabilized and reduces the tendency for localized failure. The temperature susceptibility of the binder is also less, thus reducing or eliminating the tendency of the rubber to bleed in hot weather or crack because of shrinkage or flexure during cold weather (33).

2.3.1.1 Special Construction Considerations. The major concern in construction of rubber-asphalt seal coat is the uniform distribution of the binder from a conventional asphalt distributor. Since this binder has a higher viscosity, 5.5-7.5 percent kerosene, by volume, is added to the blended asphalt and rubber to reduce the viscosity of the binder, so that the material would flow evenly from the distributor nozzle. This process temporarily decreases the viscosity of the composition and allows it to be more easily sprayed or pumped. It also increases the adhesion of the binder to the pavement and the cover stone. After about one-half hour, the viscosity of the binder will rise again to about what it was before the kerosene addition.

The tendency of the undissolved rubber in the distributor to settle to the bottom of the tank could also result in a nonhomogenous binder which can, in turn, plug the spray nozzle. Therefore, the binder is usually mixed in the tank by means of a steel shaft to which paddles are attached (33).

The pavement to be seal coated is tacked with a diluted SS-IH emulsion. The rubber-asphalt binder is applied to the pavement surface at a rate of 4.0 to 1.0 gallons per square yard. The rate depends upon the amount of absorption of binder into the old pavement, amount of absorption of binder into cover stone, and the depth of cover stone embedment desired. The cover stone, 3/8 inch nominal size, is applied at a rate of 38 pounds per square yard. It is recommended that the stone be heated to about 300°F and precoated with 0.3 to 0.5 percent penetration grade asphalt to eliminate the dust nuisance caused by construction operations. The cover stone is rolled with a minimum of three coverages by pneumatic rollers (33).

2.3.1.2 Field Trials. Three projects placed by Arizona DOT have played an important role is the evaluation of the capabilities of the system. These projects are commonly known as the Aguila, the Flagstaff, and the Minnetonka (33).

The Aguila project consisted of six miles on U.S. 60 and six miles on Arizona 71. The pavement on these highways was in an advanced stage of fatigue, and plans called for a six-inch overlay to restore the structural integrity. Insufficient funds were available for an overlay, so the asphalt-rubber seal coat was placed as an interim treatment. The seal coat was placed during July 1972, under extreme climatic conditions with ambient temperature of approximately 133°F. This asphalt-rubber seal coat has served extremely well to date (1975) although the cracking in the pavement was so pronounced that the cracking pattern can be observed in the uncracked seal (4).

The Flagstaff project was Arizona DOT's first major asphalt-rubber treatment. It was placed in August 1973 in the northern part of the state. This ten-mile project is located on U.S. 89 and is at an elevation of more than 7,200 feet. The winters are cold with minimum temperature as low as -40°F and frost depths of three feet in shady areas. The existing surface was severely "alligatored" with fatigue cracking aggravated by frost susceptible base course that caused severe break-up during thawing periods. It was necessary to place a thin cold-mixed patching course on most of the project to fill the many potholes. In August the asphalt-rubber treatment was placed. This project has performed excellently without reflection cracking and with zero maintenance to date (1975) (4).

The Minnetonka project was a thirteen-mile section of I-40 extending east from Winslow to Minnetonka. The project included twenty-six experimental sections to evaluate prevention of reflection cracking in overlays, three of which used asphalt-rubber. One placed as a stress-absorbing membrane (SAM) and the other two placed between the overlay and the asphaltic concrete friction course as a stress-absorbing membrane interlayer (SAMI). The inspection of the project in Spring 1975 concluded that the asphalt-rubber SAMI was highly effective in preventing reflection of all types of cracks, including fatigue, shrinkage, and differential vertical strain, and asphalt-rubber seal coat was effective primarily in controlling fatigue cracking (4).

2.3.2 Rubber-Modified Asphalt Pavements (PlusRide™)

The rubber-modified asphalt paving mix is prepared by a process that typically uses 3 percent 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) (13) 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 PaveTech Corporation of Bellevue, Washington (10).

The original purpose of using these mixtures was solely to increase flexibility and durability. However, it was also found to provide a new form of wintertime ice control as well as a reduced noise level and minimized light reflection. The ice control mechanism apparently results from the flexing of the protruding rubber particles and the greater flexibility of the mix under traffic action, which causes a breakdown of surface ice deposits. Roadway surface ice deposits become a major problem in urbanized areas with high traffic volumes and stop and go traffic movements. Costs of maintaining ice-free pavements through de-icing chemicals or improving traction through sand applications are very high. Considerably increased expenditures on pavement construction would be justified if ice-free

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

pavements could be obtained. Further study of rubber-modified asphalt pavements in the United States has also indicated a potential for greatly increased pavement fatigue life as a result of the elasticity of this material (32).

In addition to be 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 (8). The use of these discarded tires helps to solve the environmental problems 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 (8).
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 (10).
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 percent under icy road conditions (32).

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 (8).

6. Sanding and Salting: With improved skid resistance and deicing characteristics, the need for sanding and salting is greatly reduced. This results 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 is justified.

2.3.2.1 Use of PlusRide^{TM} Process in United States Roadway System. From 1979 to the present, the PlusRide^{TM} process has been used in approximately 52 applications throughout the United States (34). Table 2.6 and 2.7 present the summary of the number of tons of PlusRide^{TM} and Rubit^{TM} placed in the United States and Sweden. Also, a list of the completed projects is included in Appendix A. No estimate for the 1987 construction season was available at the time of this writing.

Table 2.6. Summary of PlusRide™ Projects Placed in United States (34).

Year	No. of Projects	Tons of Mix
1979	1	90
1980	1	1,700
1981	4	3,000
1982	8	5,867
1983	6	15,886
1984	7	18,883
1985	14	20,315
1986	11	38,370
Total	52	104,111

Table 2.7. Summary of Rubit™ Projects Placed in Sweden (79).

Year	Tons of Mix (assuming 140 Pcf)
1981	1,405
1982	600
1983	3,065
1984	1,020
1985	15,000
1986	25,000

2.4 Rubber-Modified Asphalt Mix Design Considerations

Rubber-modified asphalt (PlusRide^{TM}) paving mix is prepared by a process that typically uses 3 percent by weight of granulated coarse and fine rubber particles to replace some of the aggregate in the mixture. Based on experience in the United States and Sweden, three different aggregate gradation bands are recommended by the PaveTech Corporation (PlusRide^{TM}) to serve different traffic levels as shown in Table 2.8.

To those knowledgeable in the area of design of asphalt paving mixtures, a review of the above aggregate grading specifications reveals some critical differences between modified and normal pavements. The most important difference is indicated by the comparative shapes of the aggregate gradation curves (Figure 2.10). To provide space for the rubber particles, it is necessary to create a "gap" in the gradation curve for the aggregates, primarily in the 1/8" to 1/4" size range. The rubber particles replace the rock particles that normally occupy this size range. The rubber particles used in these mixes are specified to be produced in a "roughly cubical form" from grinding of waste tires, which have first had the steel wires in the tire bead area removed. The rubber may include some tire cord and steel fibers from tire belts, and must meet the gradation specifications in Table 2.9.

Mix designs for rubber-modified asphalt mixtures are normally made using the Marshall and 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

Table 2.8. PlusRide^{TM} Recommended Specifications for Rubber-Asphalt Paving Mixtures for Different Levels of Traffic (10).

	PlusRide	PlusRide	PlusRide
Mix Designation	8	12	16
Average Daily Traffic	2,500	2,500-10,000	10,000
Thickness (in.) Min.	0.75	1.5	1.75
<u>Sieve Sizes</u>:		<u>Aggregate % Passing</u>	
3/4"	--	--	100
5/8"	--	100	--
1/2"	--	--	--
3/8"	100	60-80	50-62
1/4"	60-80	30-44	30-44
#10	23-38	10-32	20-32
#30	15-27	13-25	12-23
#200	8-12	8-12	7-11
1/4" to #10 Size Fraction	--	12 Max.	12 Max.
<u>Preliminary Mix Design</u>:			
Rubber, % of Total Mix by weight	3.0	3.0	3.0
by volume (approx.)	6.7	6.7	6.7
Asphalt, % of Total Mix by weight	8-9.5	7.5-9.0	7.5-9.0
Maximum Voids (%)	2.0	2.0	4.0

Table 2.9. Particle Size Specification for Rubber (10).

	Percent Passing		
Sieve Size	Coarse Rubber	Fine Rubber	80/20 Rubber Blend*
1/4 in.	100		100
No. 4	70-90		76-92
No. 10	10-20	100	28-36
No. 20	0-5	50-100	10-24

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

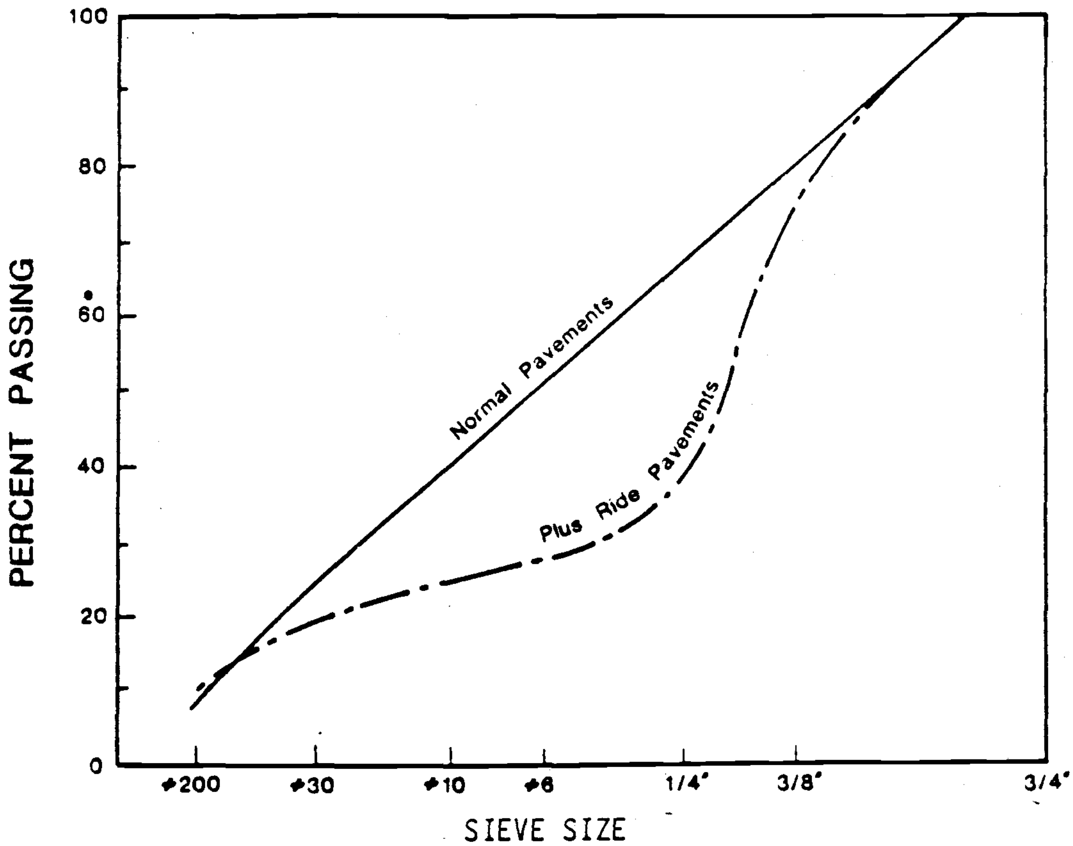


Figure 2.10. Comparative Aggregate Gradation Curves for Normal and "PlusRide™" Asphalt-Rubber Pavements (35).

density as criteria for designing conventional hot mix asphaltic concrete pavements. However, stability values for rubber asphalt mixes (PlusRide™ process) that are currently on the market are lower than values obtained for typical asphalt mixes. The flow values for rubber-modified mixes are generally greater than the maximum allowable in asphalt mix design criteria (36). Consequently, stability and flow values for rubber-modified mixes 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 (36). For example, pavements placed in Alaska that had low void contents (approximately 4.6%) and satisfactory performance had stabilities as low as 350 pounds and flows up to 0.19 inch (36). In general, the laboratory air voids are recommended to range from 0-4 percent maximum depending on the traffic level of the facility being designed (36):

1) Low traffic - 0-2 percent.
2) Medium traffic - 3 percent maximum.
3) High traffic - 4 percent maximum.

This required void content is achieved by increasing both the mineral filler and the asphalt cement content until the target value is reached (36). A detailed evaluation (strength and weaknesses) of current mix design techniques, and improved asphalt mix design procedure is provided in Appendix B.

2.4.1 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 percent to 2 percent compared with the 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, 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 to 149 °C (285 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 five pounds during cooling. This helps prevent the specimen from expanding or decompacting. The standard fifty-blow Marshall procedure is recommended by PlusRide™ to select the asphalt content for low to medium traffic (13).

2.4.2 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 (37). 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 using kneading compaction (37). 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.

The Federal Highway Administration (WDFD) has performed a mix design for rubber-modified asphalt mixtures using the standard Hveem procedure (38). After blending, the aggregate is heated to 160°C (320°F). Rubber at ambient temperature is added to the heated aggregate and dry mixed for fifteen seconds. After adding the required asphalt, the sample is mixed for an additional three minutes. Each sample was then returned to the 160°C (320°F) oven for a one-hour curing period. After curing, the samples are compacted using fifty compactor foot applications at 250 psi, followed by a 40,000-pound leveling load. The forming mold part of the compaction mold is lubricated using standard multi-purpose grease, and a release paper disk is used to prevent the mix sticking to the base. Finally, a five-pound surcharge is placed on each sample until it cools to room temperature.

2.5 Evaluation of Mix Properties

Only limited mix properties (e.g., modulus and fatigue) are available for rubber-modified asphalt mixtures (PlusRide™). Most of these data were developed by Oregon State University and Alaska Department of Transportation and Public Facilities (39,40). 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.

2.5.1 Alaska DOT & PF Study (40)

This section describes the results of resilient modulus and fatigue on rubberized asphalt mix performed by Alaska DOT & PF. Two projects were evaluated, (a) Peger Road, and (b) Upper Huffman. All tests were performed in the Central Region Laboratory (ADOT & PF) and at Oregon State University 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.

2.5.1.1 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 percent 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 of 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 percent, 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 percent additional fine rubber, and
3. mix temperatures of 190°C (375°F) and 204°C (400°F). The compaction temperature in all cases was 121°C (250°F).

The asphalt and rubber contents 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
3.0	8.0
3.5	8.5

Figures 2.11 and 2.12 show the effect of rubber content on Marshall stability and voids.

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 2.13 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 2.14, 2.15, and 2.16.

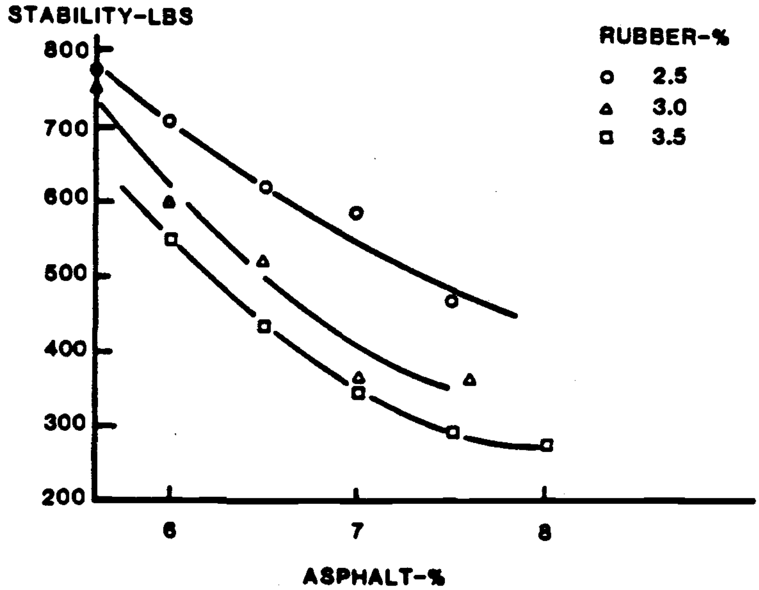


Figure 2.11. Effect of Rubber Content on Stability - Peger Road (Normal 80:20 Rubber Grading) (40).

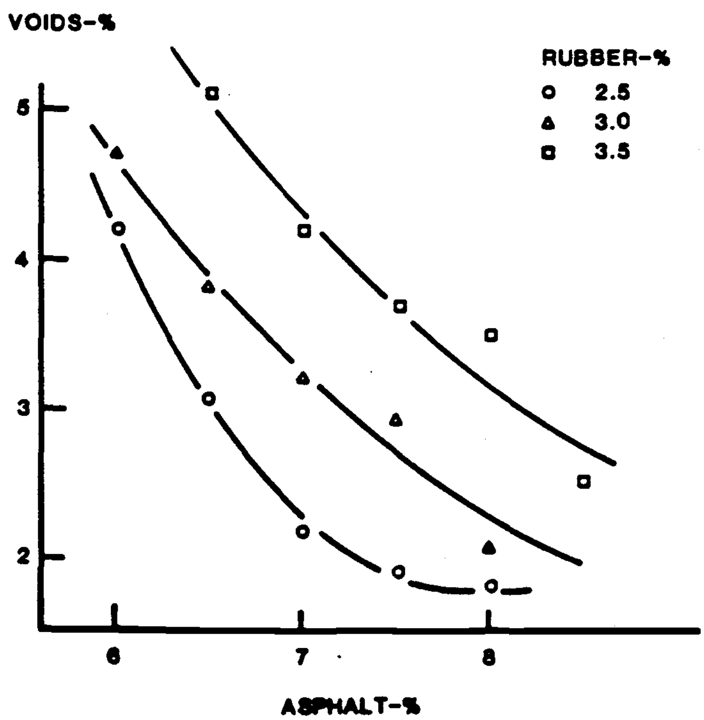


Figure 2.12. Effect of Rubber Content on Air Voids - Peger Road (Normal 80:20 Rubber Grading) (40).

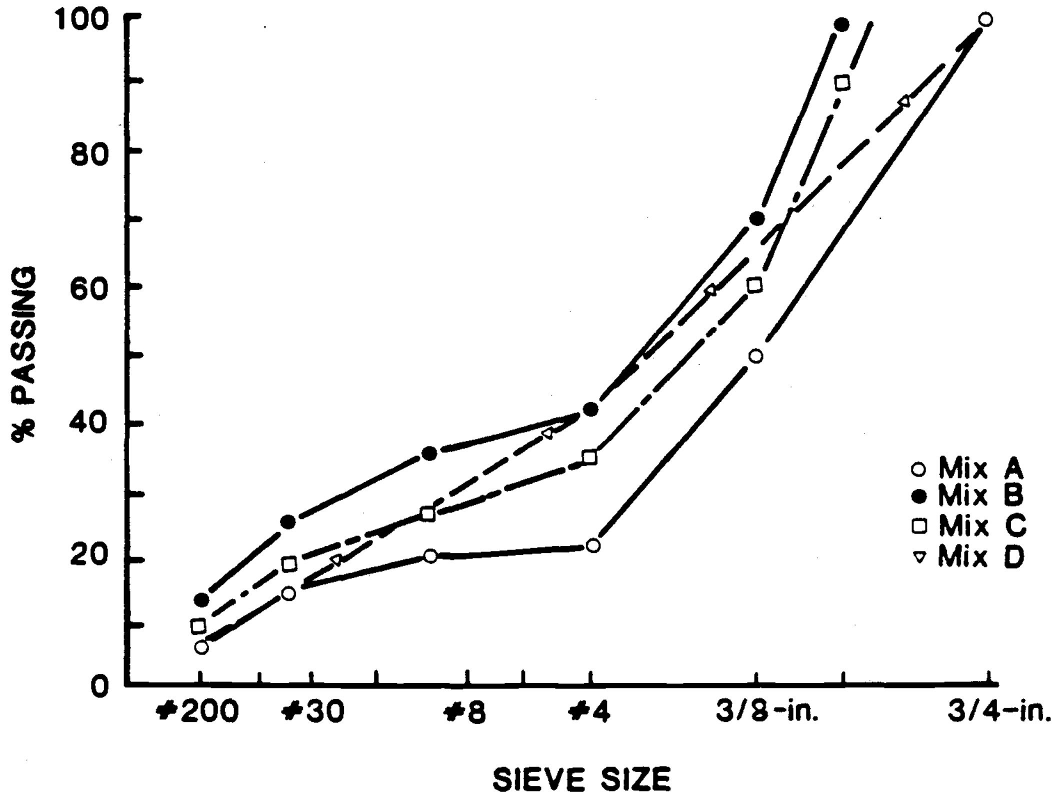


Figure 2.13. Aggregate Gradation Used - Huffman Road (40).

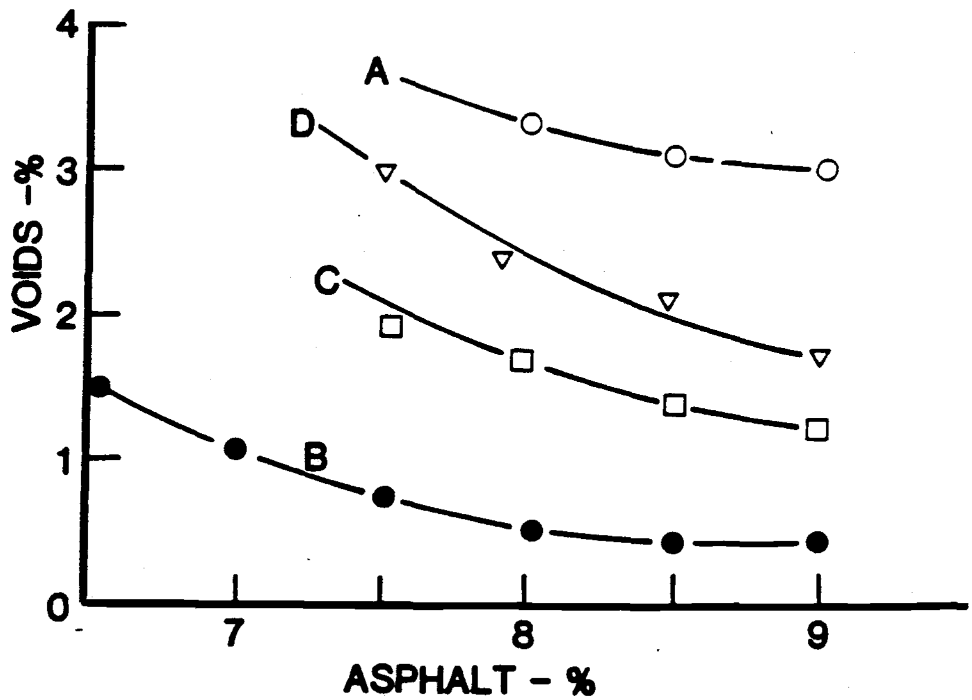


Figure 2.14. Effect of Aggregate Gradation in Air Voids - Huffman Road (40).

2.5.1.2 **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 2.10 and 2.11 summarize the results of modulus tests for each project. As indicated in Table 2.10, the effect of rubber content is slight; however, the effect of added fine rubber and mixing temperature increases the modulus from 22 to 61 percent. In Table 2.11, 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 2.17 summarizes all modulus data for both projects.

Table 2.12 and Figure 2.18 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.

2.5.1.3 **Discussion of Results**. The results of these tests generally indicate:

1. The effects of aggregate gradation (Huffman Road) were dramatic, affecting the asphalt content by 3 percent. As the asphalt content increased, the modulus decreased. When the aggregate gradation approached the fine end of the band, 2 percent voids could be obtained only at low asphalt contents, which resulted in a high modulus. The effect of aggregate gradation on fatigue was not evaluated.

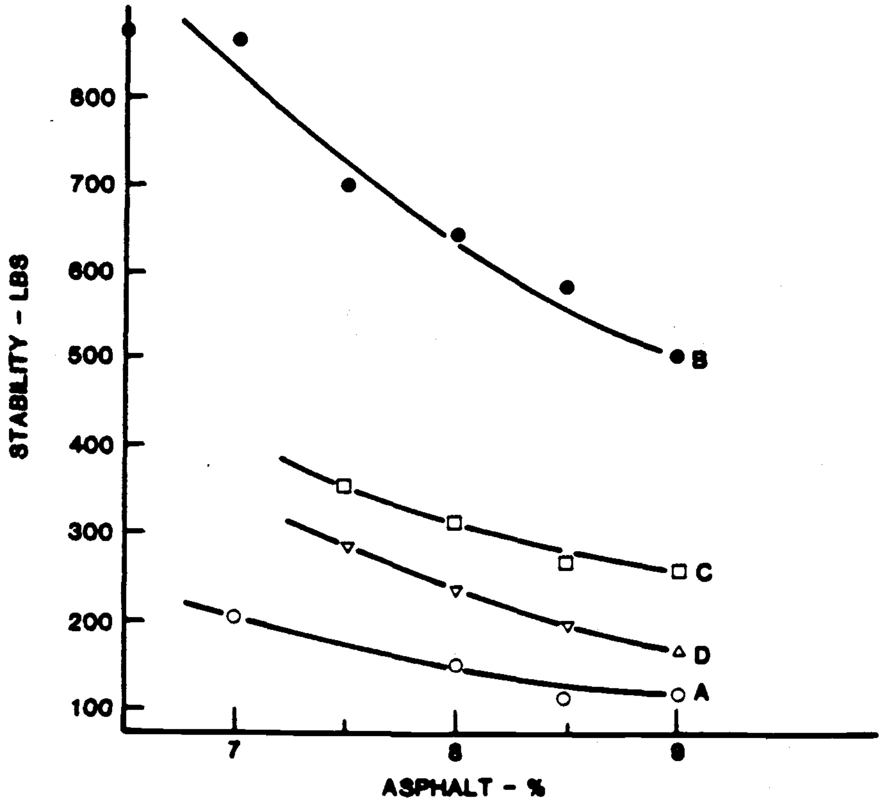


Figure 2.15. Effect of Aggregate Gradation on Stability (40).

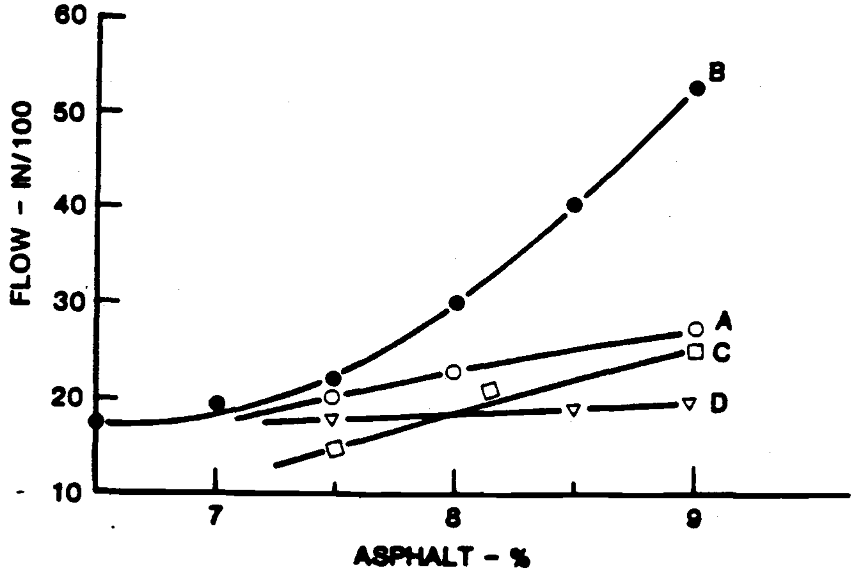


Figure 2.16. Effect of Aggregate Gradation on Flow (40).

Table 2.10. Summary of Modulus Data - Peger Road.

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

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 2.11. 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

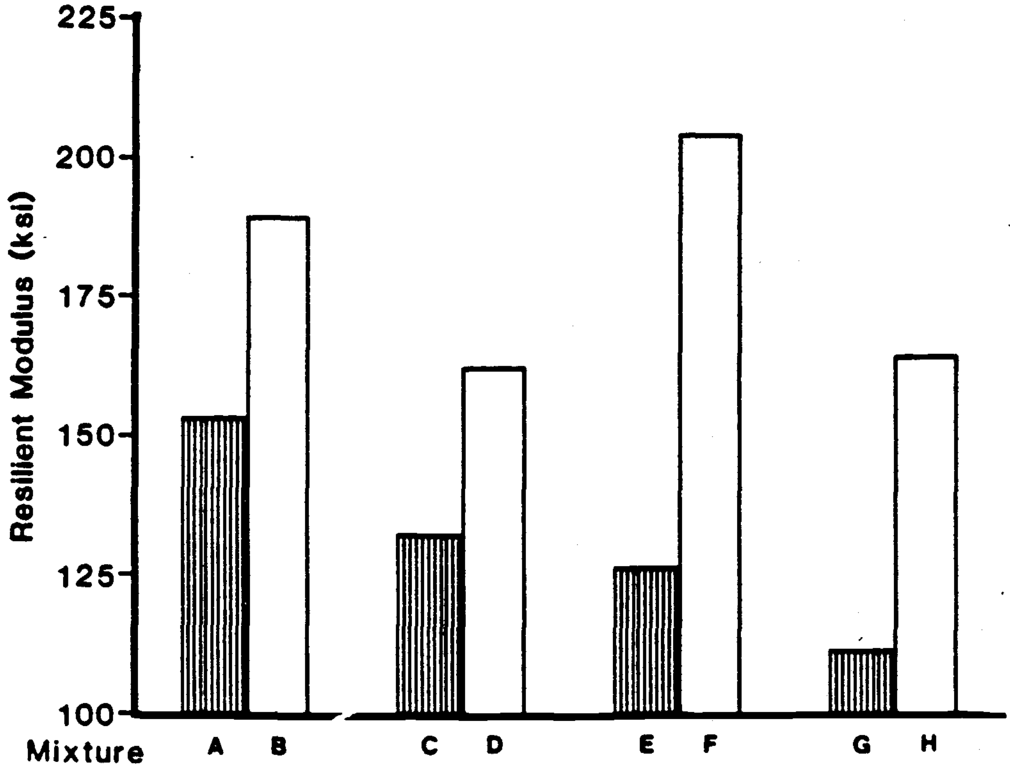
Standard Mix (1)			Modified Mix (2)			% Increase in Ave. Modulus
Sample Number	Modulus, ksi Ind	Avg	Sample Number	Modulus, ksi Ind	Avg	
4	204		13	326		
5	200	206	14	314	329	+59.7
6	213		15	347		

c) 8% AC-5, Middle Aggregate Gradation

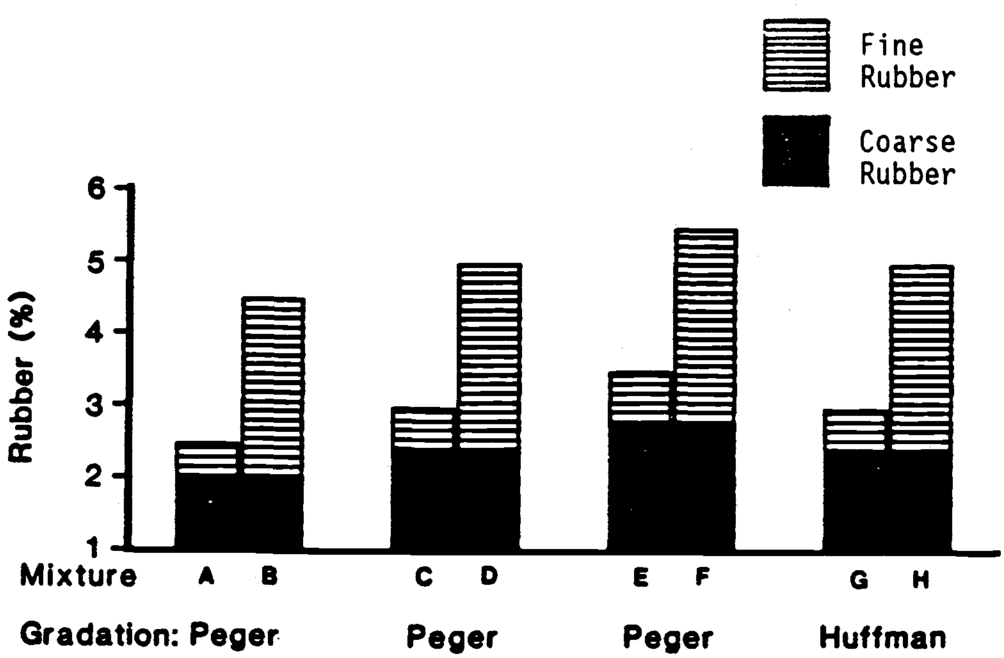
Standard Mix (1)			Modified Mix (2)			% Increase in Ave. Modulus
Sample Number	Modulus, ksi Ind	Avg	Sample Number	Modulus, ksi Ind	Avg	
7	126		16	134		
8	91	112	17	193	177	+59.0
9	118		18	205		

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



b) Rubber content

Figure 2.17. Modulus vs. Amounts of Coarse and Fine (-30) Rubber in Mix (35).

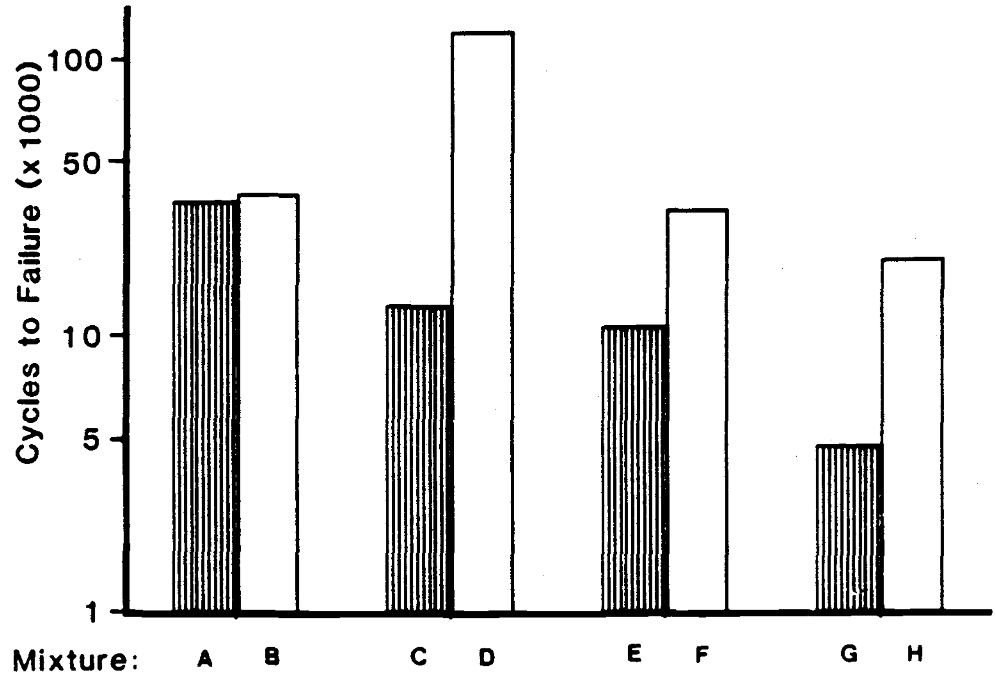
Table 2.12. Summary of Fatigue Tests - 10°C (50°F).

a) Peger Road

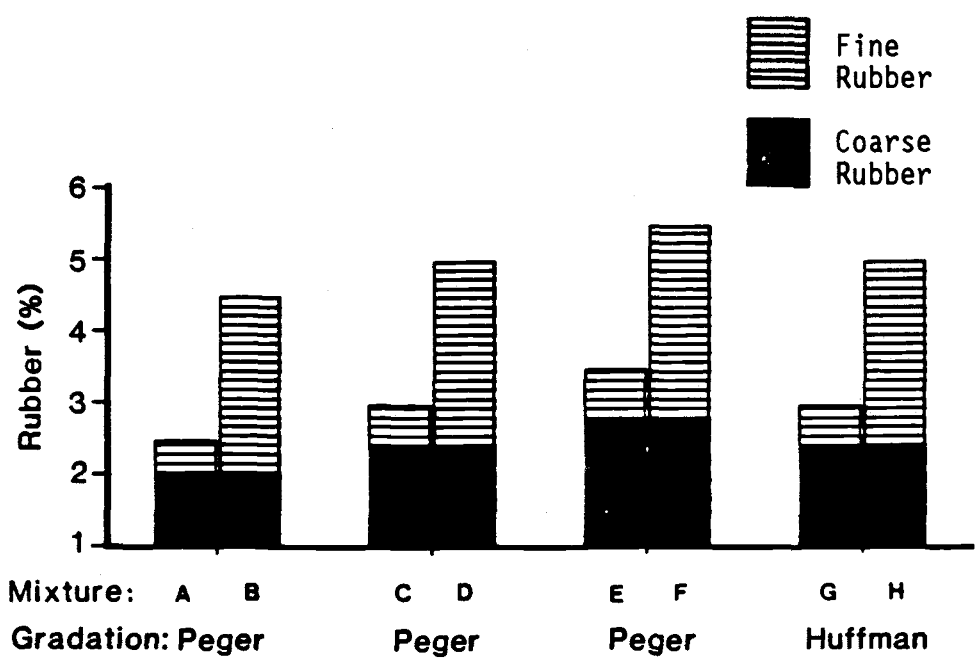
Sample No.	Tensile Strain, 10^{-6} m/m	Fatigue Life Ind Result	Fatigue Life Average
2	200	31,360	
4	200	13,180	
7	200	6,686	11,095
8	200	15,504	
10	200	33,463	
14	200	134,000	131,726
15	200	129,452	
18	200	29,239	

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



a) Fatigue life for mixes with rubber contents



b) Rubber content

Figure 2.18. Fatigue life for Mixes with Fine and Coarse Rubber (35).

2. The effect of rubber content (Peger Road) on modulus was slight (Figure 2.17). However, the maximum fatigue life was achieved at 3 percent rubber content increased to 3.5 percent as shown in Figure 2.18.
3. Added fine rubber proportions increased the modulus and fatigue values in all cases. The maximum fatigue life was obtained with 5 percent total rubber (2.4% coarse and 2.6% fine).

2.5.2 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 (25). 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.

2.5.2.1 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 8 aggregate gradation and 3 percent 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 (319°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.

2.5.2.2 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 1.0 s at a frequency of 1 Hz.

Tables 2.13 and 2.14 summarize the results of tests for modulus at 75 and 100 microstrain, respectively indicated in Tables 2.13 and 2.14, 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 2.15 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.

Table 2.13. 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.	Modulus, ksi Avg.
Bag House Fines	317	
Fly Ash	160	
Volcanic Ash	191	210
Limestone Dust	178	
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%	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.	Modulus, ksi 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.	Modulus, ksi 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 2.14. 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

Variable, 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 2.15. 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.

2.5.2.3 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 (39).
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 2.13 and 2.14). 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.
4. The effect of filler and rubber content on resilient modulus and fatigue life is interesting. The mixtures with 12 percent filler and with 10 percent 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

effects of type and amount of rubber or filler on mix properties.

2.6 Evaluation of Field Projects

This section presents a summary of the results of initial and follow-up questionnaire surveys for evaluating the field performance. 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 (41), and the results from twelve test projects conducted between 1979 and 1986 (36,42) by the Alaska Department of Transportation and Public Facilities (ADOT & PF). The follow-up questionnaire was sent in July of 1984 to the same agencies originally surveyed. The follow-up questionnaire was used to define the performance of the Plusride mixes. Also, a telephone questionnaire was conducted in May of 1987 to define further the present condition of the PlusRide™ mixes. The complete description of three selected projects which have used PlusRide™ mixes are given in Appendix C.

2.6.1 Questionnaire Survey

The results of both surveys are summarized in Appendix D 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. projects condition.

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 (36,41,42,43,44).

2.6.2 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 2.16.

The aggregate gradation used by those agencies which reported a gradation different from that specified is shown in Figure 2.19, along with the gradation envelope recommended by PaveTech Corporation for Plusride (45).

The results of the follow-up questionnaire are summarized in Table 2.17. 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. The City of Bellevue, one of the agencies which did not include a preliminary evaluation report with its reply, reported no problems with the mix used. The existing pavement was PCC with transverse cracks every ten to twelve feet, along with random cracks and moving slabs. As reported in Table C.1, the main reason

Table 2.16. Summary of Initial Questionnaire Survey (1983).

	Average	Range
Asphalt Content, %	7.7	5.0-9.5
Rubber Content, %	3.0	2.5-4.0
Mix Temperature, °F	330	285-360
Total Mix Time, Sec.	30	14-45
Compaction Temperature, °F	320	200-330
Voids in Mix, %	4.8	0.5-12.0

Table 2.17. Summary of Follow-up Questionnaire Survey (1984).

a) Present Condition of Rubber-Modified Asphalt Mixes From Eight 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 Eight 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

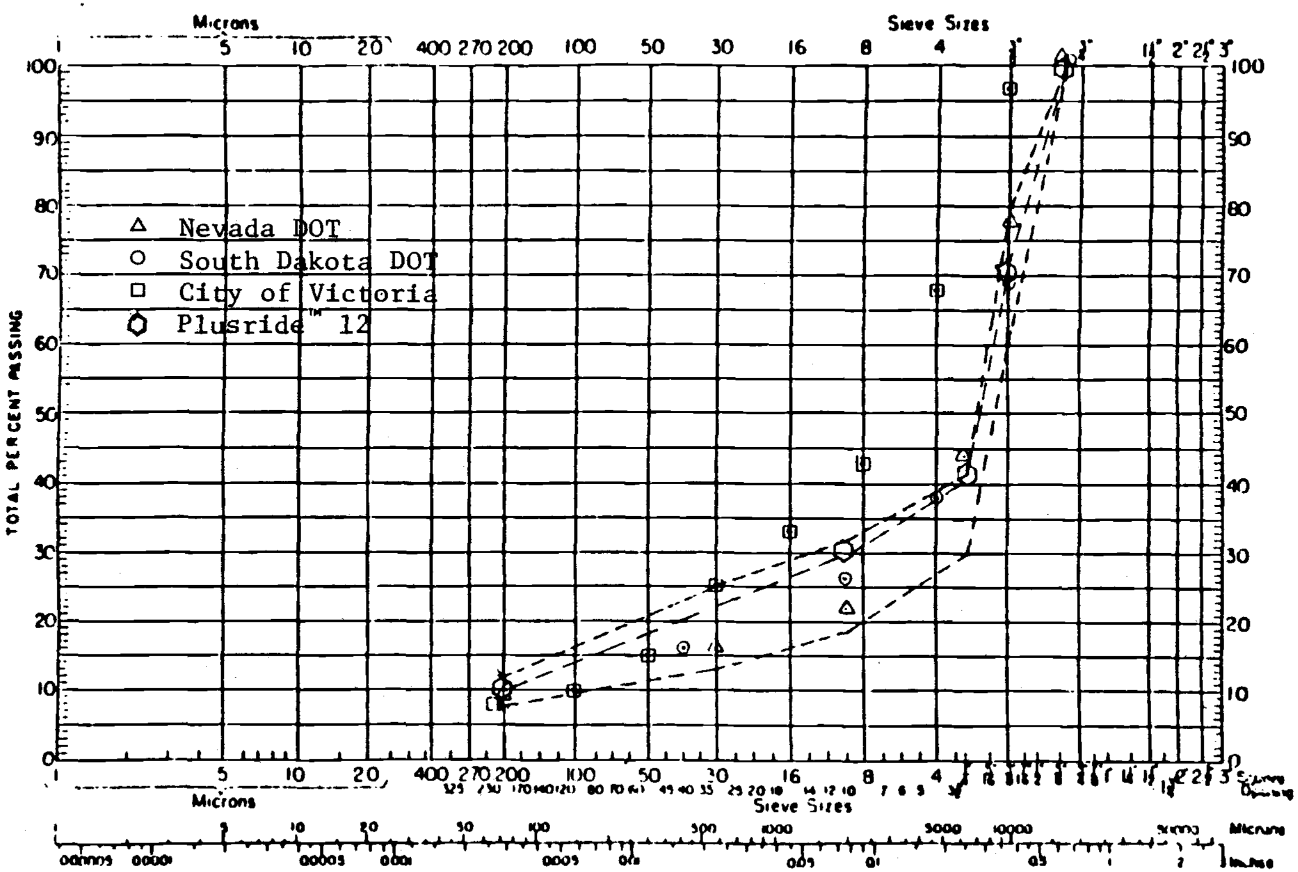


Figure 2.19. Aggregate Gradation Used on Selected Rubber Asphalt Projects.

for use was based on a comparison between rubber-modified asphalt and geotextile-reinforced pavement for the control of reflective cracking. To date (1987), after five 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 1987, WSDOT had used rubber-modified asphalt in three projects. Of these three, the questionnaire received concerned only the Union Gap Project (Table C.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 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 (36) as the wearing course. The area, Eastern Washington, experiences below freezing temperatures in the winter and summer temperatures exceeding 100°F. Preliminary data indicate some problems with rutting and bleeding. The asphalt content was 8 percent with an air void content of 3.5 percent.

Data were limited on the other two projects in Washington (46). 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 (46). The climatic conditions are similar to those reported above. The expected ADT is 14,000 with 13 percent 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 (46). The existing pavement was overlaid with two 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. 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 (see Table D.1).

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 D.2).

The mix contained 8.4 percent P200 and air voids of 3 percent. In 1982, Dynaflect testing was conducted on both the Class G and the rubber-modified asphalt. 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 (1984) 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%). In the follow-up questionnaire (1987), South

Dakota DOT reported extensive raveling and potholing in the PlusRide section and the mix was subsequently removed.

City of Victoria. This project involved overlaying 1.3 km of downtown streets in Victoria, B.C. The mixture had 7 percent asphalt and approximately 3 percent 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 D.7).

Some raveling problems were reported from the first 150 tons of the 1200 tons placed (4). 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 percent 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 percent are suggested as laboratory mix design criteria for a stable, durable product (47).

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 (41). 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 percent. 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 pavements (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 D.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 percent. After seven months, the experimental section showed no signs of distress (Table D.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 percent. The average air void content was 5.5 percent. This pavement was placed to evaluate reflective crack control and skid resistance compared to conventional mixes (Table D.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 percent trucks (Table D.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 (44). 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 (48) offered a different explanation for the observed distress. They reported that excessive voids (10 to 22%), instead of the 3 to 5 percent 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 resulting in early pavement failures.

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.

<u>Alaska DOT - Carnation Curve and Fairhill Access Road</u> (36). 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 to two inches over existing asphalt concrete paving which had been tacked with RC-800. The final air void, as determined by coring, was 4.6 percent (Table D.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 percent.

Both sections are still serviceable. The second site raveled slightly, but was reported to still be functional after eight years.

Alaska DOT: Old Seward Highway (36). 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 percent, 3.5 percent, and 4 percent 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 percent section was placed considerably below 260°F due to traffic control delays. Cores of the various test sections indicated air voids in the 4 percent rubber section averaging up to 12 percent, and 7.5 percent in the other two sections (Table D.6). The 4-percent section raveled almost immediately and the other sections within two to three months. Subsequent testing revealed that most samples were out of gradation specifications and lacked mineral filler. All sections were replaced with conventional mix in 1982.

Alaska DOT: Peger - Van Horn Intersection (36). Because Alaska DOT & PF believed the failure of the 4-percent test section of the Old Seward Highway was due, in part, to the heavy truck turning movements, this intersection was chosen to investigate further 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 percent (by weight of total mix) at 310°F was raised by 8.2 percent (by weight of total mix) at 330°F and finally increased to 8.5 percent (by weight of total mix) 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 percent (Table D.7). This section demonstrated de-icing characteristics of Plusride during the winters of 1981 through 1983 as measured by Tapley meter stopping distance tests. This test section was seal coated in 1986.

Alaska DOT: Upper Huffman Road (36). 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 percent AC-5 asphalt which was discharged from a batch plant at 360°F. The apparent air void content was 10 percent, but this value may be in error due to the thin overlay (Table D.5). To date (1987) the section is performing well with no raveling or surface failures apparent.

Alaska DOT: Lemon Road. This project undertaken by Alaska DOT&PF 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 percent (by weight of total mix), with a mix temperature of 275°F (Table D.4). To date (1987), after four years, the rubber-modified asphalt mix remains virtually unchanged.

Montana DOH (49). 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 percent. 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 percent (Table D.3). To date (1987), after four years, the rubber-modified asphalt remains virtually unchanged. Montana DOH reported that pavement performed well with respect to noise and reflective cracking, but pavement performance against ice, fatigue, and skid resistance was not noted.

CALTRANS (50). The California Department of Transportation has begun compiling test data on a nine-mile test section. This section was designed to compare Plusride and ARCO rubberized binder and others, 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 D.3). To date (1987), after four years, 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 (38). 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 D.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 (1987), the Plusride Section is performing as well as the control.

City of Corvallis, Oregon. In September 1986, The City of Corvallis constructed an experimental rubber-modified section to compare rubber-modified asphalt and geotextile-reinforced pavement for the control of reflective cracking. The mix was placed 1-3/4 inches thick with an asphalt content of 7.8 percent. The mixture was produced in a batch-type plant at 330°F. The CC42 Dynapac roller was used for breakdown and finish rolling. To date (1987), the section is performing well with no raveling or surface failure apparent.

2.7 Construction of Rubber-Modified Asphalt

The purpose of this section is to determine why the construction costs of the rubber-modified mixes have been so high. This question is be addressed in the following sections by reviewing the literature related to the construction practices, a survey of contractors through the use of the questionnaire, and contractor interviews.

2.7.1 Special Construction Considerations

Aggregate Production. The most common problem with project batching of acceptable PlusRide^{TM} mixes has been in achieving the proper gap in the grading curve, and obtaining sufficient fines (- #200) to serve as a void filler. The lack of mineral filler in the mix causes high air voids, and thus is of concern to the contractor and road agency. Contractors have achieved the fines (- #200) requirement by adding baghouse fines, or introducing filler such as Cottrell flour, fly ash, limestone dust or one of several other types of mineral filler (51). The percentage by weight of total aggregate for the additional filler material has varied from 2 to 9 percent with an average of 5.3 percent as determined from fifteen project summaries (51).

Mix Production. Batch, continuous, and drum-dryer plants have been used for rubber-modified asphalt mix production (32,38,52). Based on the experience of Alaska Department of Transportation and Public Facilities, in the preparation of rubber-modified mixture, a "batch" mixing plant is preferred because the required quantities of rubber, asphalt, and aggregates can be exactly measured and added separately to the "pugmill" or mixing chamber (see Figure 2.20). In this plant type, preweighed and sacked rubber can be used to advantage, with quantity control by bag count. However, both continuous mix and drum-dryer mix asphalt paving plants have been used without difficulty. In these plants the mixing operation goes on continuously rather than in batches, and the rubber must be added from a separate bin with a belt feed to maintain uniformity. The control in this type of feeding is more difficult (see Figure 2.21). Two additional disadvantages to drum-dryer plants have also been reported. The first problem is the potential for producing smoke. The second problem occurred when a contractor decided to lower the mixing temperature from 325 to 305 °F. At these temperatures, asphalt mix began sticking to the flights which caused the trunnion to slip with the increased load. The slippage was also due to some rubber granules blowing from the feeder belt and onto the trunnion. The problem was corrected by cleaning the trunnions and elevating the mix temperature back to 325°F (52).

Laydown. The laydown of the hot mix must be performed by paving machines equipped with full width vibratory screeds to aid in compaction (32). The laydown machinery used includes both hopper and pick-up type (32,38,49,52). Alaska DOT&PF also made one attempt to place the mix by using a motor patrol after end dumping the material (32). The mix placed by grader was too sticky to be easily leveled.

Handwork (such as raking longitudinal joints, placing radii, etc.) for the rubber modified asphalt mixes are affected by the mix gradation and temperatures. According to contractors, the best result of handwork was observed while the mix was at normal laydown temperatures (300°F to 320°F) (51).

Compaction. The conventional compaction equipment has been used to roll the rubber-modified asphalt mix by contractors. The breakdown rollers are typically 10 to 12 ton vibratory steel drum units (32,38,

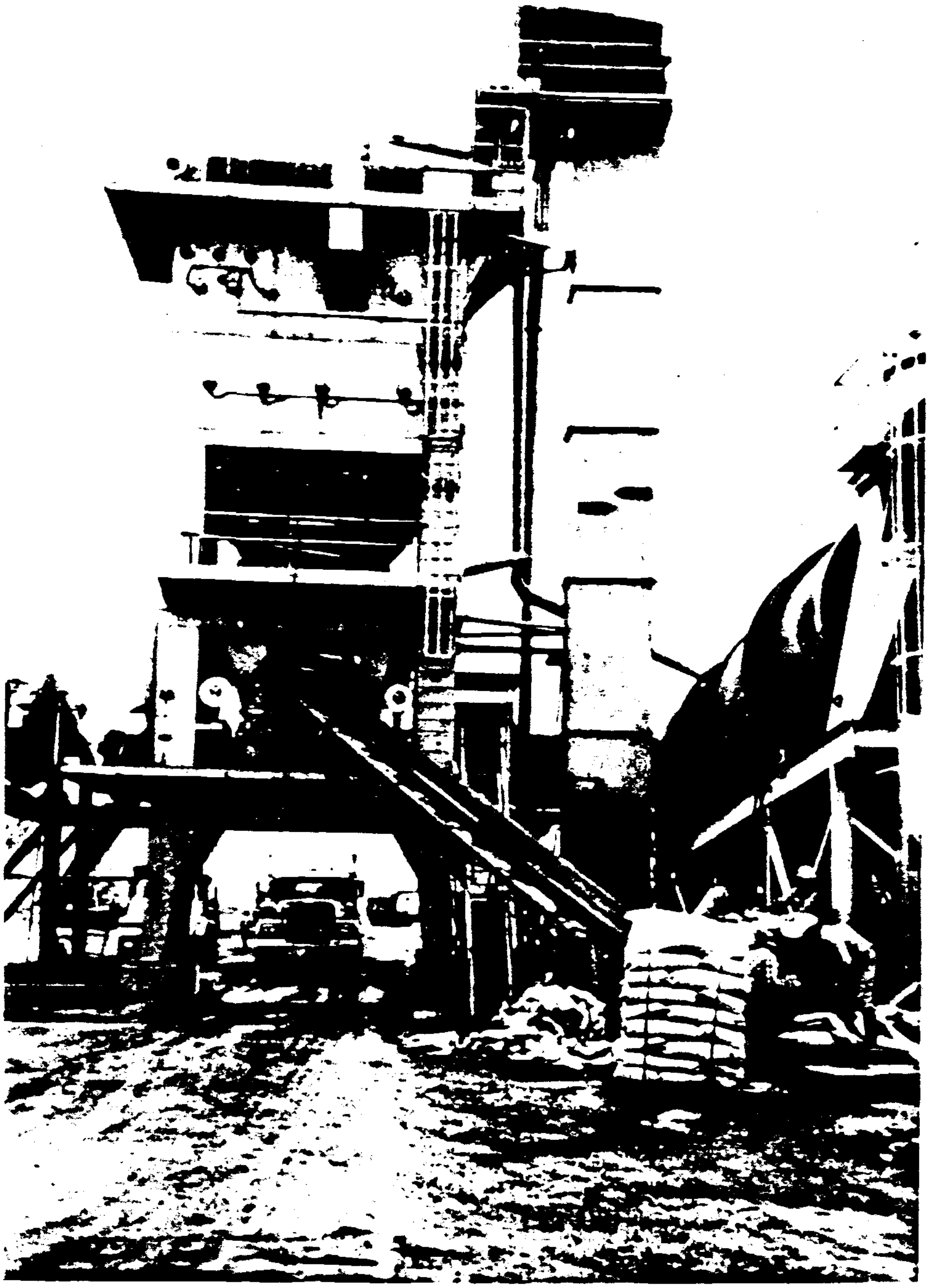


Figure 2.20. Schematic of Batch Plant for Rubber Modified Production (Conveyor Loading Rubber into Pugmill) (51)

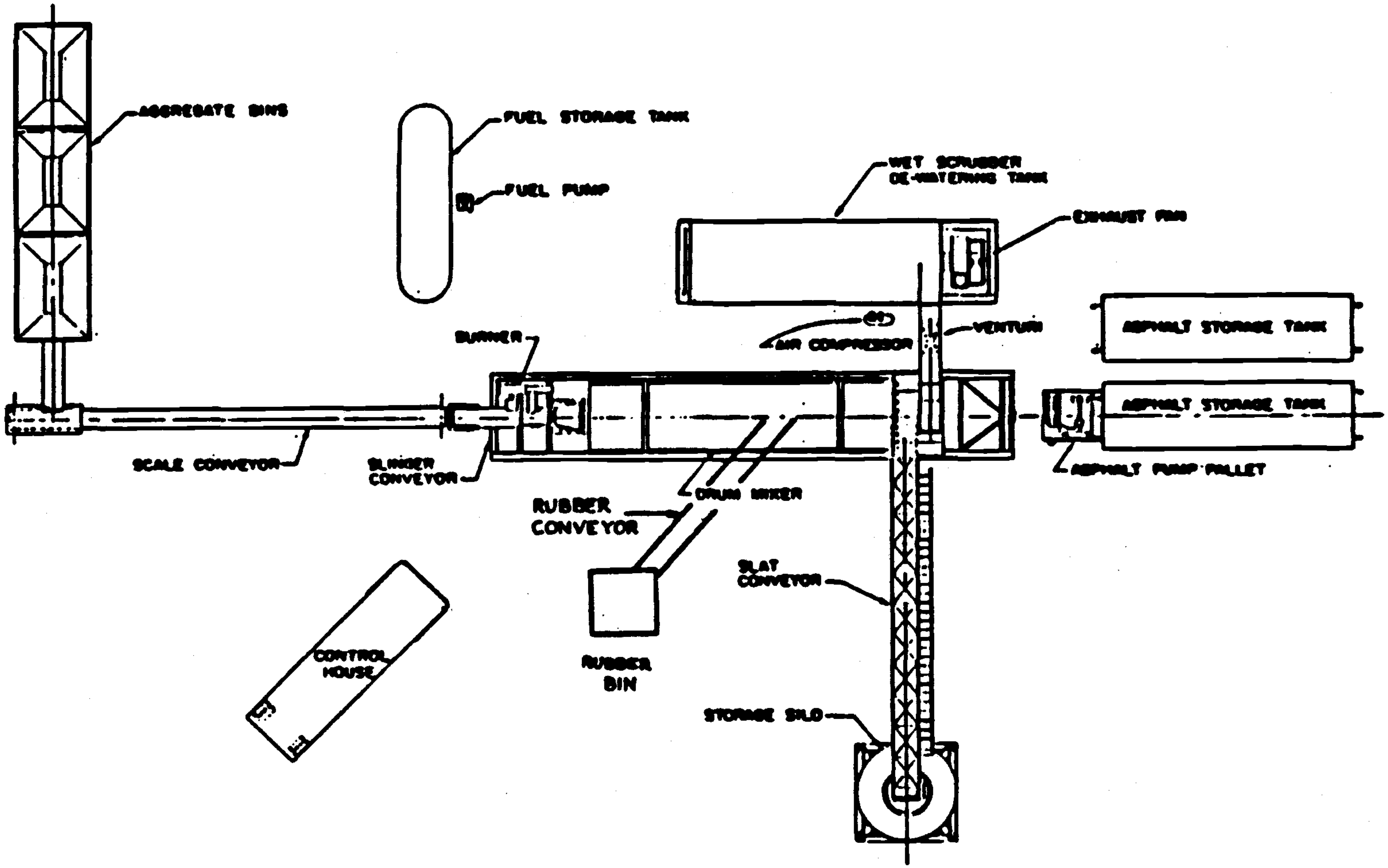


Figure 2.21. Schematic of Center Feed Drum Dryer Plant for Rubber-Modified Asphalt (51).

42,52,53). The finish or intermediate rollers are also steel drum units, but are not always required to be vibratory nor are they as heavy. Rubber-tire rollers are not recommended according to Swedish engineers. However, experiences with rubber-modified asphalt placed in Vancouver, B.C. and Anchorage, Alaska in 1981 indicate that significant surface tightening might be achieved by use of a rubber-tire roller after the mix has cooled below 140°F (36). Current practice is to avoid use of rubber tire rollers, as rutting and pickup problems can occur too easily. The rubber-modified asphalt mix being picked up by the rollers has been reported by several (32,38) agencies. The methods used by contractors to prevent or reduce pick-up are as follows (32,38,49):

1. removing rubber-tired rollers from the rolling pattern,
2. making sure all water nozzles are fully operational,
3. using liquid detergent in the drum water,
4. using a special wetting agent, Dewko wetting concentrate, in the drum water, and
5. letting the mix cool prior to breakdown rolling.

The most successful method appears to be a combination of making sure that the wetting system was fully operational and including some sort of liquid soap with the drum water (51).

2.7.2 Evaluation of Current Construction Practices

To obtain construction information from contractors regarding their experience with rubber-modified asphalt mix, a questionnaire survey and interview were conducted at Oregon State University (51).

The questionnaire was designed to obtain the following three key items of information from the contractors:

1. the existing differences between construction of rubber-modified asphalt and a conventional mix,
2. how these differences affect the mix price, and
3. any modifications to the construction process which they would recommend.

Based on nineteen questionnaires filled out by contractors, interviews with road highway departments, and reviews of the construction reports, the following items were identified as the most important factors in construction of rubber-modified asphalt mix.

1. Contractors perceive a significant risk increase for rubber-modified asphalt mixtures. To reduce costs, an owner must carefully develop the specifications so that a contractor will not be required to use large contingencies during bidding. One method of reducing this risk would be to request a unit price for all of the mix ingredients.
2. An aggregate grading change from the conventional dense-grading to a specialty grading, such as that required for rubber-modified asphalt mixture, is costly. Aggregate gradings which are more typical of the area should be employed if possible.
3. Increasing the mixing temperature or time significantly affects the mix price primarily when the increase is a substantial change from conventional mixing. However, an owner should be aware that the cost may increase, and that

mixing temperatures and times should be kept to the minimum needed for good mix performance.

4. Batch, continuous, or drum dryer plants can be used to produce the rubber-modified mixes. It is recommended, however, that the rubber be introduced into the mix via a center feed on drum dryer plants. Drum dryer operators should also be aware that air quality problems may still develop when the rubber is introduced in a rubber-modified asphalt type process. Solving the problem has required changes to the plant (e.g. wet scrubbers).
5. Both types of laydown machinery, hopper and pick-up, can be used to place the rubber-modified mixes. The main requirement of the machine is that it have a full width vibrating screed.
6. Steel drum rollers, weighing 10 to 12 tons and having vibratory capabilities, have been successfully used to compact the modified mixes. Pneumatic rollers have not been successfully used for breakdown and intermediate rolling. However, pneumatics have been used for finish rolling when the mix temperature is below 140°F.
7. Roller pick-up of the rubber-modified mix has been very common. The rollers should have a fully functional water spray system. Also using different wetting agents may help the water fully coat the drum. Wetting agents may be liquid dish soap, tri-sodium phosphate, or ethylene glycol.

2.7.3 Construction Guidelines

The following guidelines for construction rubber-modified asphalt mix were developed based on the study at the Oregon State University (51).

1. Owners should use project specifications that have been developed specifically for rubber-modified asphalt. Contractors should not be required to meet the same construction requirements for a rubber modified material as for a material with which they have had years of production and construction experience. First, a contractor knows less about what to expect from this new type of material. Secondly, changes to the mix design may be required once the actual production begins. Both of these factors serve to increase a contractor's contingency mark-ups. An owner can share the risk with a contractor in several ways. First, unit prices may be set as bid items for the aggregate, asphalt, rubber, and mineral filler. The contractor can therefore be compensated for exact production quantities. Secondly, construction of a test strip will determine target densities for compaction. Third, projects should be large enough to enable a contractor to cover the costs of a new set-up adequately and to learn to work with a new material. Fourth, provision should be made for a contingency item for purchase from the contractor of waste aggregate and rubber that are not used on the project. This might occur due to changes in the project scope by the owner after construction has begun. And lastly, the owner should make the contractor

aware in the early stages of the project that this is an experimental material, and if conditions in the field warrant a change in the methods, the contractor will be fairly compensated for additional work.

2. Rubber-modified asphalt should be tried using more conventional gradings. A dense-graded rubber-modified asphalt mix has been prepared in the laboratory without any unusual problems. The mix still had the same favorable fatigue resistant characteristics as the gap-graded material. Use of a commonly produced dense-graded aggregate could result in a $6.00/ton savings on the mixture price.
3. For large projects (5,000 tons or more), project specifications should require the to contractor calibrate the plant so material can be precisely controlled as it is introduced into the mix.
4. In the project specifications, drum dryer plant operators should be made aware that center feed of the rubber material is preferable. Also contractors (drum dryer plants in particular) should be forewarned that modifications to the plant may be required to meet local air quality standards.
5. Drum dryer operators should not reduce the mixing temperatures below 325°F.
6. Tarps should not be used to cover the haul units when loaded with the rubber-modified mix, nor should the bed of the haul units be oiled.
7. The project specifications should require the contractor to use steel drum rollers for compaction. The rollers <u>must</u> be

equipped with fully operational spray equipment for wetting the drums. Water is the best repellent of rubber for the money. However, several agents are available which help the water do its job better. The first is liquid detergent which reduces the surface tension in the water, helping it to coat the drum. A wetting agent that could be tried on an experimental basis is tri-sodium phosphate (51), the compound used when washing house paint, available at any hardware store. This compound lowers the pH of the water and makes it more ionic and more repellent of rubber. Another wetting agent that could be tried experimentally is ethylene glycol (anti-freeze) (51). Including some of this compound with the water also aids in wetting the drum.

8. Use of pneumatic rollers should be avoided unless the mat temperature is below 140°F.

2.8 Summary

The material described in this chapter may be summarized as follows:

1. Use of asphalt-rubber provides an attractive alternative for construction, rehabilitation, and maintenance of roadway networks. 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 deter-

mining the elastic properties of an asphalt rubber mix. Particles with a low bulk density yield blends with desirable high elastic recovery, whereas those particles with a high bulk density, as produced by cryogenic processing, give products with poor elastic properties (21).

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 (13). 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 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 0 to 4 percent 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 twenty experimental projects constructed between 1976 and 1986 were evaluated using a questionnaire survey. Almost all of these 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: (a) incomplete mixing, (b) excess or insufficient asphalt, (c) high voids, and (d) 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 percent 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.
9. The rubber-modified asphalt mixture weaving course has lower friction numbers compared to the conventional asphalt mixture course when tested during the summer periods. However, extensive measurements by Alaska DOT & PF showed an average reduction in stopping distances of 20 percent for the rubber-modified pavements in icy conditions.
10. Rubber-modified asphalt mixture is more susceptible than conventional mixtures to preparation and compaction problems when adverse weather or equipment problems occur. However, with adequate equipment and favorable weather conditions, the rubber-modified asphalt mixture placement is similar to conventional mixture placement.

3.0 LABORATORY PROGRAM

On the basis of the literature review presented in the previous chapter, it was possible to design an appropriate 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 E.

3.1 Variables Considered

To evaluate the effect of mix variations on the behavior of rubber-asphalt mixture, it was first necessary to establish a list of variables to be considered. Each variable was selected based on discussions with Alaska DOT & PF 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 to 10 percent (normally obtained in the field) were selected for study. Rubber contents of 2 percent and

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

3 percent were also selected to determine their effects on optimum asphalt content, resilient modulus, and fatigue life. The existing rubber gradation employed isa mixture of 20 percent fine (- #40) and 80 percent coarse rubber (#40 x 1/4 in.). Increasing the amount of fine rubber to 40 percent and 100 percent 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-percent void content in the mix, the compaction temperature, as well as compaction effort (normally fifty blows), were lowered to 99°C (210°F) and ten blows, respectively. Two mix curing periods (zero and two hours) were also selected for study to determine whether increased curing or "reaction time" can impart any beneficial effects. Two aggregate gradations (gap and dense graded) were used to perform the tests. These are the aggregate gradations recommended by PlusRide Asphalt, Inc., gap-graded and the mid-band gradation (dense-graded), 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

Table 3.2. Aggregate Gradations Used and Corresponding Specification.

Sieve Size	Gap-Graded	All Seasons Specification (Plusride™ 12)	Alaska Type II Dense-Graded	Alaska Type II Specifications
3/4 inch	-	-	100	100
5/8 inch	100	100	-	-
3/8 inch	70	60-80	76	68-88
1/4 inch	37	30-42	-	-
No. 4	-	-	55	45-65
No. 10	26	19-32	36	30-50
No. 30	18	13-25	-	-
No. 40	-	-	22	12-78
No. 200	10	8-12	7	3-10

began 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 sieve #-100. The different sized fractions of the aggregates were stored in separate containers. Tables 3.2 and 3.3 include the gradations and properties of aggregate that 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 (54,55,56). 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

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

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 of 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 3.5. Chemical Analysis by Rostler Method.*

Composition	Percentages
Asphaltenes	14.8
Nitrogen Gases (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 = $\frac{N + A1}{A2 + P}$

in identifying embrittlement of asphalts in aging, as measured by the Pellet abrasion test and also shown to relate to field performance (56,57,58).

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 (56).

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 percent 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 Table 3.6.

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 is summarized in Table 3.7. The following sections describe the procedures and equipment used in performing each of these tests.

Table 3.6. Rubber Properties.*

a) GRADATION

Sieve Size	Coarse	Fine	80/20	60/40	0/100	PlusRide Asphalt, Inc. 80/20 Rubber (10) 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/ft3)	30
Mixture	
Carbon black (%)	30
Acetone (%)	15
Hydrocarbon (%)	45
Fiber (%)	10

*Rubber Data Source: Rubber Granulators, Everett, Washington (59).

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 @ +10°C, -6°C
	Dynamic Creep @ 25°C, 40°C
	Static Creep @ 25°C, 40°C

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

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 DOT & PF procedure T-17 (60). This method is the fifty-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 twelve 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 190°C (375°F) prior to mixing. Previously 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 three 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 for fully coating the aggregate with asphalt. The entire batch was placed in the preheated, greased mold and based with greased filter paper. The compaction was performed according to Alaska DOT & PF procedures. The mixture was spaded vigorously with a heated spatula. Each of the two faces was then compacted with a fifty-blow Marshall hammer assembly at 129°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 five hours). The specimens were removed from the mold with an extrusion jack. The equipment is shown in Figure 3.4.

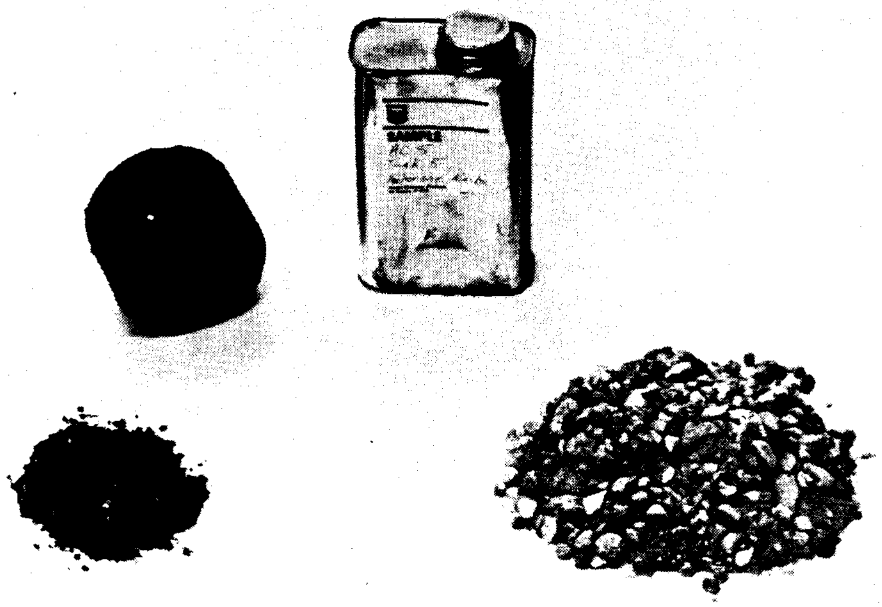


Figure 3.1. Material Components for Specimen Preparation.

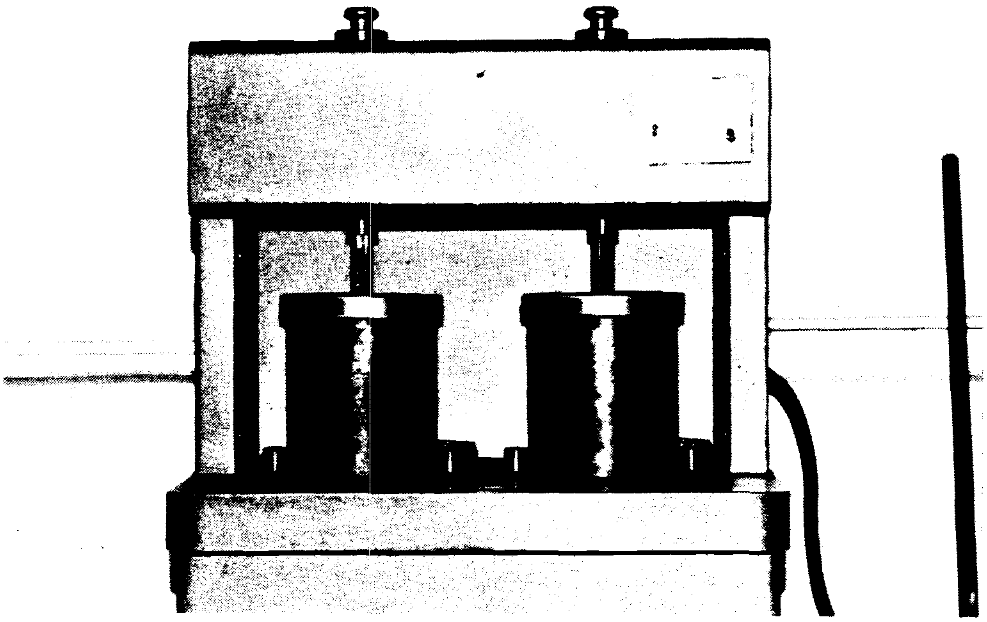


Figure 3.2. Cox Mixer.

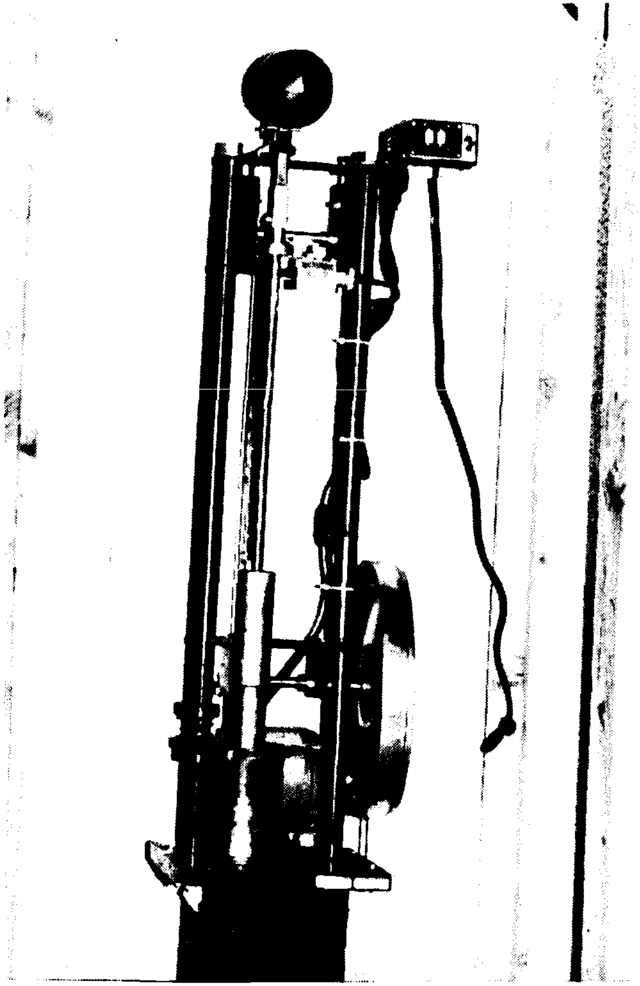


Figure 3.3. Marshall Assembly.

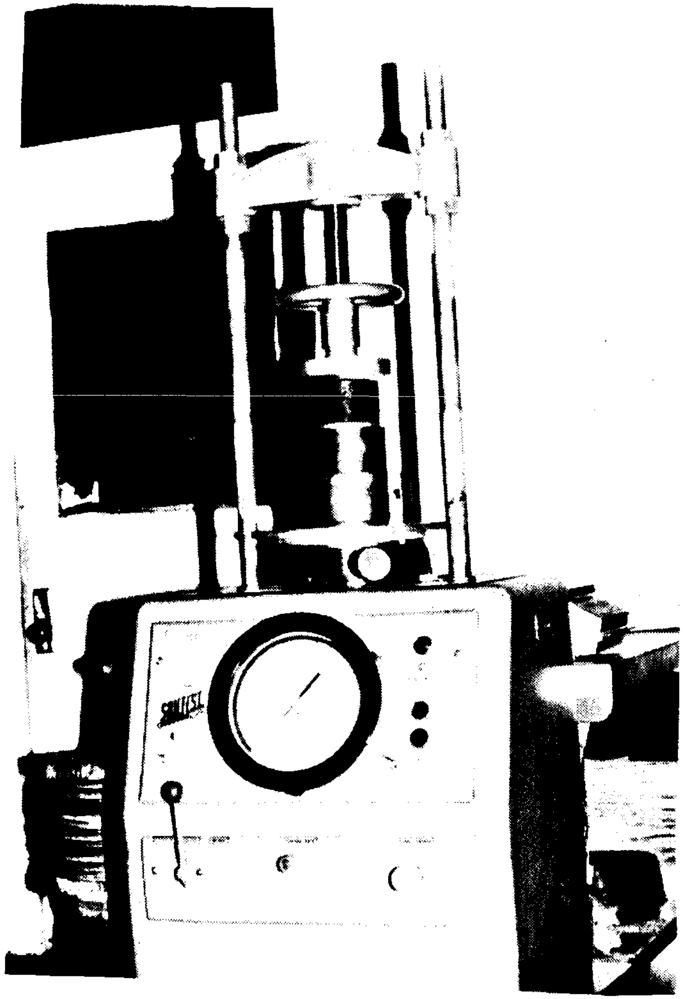


Figure 3.4. Sample Extrusion Assembly.

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, and 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:

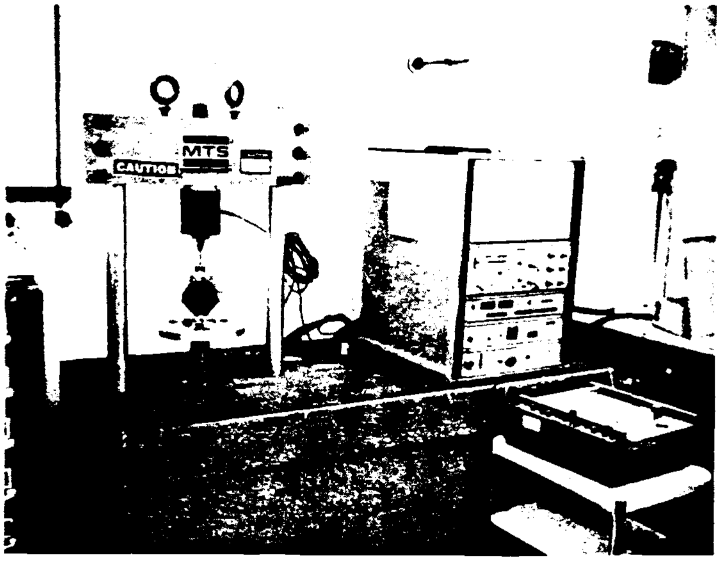
1. rubber content - 2 and 3 percent,
2. rubber gradation - coarse, medium, and fine, and
3. aggregate gradation - gap-graded and dense-graded.

The 2 percent void content was part of the criteria used 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.

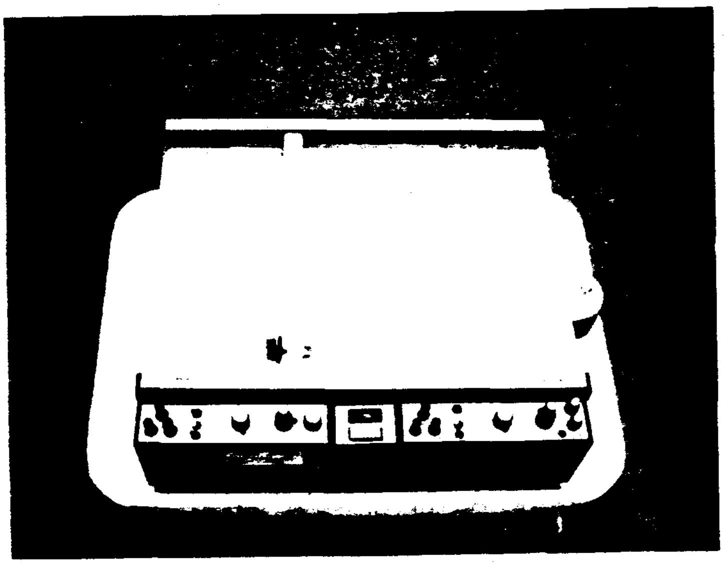
3.3.2 Mix Property Tests

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 sixty cycles 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 then determined that the temperature of the specimens had varied considerably.



a) MTS Loading System



b) X-Y Recorder

Figure 3.5. Stability and Flow Determination by MTS Machine

Table 3.8. 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 twelve hours,

3) Heat asphalt to 135°C (275°F),

4) Blend aggregate with rubber and cure for three minutes in 190°C (375°F oven,

5) Add proper amount of asphalt cement to the mixture of aggregate and rubber and mix for three minutes,

6) Grease the mold with vacuum silicone grease and place in 190°C (375°F) oven,

7) Place the mixture in the mold,

8) Compact at 129°C (265°F), apply fifty blows per side with Marshall hammer assembly,

9) Allow to air cool approximately five hours,

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.

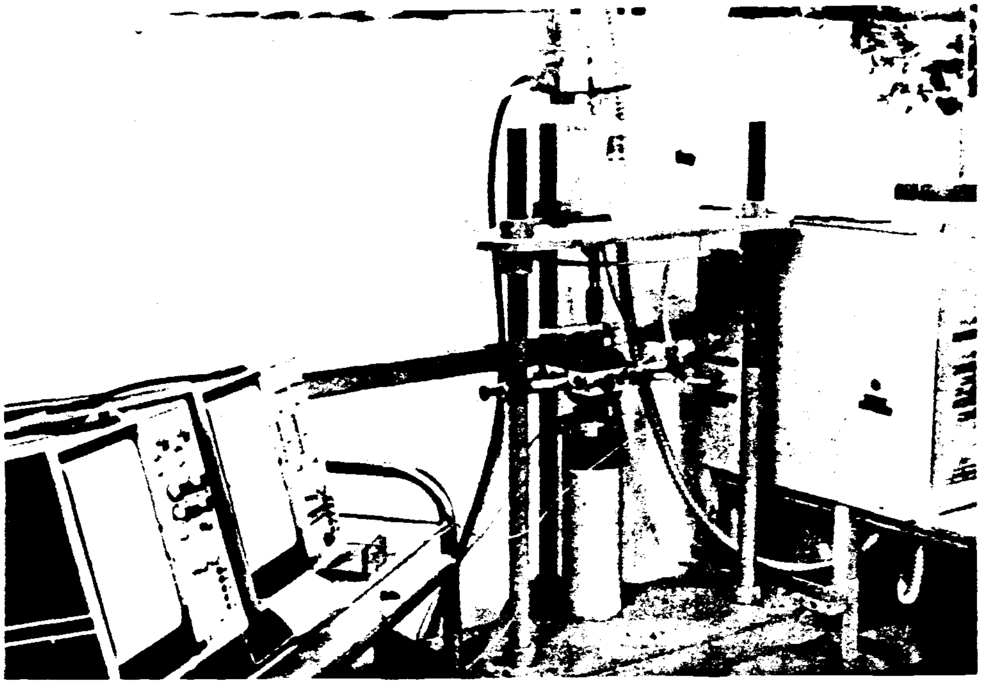


Figure 3.6. Resilient Modulus Setup.

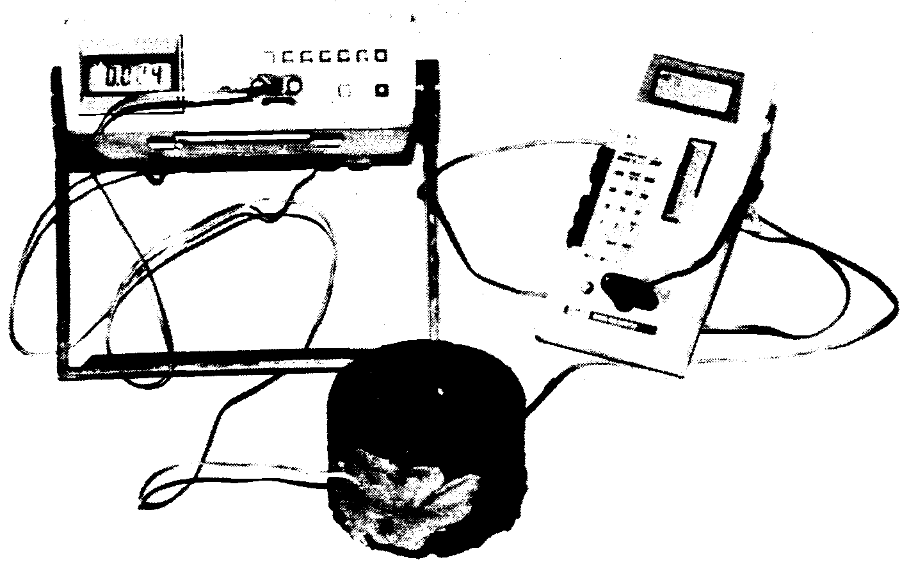


Figure 3.7. Temperature Control System.

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 among the three probes after about four 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 five 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

Table 3.9. 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.

resilient modulus of the samples. These tests are discussed in the following sections.

3.3.2.1 Fabrications of Samples for Modulus, Fatigue and Creep 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 twelve 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 at 375°F or 425°F for approximately three minutes.
4. The asphalt required was added to the mixture of aggregate and rubber and mixed for at least three 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 sili-

cone 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 two 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-percent void content in the samples, the compaction temperature and compaction effort was lowered to 210°F and ten 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 five-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 <u>Effect of Compaction Effort and Compaction Temperature</u>. 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 (thirty, ten, and five 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 <u>Resilient Modulus Test Method</u>. 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 thirty mph actual tire speed (61). The load is applied at a frequency of sixty cycles per minute. A seating load of about 10 percent 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 (61):

$$M_R = \frac{P(\quad + 0.2734)}{t \text{ X } H} \qquad (3.1)$$

where, M_R = resilient modulus (psi)

P = dynamic load (pounds)

= Poisson's ratio (is assumed equal to 0.40)

t = thickness of specimen (inches)

H = total elastic horizontal deformation (inches)

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					

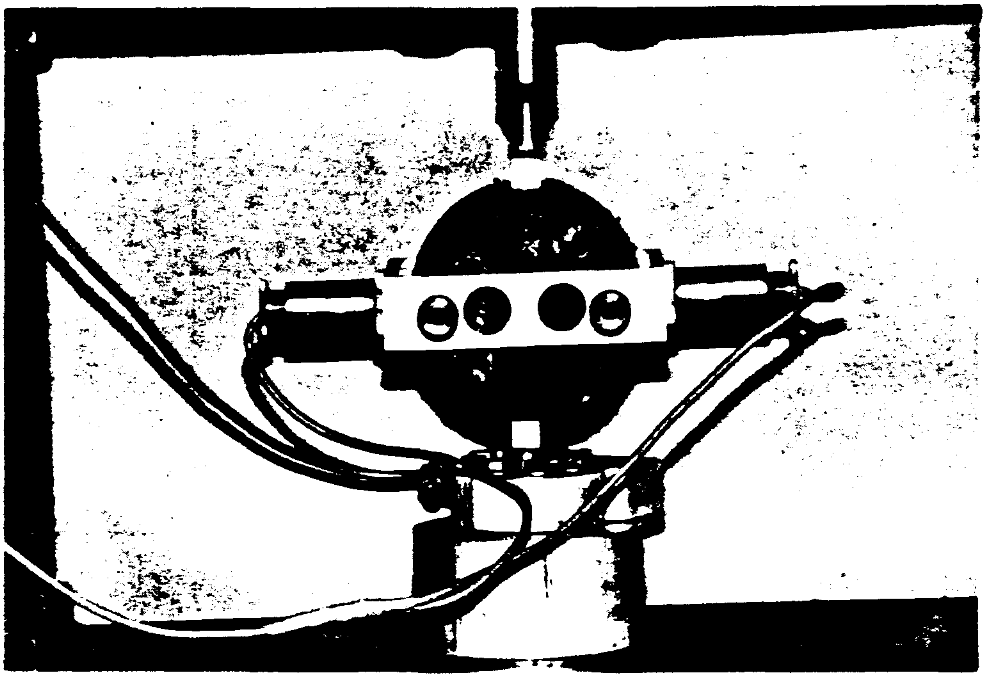
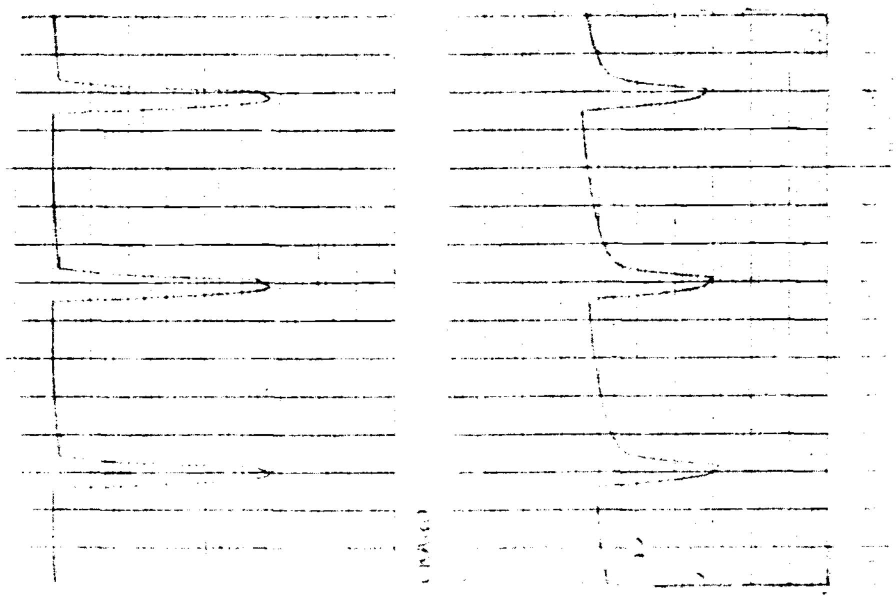


Figure 3.8. Resilient Modulus Setup.



a) Load b) Deformation

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

All tests were performed in a controlled temperature environment.

The test system shown in Figure 3.10 allows the operator to control both static and dynamic load magnitudes. Load duration and frequency can also be controlled. A Shel-Lab low-temperature incubator was also used to control testing temperature (Figure 3.11). In order to sense the temperature at the geometrical center of the specimen, three linear response thermistors were used (Figure 3.7).

Horizontal deformations were measured by a horizontal transducer attached to a yoke, which is attached to the specimens (Figure 3.12). A two-channel oscillographic recorder (Figure 3.13) was used to measure loads and deformations. Modulus was measured after approximately 150 load applications, the point at which resilient deformation starts to stabilize.

3.3.2.4 Fatigue Life Method and Procedure. The diametral test was also used to predict fatigue life for different material combinations. Tests were conducted for twenty different material combinations, at two different temperatures (+10°C and -6°C), with at least three different tensile strain levels. Between four and ten specimens were tested for each material combination at each temperature and strain level.

Once the resilient modulus was determined for each combination at the desired strain level (after 150 repetitions), the specimen was prepared for fatigue testing by attaching foil tape, which serves as the shut-off mechanism upon specimen failure (Figure 3.14). The specimen was placed between two 1/2-inch-wide loading strips (Figure 3.15). A seating load was applied (normally less than 10% of dynamic

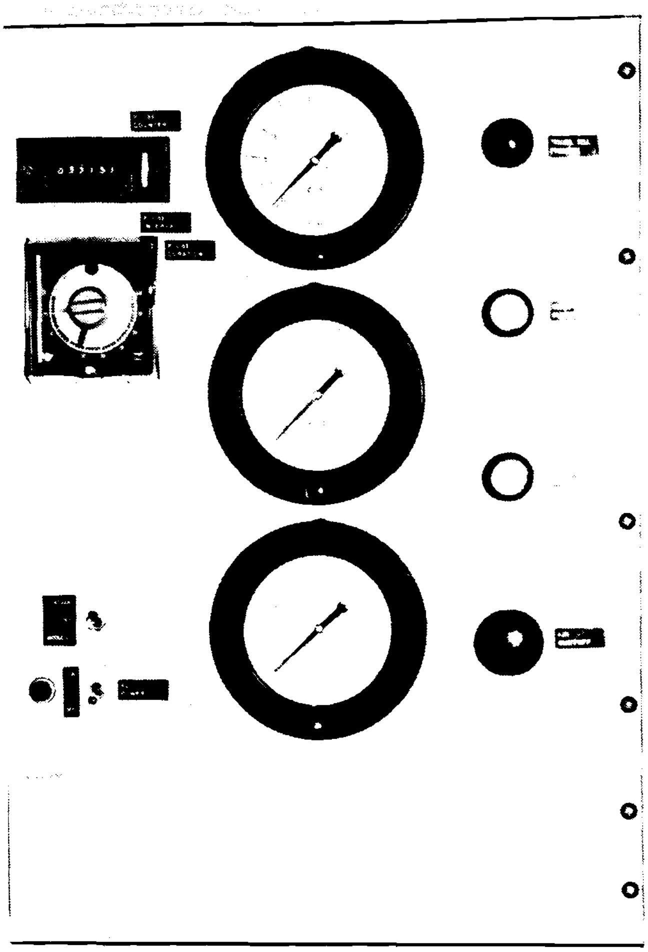


Figure 3.10. Control Panel.

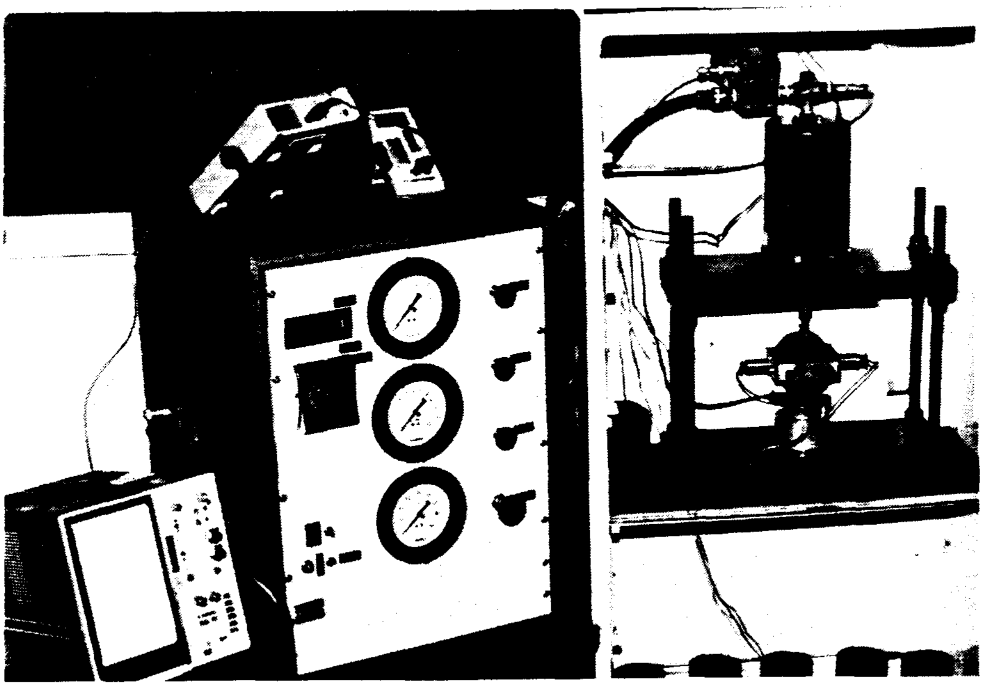


Figure 3.11. Testing Apparatus and Shel-Low Temperature Incubator.

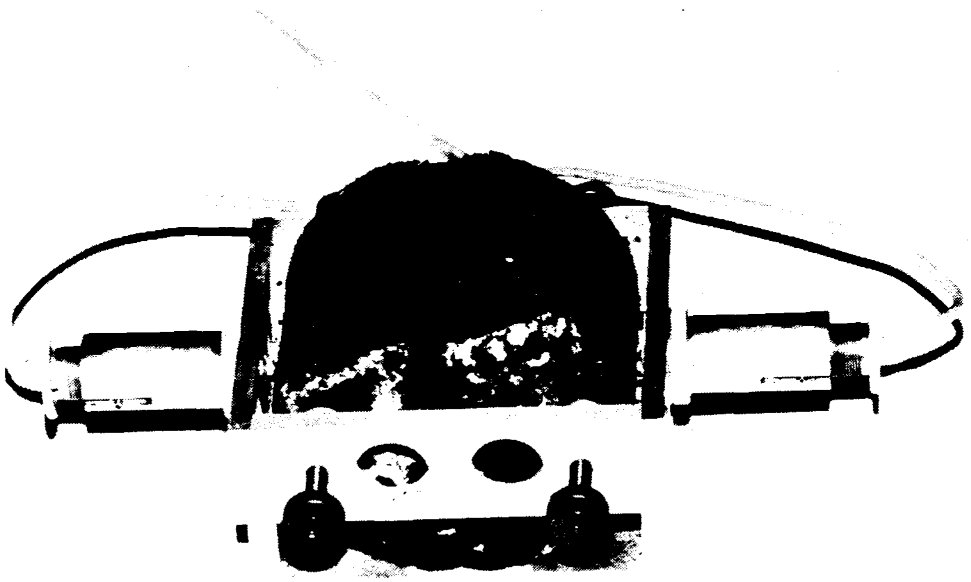


Figure 3.12. Sample with Diametral Yoke.

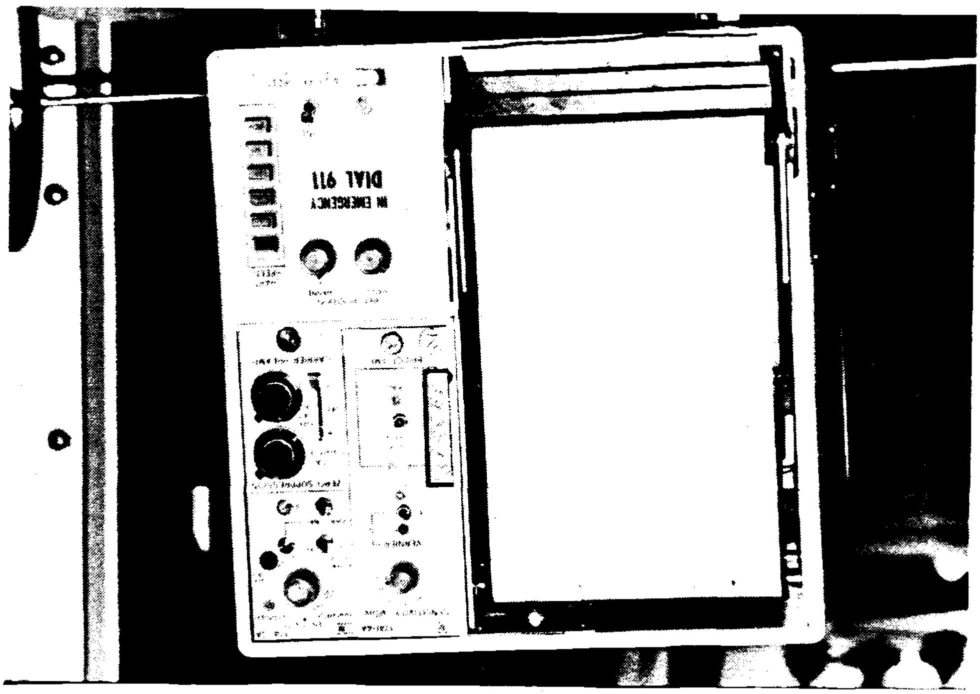


Figure 3.13. Two-Channel Oscillographic Recorder Hewlett-Packard Model 7402A).

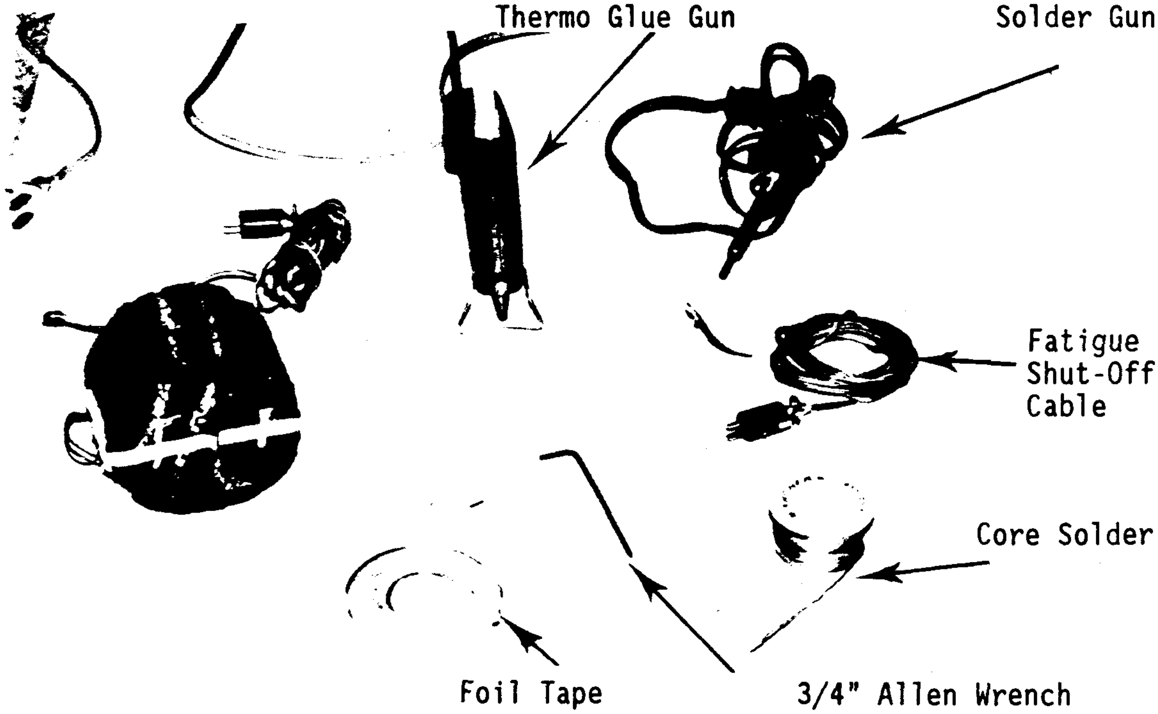


Figure 3.14. Specimen Setup for Fatigue Testing.

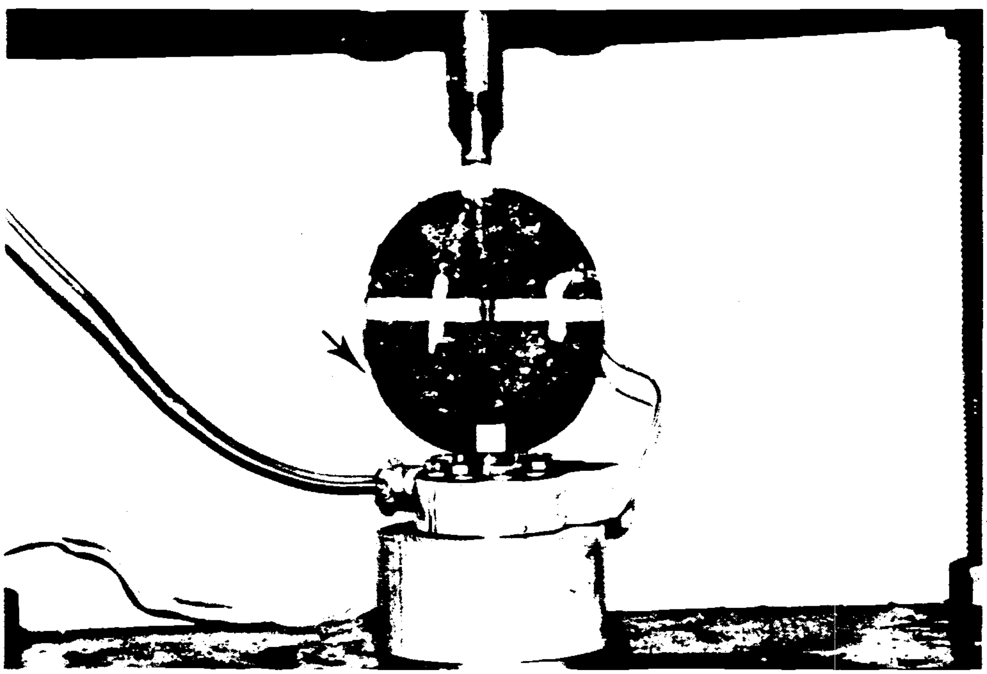


Figure 3.15. Specimen Orientation for Diametral Fatigue.

load) to hold the specimen in place, and fatigue testing was then started. When the specimen failed, the foil tape was broken, causing the machine to switch off (Figure 3.16) and the counter on the control panel to stop.

Fatigue test results are expressed in numbers of load repetitions to failure for initial tensile strain ε_T can be computed from the mix horizontal elastic deformation ΔH.

$$\varepsilon_T = \Delta H \left(\frac{.03896 + .1185}{.0673 + .2494}\right) \tag{3.2}$$

where:

ε_T = horizontal elastic tensile strain

ΔH = horizontal elastic tensile deformation, inches

3.3.2.5 Specimen Aging Method. Eighteen samples were prepared to evaluate the effect of aging on the modulus of rubberized asphalt mixtures. All samples were fabricated using the method described in the previous section. All samples were tested at +10°C and 100 microstrain immediately after fabrication (no aging). Then, the samples were placed in outdoor environment conditions (35°F at night and 55°F during daytime (Figure 3.17). Four resilient modulus readings were taken every month.

3.3.2.6 Creep Test. In a creep test cylindrical or primatical asphalt test specimens are compressed in the axial direction with a constant load and deformation per unit time in the loading direction is measured. This test can be used as a determination of the creep strain. The creep strain is the ratio of the total deformation ΔH to

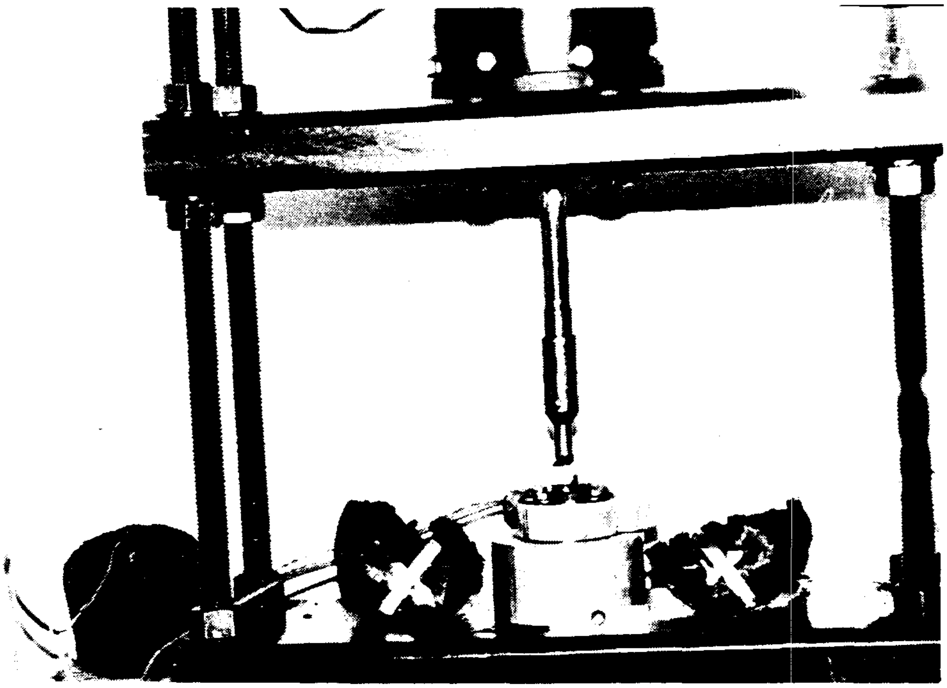


Figure 3.16. Failed Specimen with Broken Foil Tape that Stops the Test Machine.

Figure 3.17. Specimen Aging Method (Placed in Outdoor Environment).

the original height of the test specimen h, at any instant during the test (39).

The static creep test was also used to determine material characteristics for use with viscoelastic theory to predict rutting. Tests were conducted for five different material combinations, at two different temperatures, 40°C and 25°C (104°F and 77°F). At least three specimens were tested for each material combination at each temperature.

For the creep test, a loading device for soil consolidation and data acquisition/control unit with a personal computer were used. The creep test was run for three hours at 40°C, and a compression stress of 0.1 MPa (14.5 Psi) was applied. The creep test procedures are as follows (42):

1. Put a loading device for the solid consolidation in an environmental cabinet and connect to the repeated load test control cabinet. Put the specimens and a dummy specimen with a thermistor into the environmental cabinet. Set the regulator at 0.1 MPa and control the air pressure by the repeated load test control cabinet (Figure 3.18).
2. Warm the inside of the environmental cabinet to 40°C or 25°C and check the temperature of the dummy specimen using the data acquisition system and thermistor.
3. After the temperature of the dummy specimen core reaches 40°C or 25°C, put a specimen on a load plate, put an LVDT on the bottom plate, and attach a thermistor to the specimen. Check the level of the bottom plate before running the test.

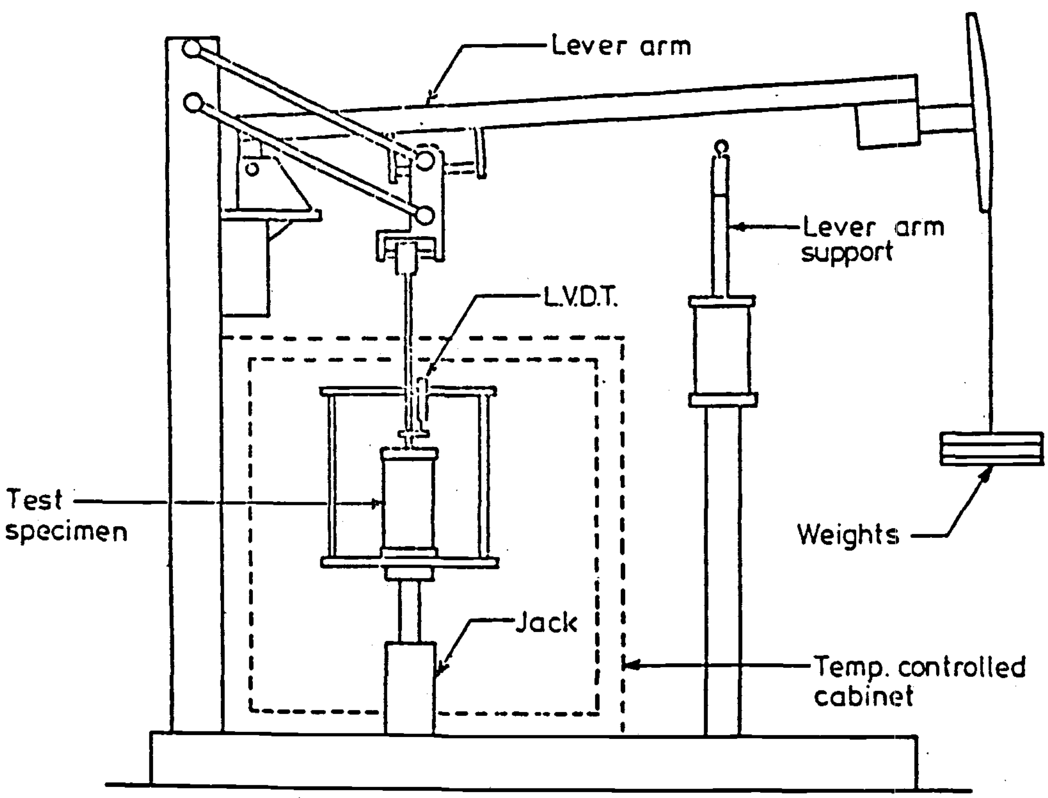


Figure 3.18. Static Creep Setup.

4. Wait for five to ten minutes after closing the environmental cabinet door to keep the temperature at 40°C or 25°C.
5. Apply a pressure of 10 kPa as a preload for two minutes.
6. Apply a pressure of 0.1 MPa and run the computer program.

Appendix F describes the apparatus and the procedure for sample preparation in detail. Also in Appendix F are the computer programs to monitor the temperature and measure the deformation of a specimen.

3.3.2.7. Permanent Deformation Test Method. The diametral test was also used to estimate the permanent deformation characteristics of different material combinations. Tests were conducted for five different material combinations, at 15°C (59°F). At least three specimens were tested for each material combination at 100 micro-strain.

Once the resilient modulus was determined for each combination at the 100 micro-strain, the specimen was prepared for fatigue testing by attaching foil tape, which serves as the shut-off mechanism upon specimen failure. The specimen was placed between two 1/2-inch wide loading strips. The total vertical deformation was measured using a dial guage accurate to 10^{-3} inch as shown in Figure 3.19.

3.4 Summary

To evaluate the effect of mix variations on the behavior of rubber-modified asphalt, twenty different mix combinations were considered. These variables included two mix voids, two rubber contents, three rubber gradations, two mixing temperatures, cure time, and use of surcharge.

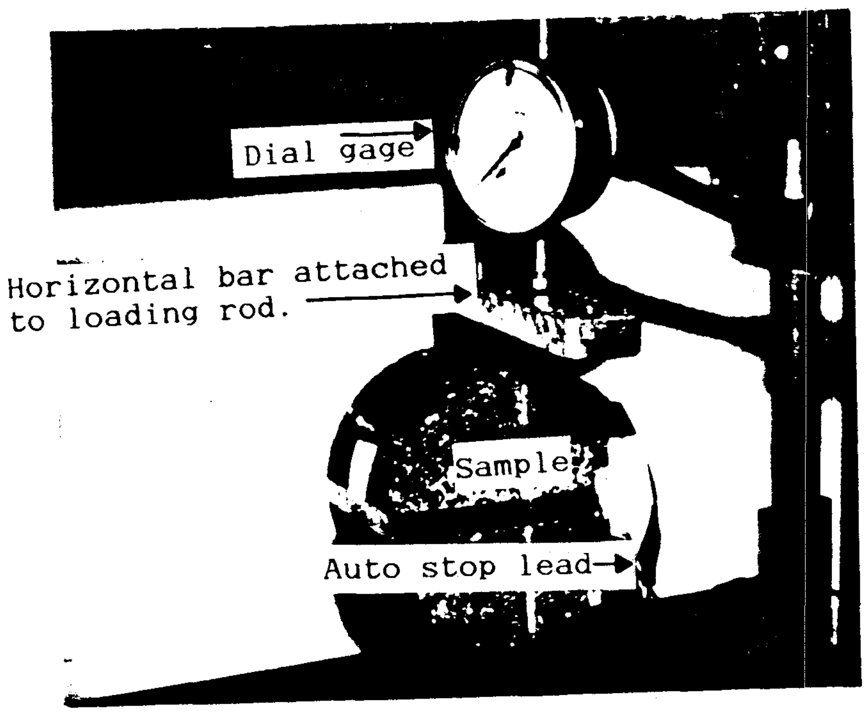


Figure 3.19. Permanent Deformation Test Setup.

The aggregates were obtained from the actual source used for the Lemon Road Project in Juneau, Alaska. The asphalt (AC-5) was supplied by Chevron USA. The recycled rubber was obtained from Rubber Granulators in Everett, Washington.

The two general types of tests used in this study were mix design tests and mix properties tests. The Marshall mix design procedure was used in this study and mix design samples prepared using the standard Alaska DOT & PF procedure (T-17). To evaluate mix properties, the diametral modulus and fatigue tests were performed on all 20 different combinations at two different temperatures.

To evaluate the effect of compaction effort and compaction temperature, 20 samples with three different mix formulas were prepared. Also, to study the effect of aging on the resilient modulus, two different mix combinations were tested at 100 microstrain in a +10°C environmental chamber. Finally, to determine material characteristics for use with viscoelastic theory to predict rutting, five different mix combinations were tested for static creep and permanent deformation.

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, and creep behavior of rubber-modified mixes 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 two inches per minute. The tests for diametral modulus were conducted using a load duration of 0.1 s, a frequency of 1 Hz, and a temperature of 22° ± 2°C.

Tables 4.1 to 4.8 summarize the results of tests for percentage 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 criteria for mix design. Air voids (2%) were used as the sole criterion for mix design. Recommended asphalt contents for each mix design combination are given in Table 4.9.

Tables 4.10 to 4.13 summarize the results of tests for modulus on each rubber gradation and rubber content. As indicated by the data in Tables 4.10 to 4.13, the conventional asphalt (no rubber) showed the highest resilient modulus with lowest design asphalt content, and

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

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

Table 4.2. Results of Mix Design (Gap-Graded Aggregate 0/100 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 (Gap-Graded Aggregate 60/40 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

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

Table 4.4. Results of Mix Design (Gap-Graded Aggregate 60/40 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 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

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

Table 4.6. Results of Mix Design (Gap-Graded Aggregate 80/20 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 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

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

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

**Asphalt Content is % by weight of aggregate.

Table 4.9. Recommended Asphalt Contents at 2% Air Void.

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

Table 4.10. 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 4.11 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 4.12. 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 4.13. Summary of Modulus Data for Dense-Graded Mixes - Coarse Rubber (Strain Level 100 Microstrain).

Asphalt Contents %, AC-5	Temperature (°C)	Modulus (ksi)
	a) 2% Rubber (80/20)	
6	20.0	55
7	19.0	51
8	20.0	45
	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.

the rubber asphalt with 3-percent rubber 80/20 blend showed 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 4.1. 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 4.2 shows the rubber-modified mix requires approximately 2 percent more asphalt cement than a conventional mix.

The effect of rubber content on resilient modulus is shown in Figures 4.3 and 4.4. The highest asphalt content, and lowest resilient modulus, was achieved at 3-percent coarse rubber with gap-graded aggregate. Figure 4.4 shows that the control mix had 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 was noticeable. For example, the design asphalt content at 2-percent voids for dense-graded aggregate

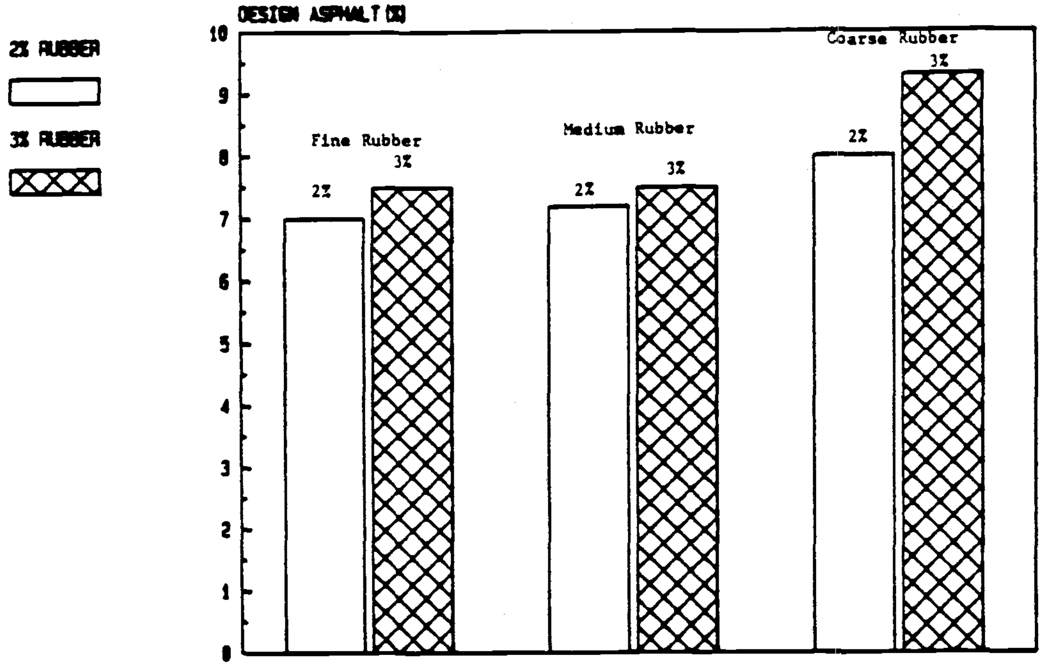


Figure 4.1. Effect of Rubber Gradations and Content on Design Asphalt Content

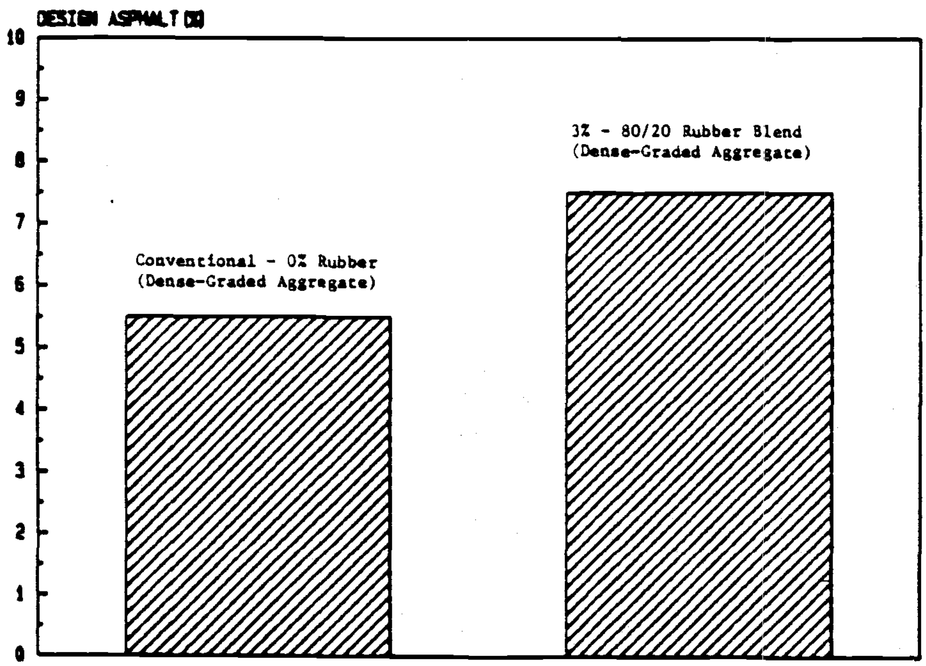


Figure 4.2. Comparison of Design Asphalt Content Conventional vs. 3% Rubber

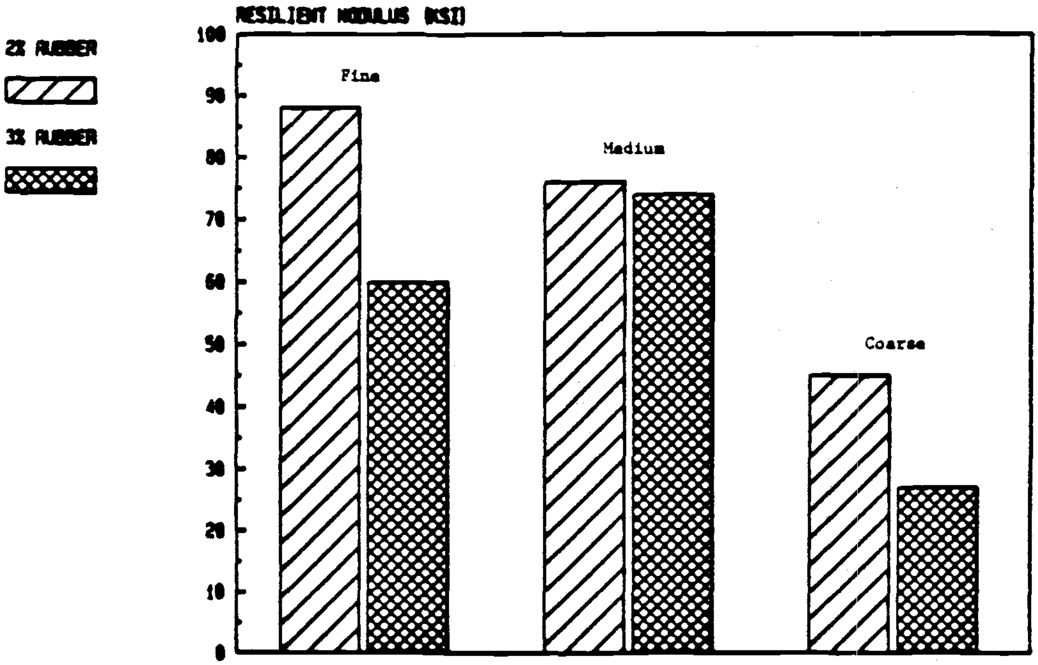


Figure 4.3. Effect of Rubber Content on Resilient Modulus at 22 ± 2°C.

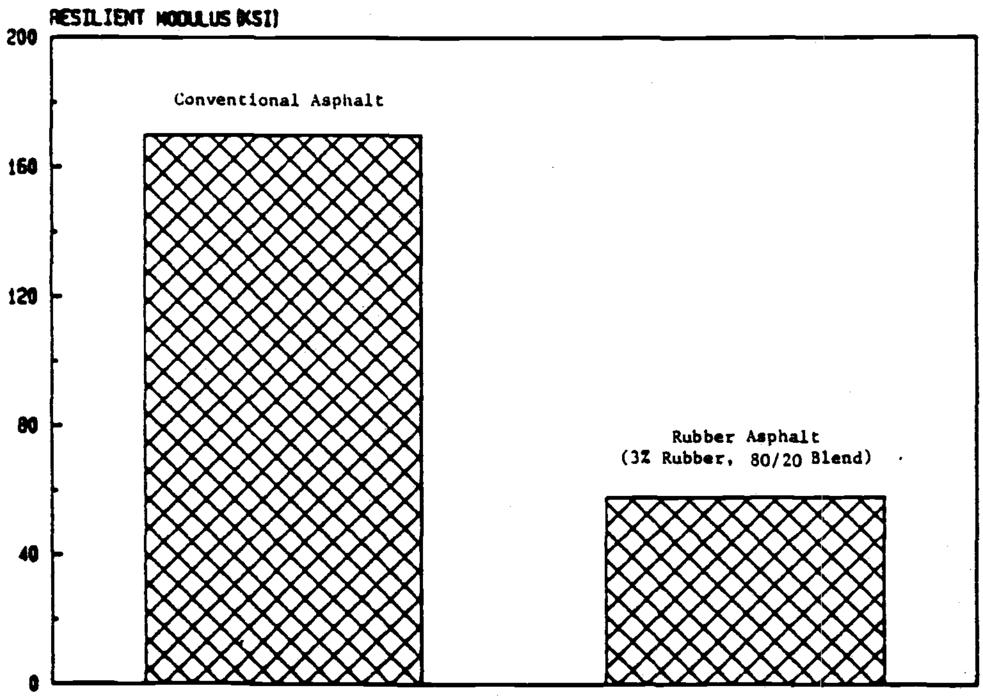


Figure 4.4. Comparison of Resilient Modulus Conventional vs. Rubber Asphalt at 22 ± 2°C.

was 1.8 percent less than the gap-graded aggregate. Figure 4.5 shows this relationship.

The effect of aggregate gradation on resilient modulus is shown in Figure 4.10. The dense-graded aggregate had 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 4.14). 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 are presented in Appendix F. The results of resilient modulus and fatigue for 20 different mixes are summarized in Table 4.15.

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 4.7 and 4.8. These figures show that the mixtures with gap-graded aggregate in all three mixing conditions had lower resilient modulus and higher fatigue life than the mixtures with dense-graded aggregate.

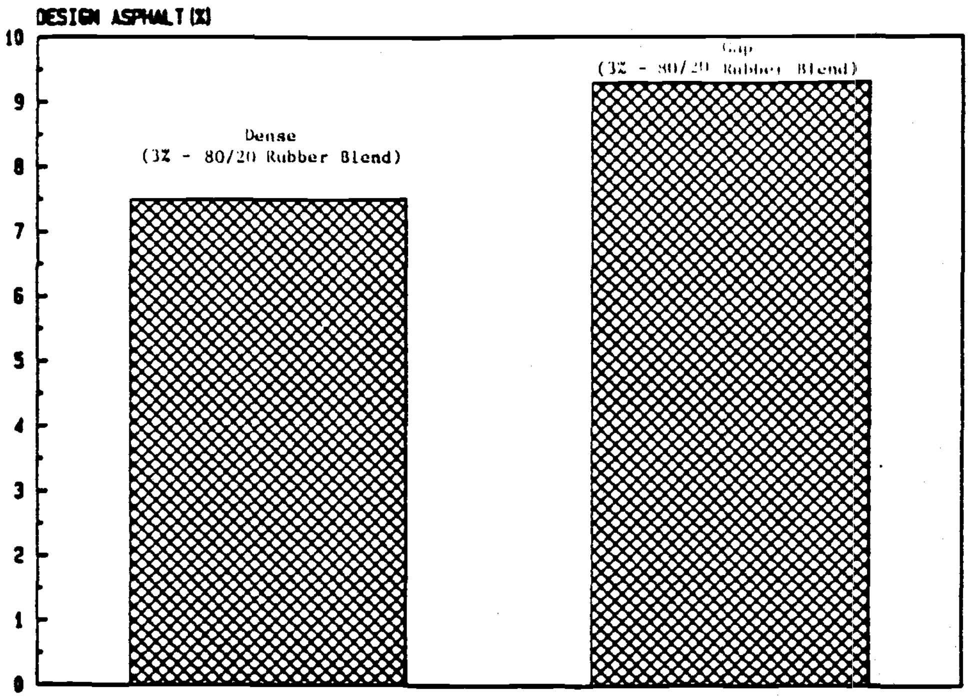


Figure 4.5. Effect of Aggregate Gradation on Design Asphalt Content.

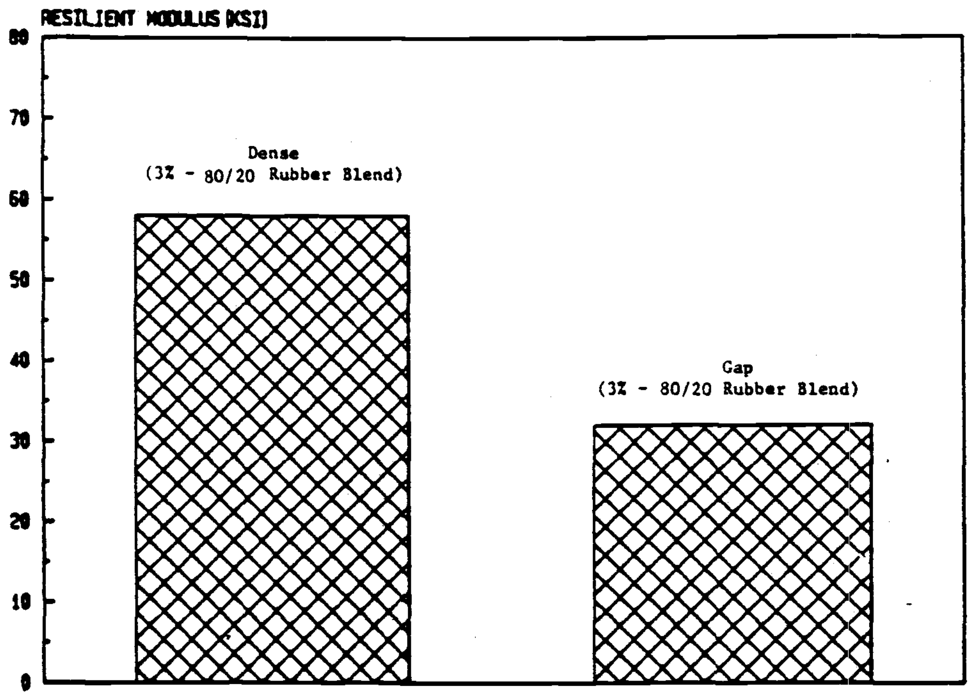


Figure 4.6. Effect of Aggregate Gradation on Resilient Modulus at 20 ± 2°C.

Table 4.14. 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.

Table 4.15. 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	4.14	0.38	298	17	13,445	3,520
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	4.07	0.23	204	14	8,139	2,120
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	3.87	0.34	324	71	5,354	1,530
T	5	2.13	0.25	1,105	67	9,323	2,758

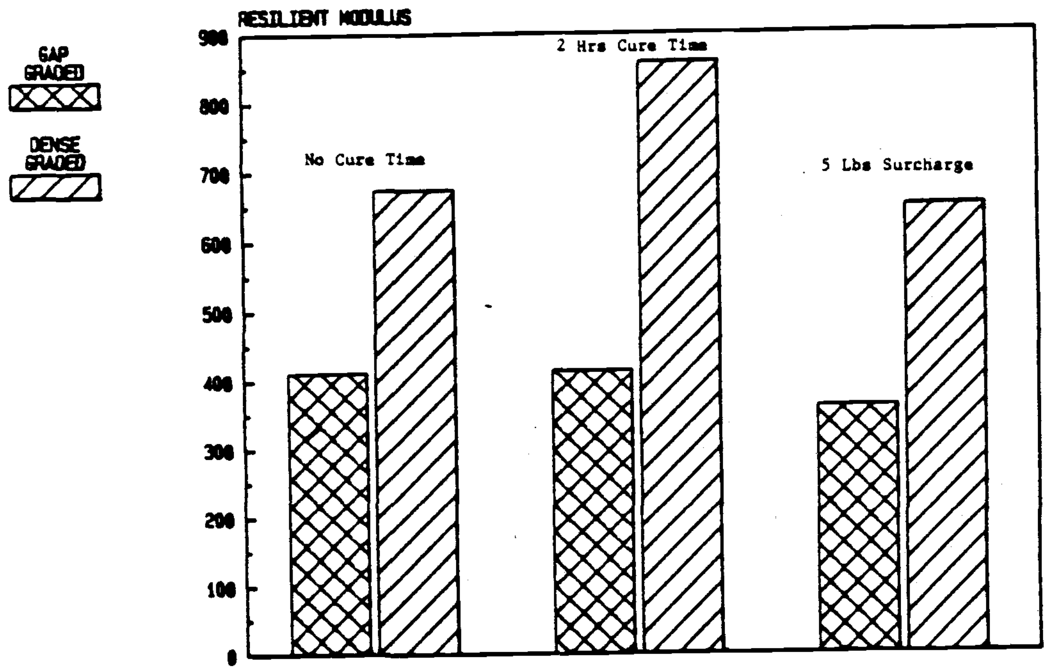


Figure 4.7. Effect of Aggregate Gradation, Cure Time, and Surcharge on Resilient Modulus at +10°C (3% Rubber 80/20 Blend).

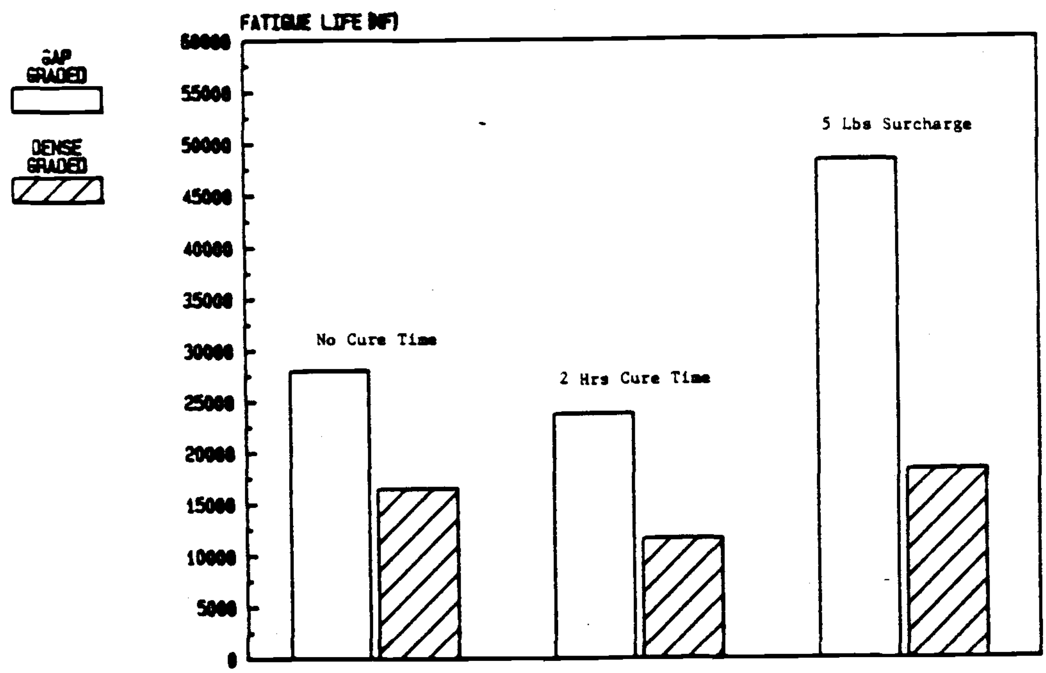


Figure 4.8. Effect of Aggregate Gradation, Cure Time, and Surcharge on Fatigue Life at +10°C (3% Rubber 80/20 Blend).

4.2.1.2 Effect of Rubber Gradation (Fine, Medium, and Coarse). The resilient modulus and fatigue life for three different rubber gradations (fine, medium, and coarse) are compared in Figures 4.9 and 4.10. The mixture with fine rubber had the highest modulus and lowest fatigue, and the mixture with coarse rubber had the lowest modulus and highest fatigue life. These results contradict those obtained by Alaska DOT & PF on Peger Road where 2 percent additional fine rubber extended the fatigue life in all cases, as well as increasing the modulus (Figures 2.13 and 2.14).

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 4.11 and 4.12. The samples with 3-percent rubber content generally had lower resilient modulus than the samples with 2-percent rubber content (Figure 4.11). The rubber content variations did not show any significant impact on fatigue life (Figure 4.12), with the exception of the fine rubber (0/100) samples. These fine rubber results agree with the Alaska DOT & PF observations that a high content of fine rubber may greatly increase fatigue life.

4.2.1.4 Effects of Mixing Temperature (375°F vs. 425°F). The effects of mixing temperature on resilient modulus and fatigue life are shown in Figures 4.13 and 4.14. 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 for the samples with 375°F mixing temperature. This may be due to the type of fatigue failure. The gap-graded and

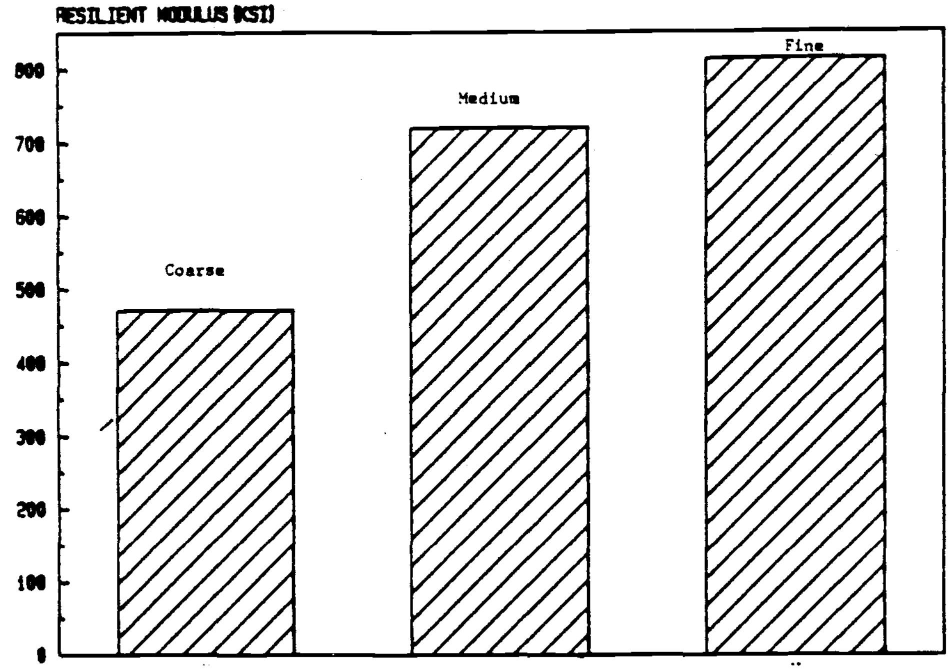


Figure 4.9. Effect of Rubber Gradations on Resilient Modulus at +10°C (Gap-Graded Aggregate).

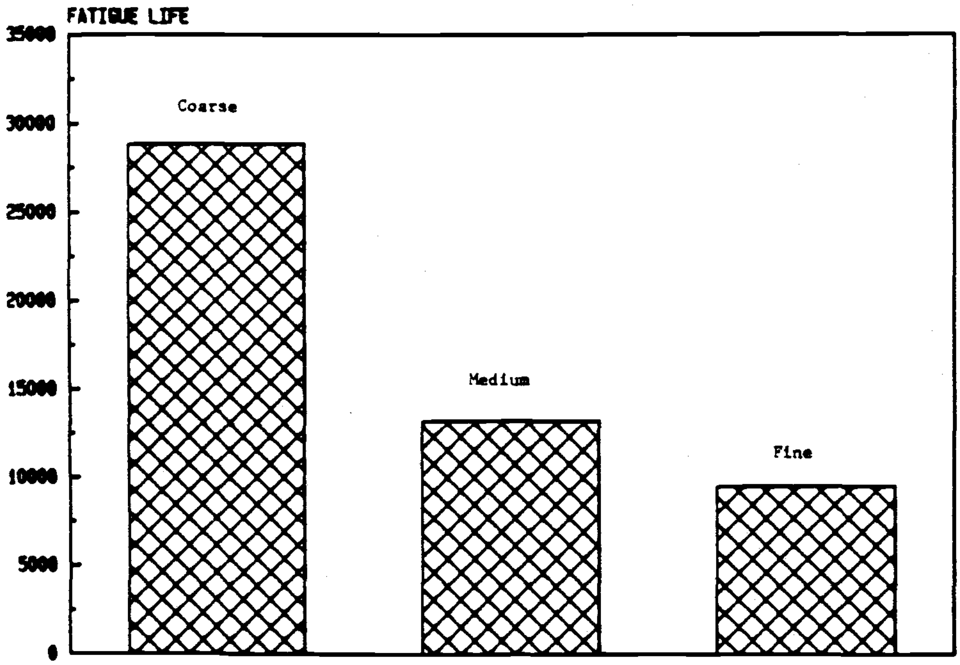


Figure 4.10. Effect of Rubber Gradation on Fatigue Life at +10°C (Gap-Graded Aggregate).

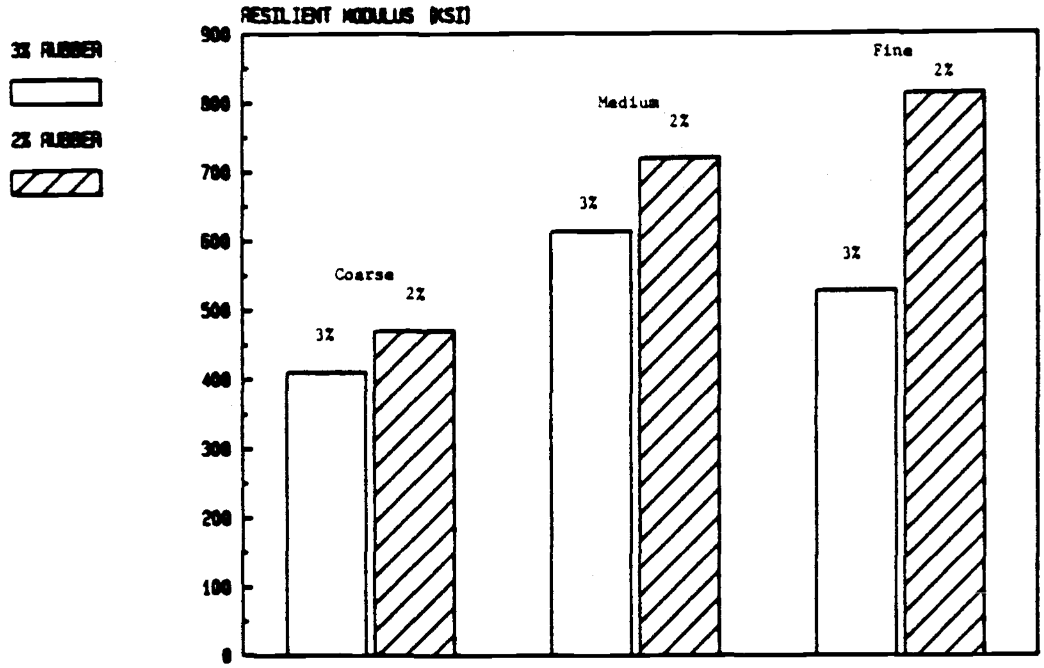


Figure 4.11. Effect of Rubber Content on Resilient Modulus at +10°C (Gap-Graded Aggregate).

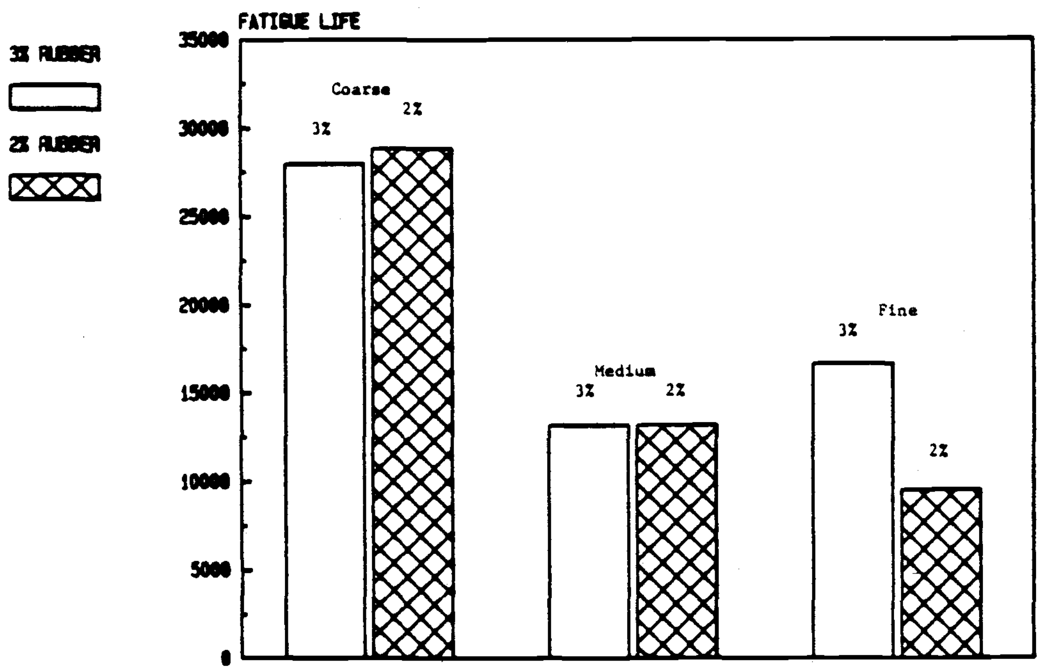


Figure 4.12. Effect of Rubber Content on Fatigue Life at +10°C (Gap-Graded Aggregate).

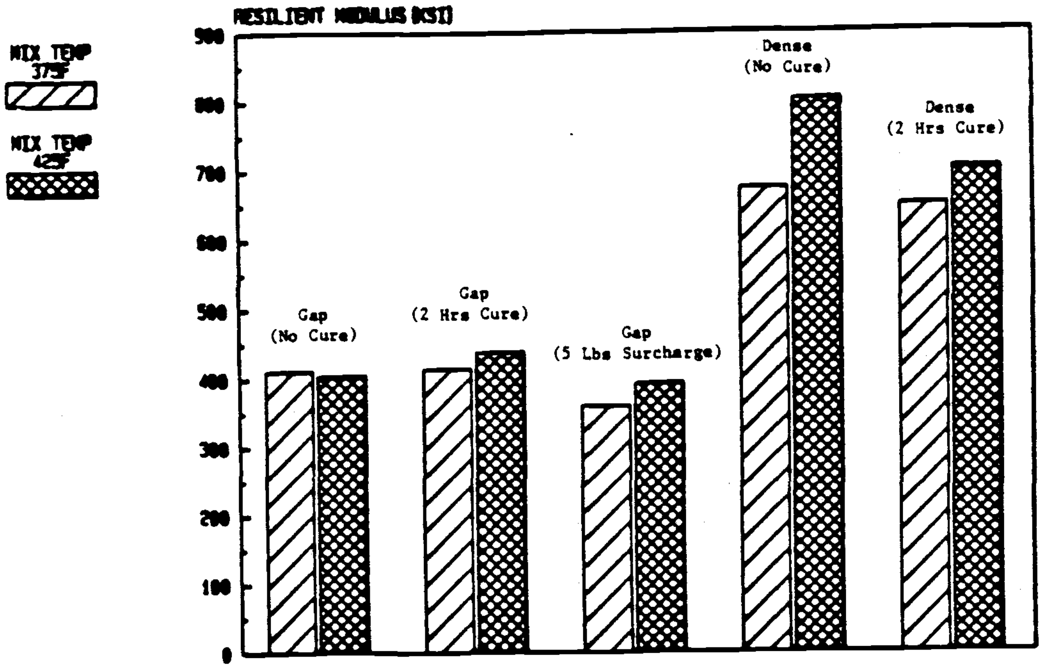


Figure 4.13. Effect of Mixing Temperature on Resilient Modulus at +10°C (3% Rubber 80/20 Blend)

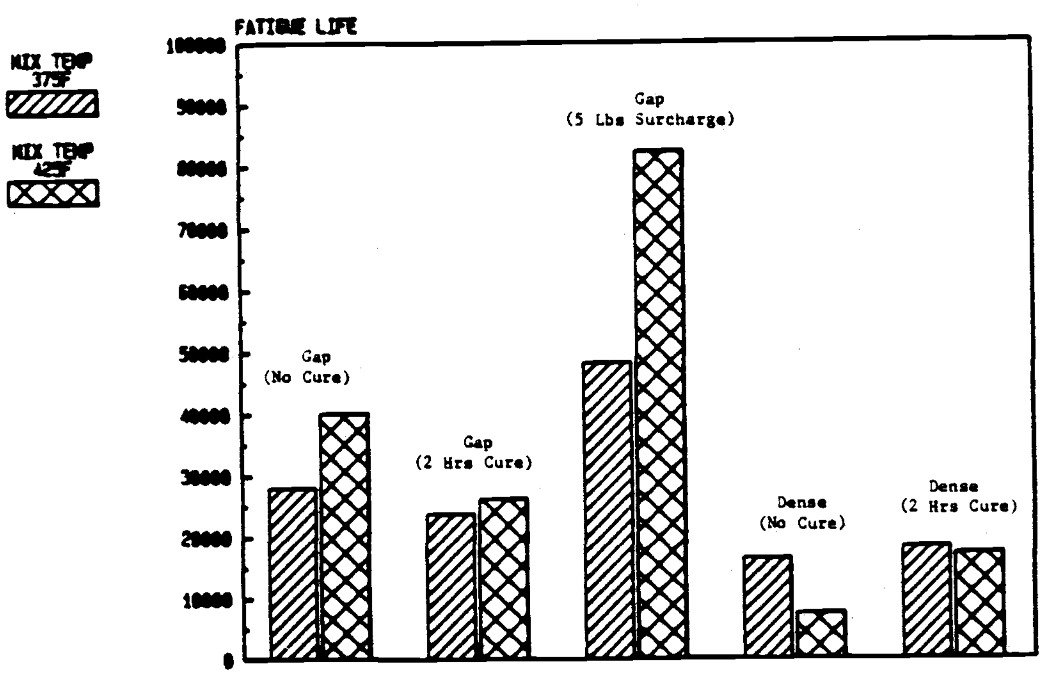


Figure 4.14. Effect of Mixing Temperature on Fatigue Life at +10°C (3% Rubber 80/20 Blend).

dense-graded 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 Effect of Cure Time (0 vs. 2 hr). To evaluate the effect of cure time, samples were cured in the mold open to air at 375°F and 425°F for two hours prior to compaction. The cure time did not have an effect on the modulus (Figure 4.15), but had an effect on fatigue life (Figure 4.16). For example, the fatigue life for samples cured at 425°F decreased by 35 percent, while the fatigue life for samples cured at 375°F mixing temperature decreased by 15 percent. These are shown in Figures 4.15 and 4.16. The results do not compare with those of Alaska DOT & PF on cores with additional 2 percent 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 Effects of Surcharge (0 vs. 5 lb). The effect of surcharge on resilient modulus and fatigue life is shown in Figures 4.17 and 4.18. The five-pound surcharge had little effect on modulus, but had 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 Effect of Air Voids (2% vs. 4%). The resilient modulus of the gap-graded mix was reduced by 27 percent when the air void content increased from 2 percent to 4 percent (Figure 4.19). Also, the modulus of the dense-graded mix was reduced by 50 percent when the air void content was increased. The difference in sensitivity to air

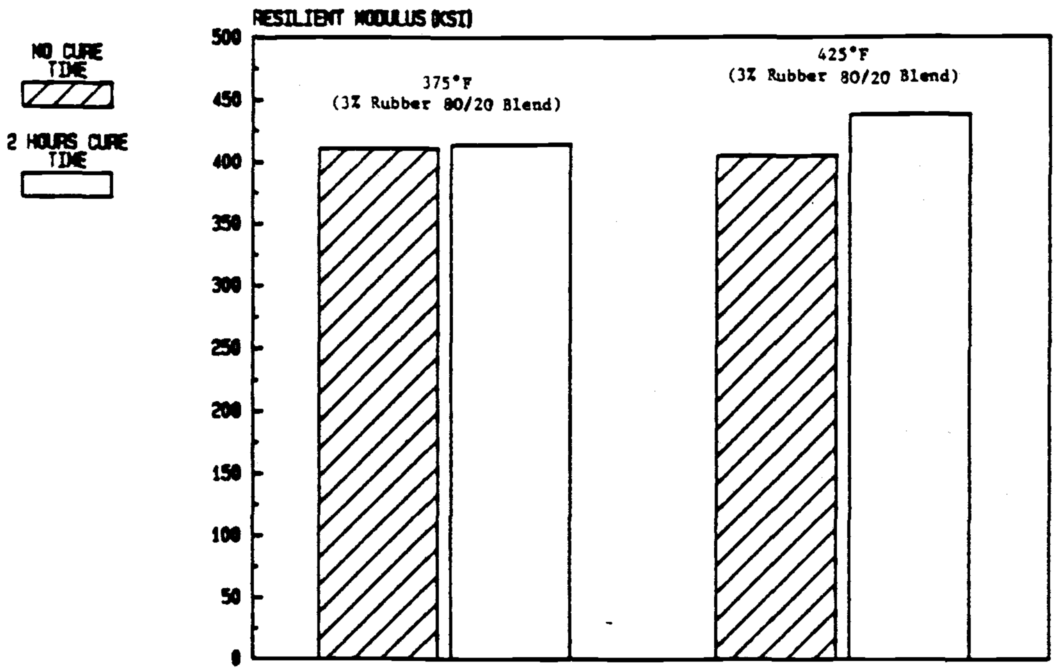


Figure 4.15. Effect of Cure Time at 375°F and 425°F with Gap-Graded Aggregate at +10°C.

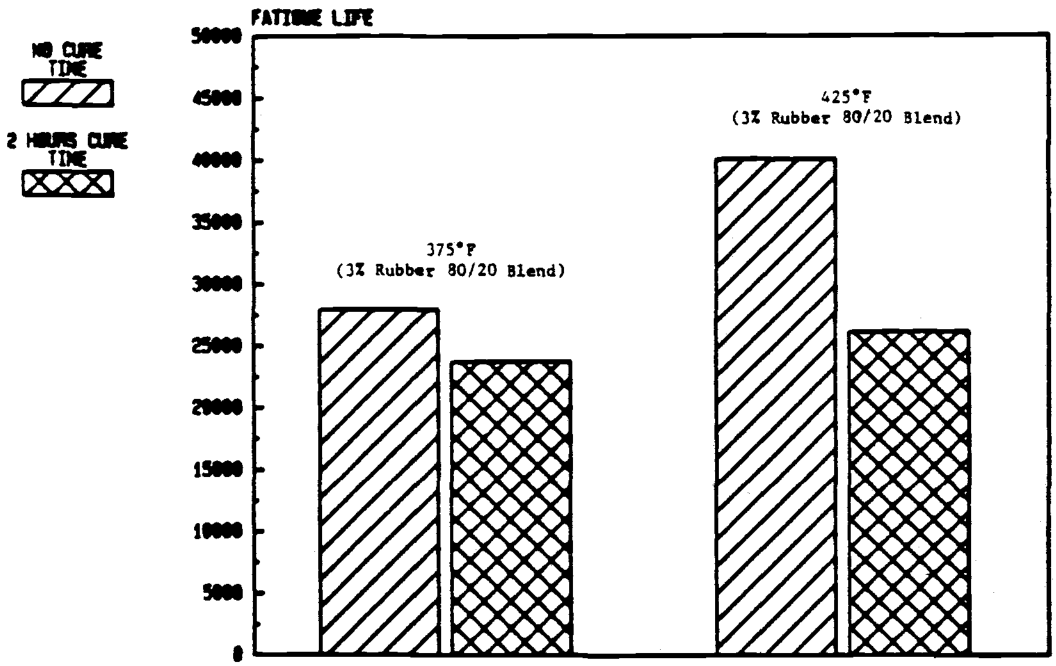


Figure 4.16. Effect of Cure Time at 375°F and 425°F with Gap-Graded Aggregate at +10°C.

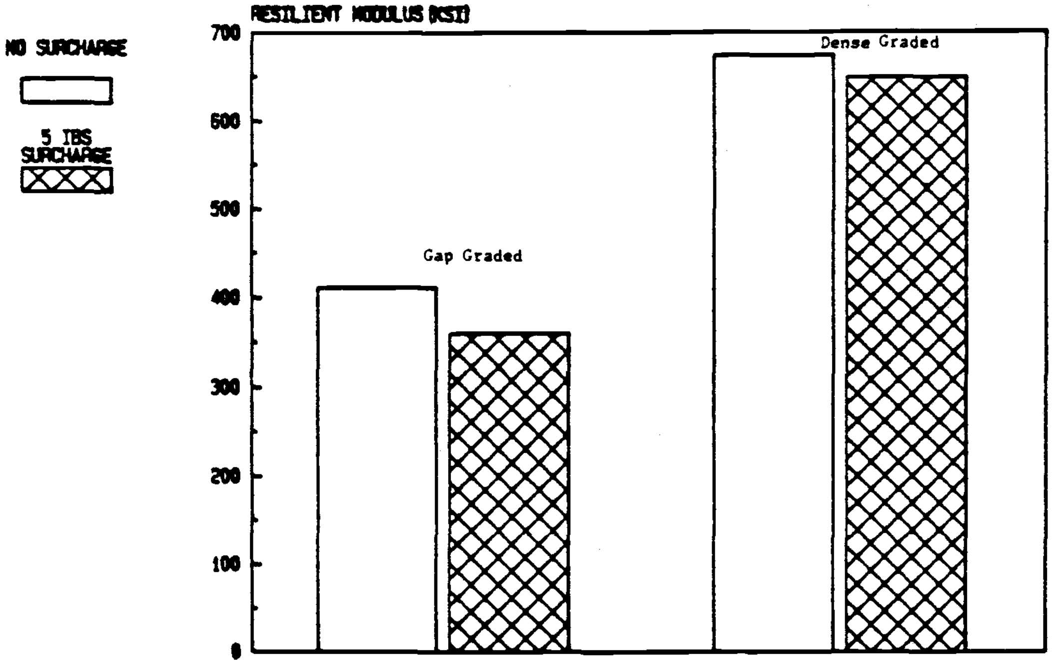


Figure 4.17. Effect of Surcharge on Resilient Modulus +10°C (3% Rubber 80/20 Blend).

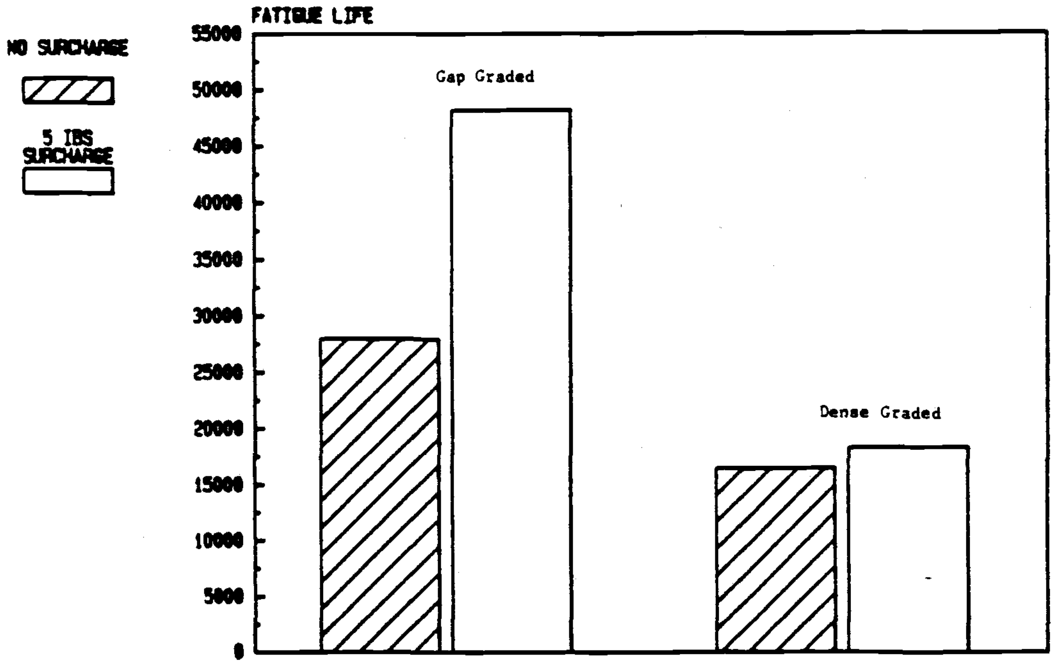


Figure 4.18. Effect of Surcharge on Fatigue Life at +10°C (3% Rubber 80/20 Blend).

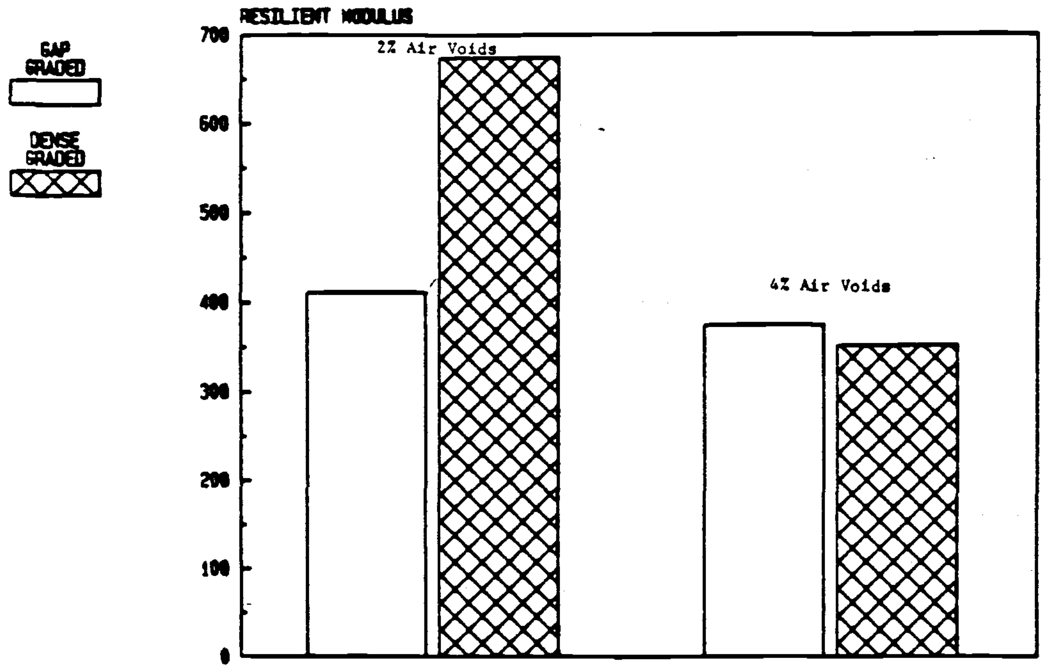


Figure 4.19. Effect of Air Voids on Resilient Modulus at +10°C (3% Rubber 80/20 Blend).

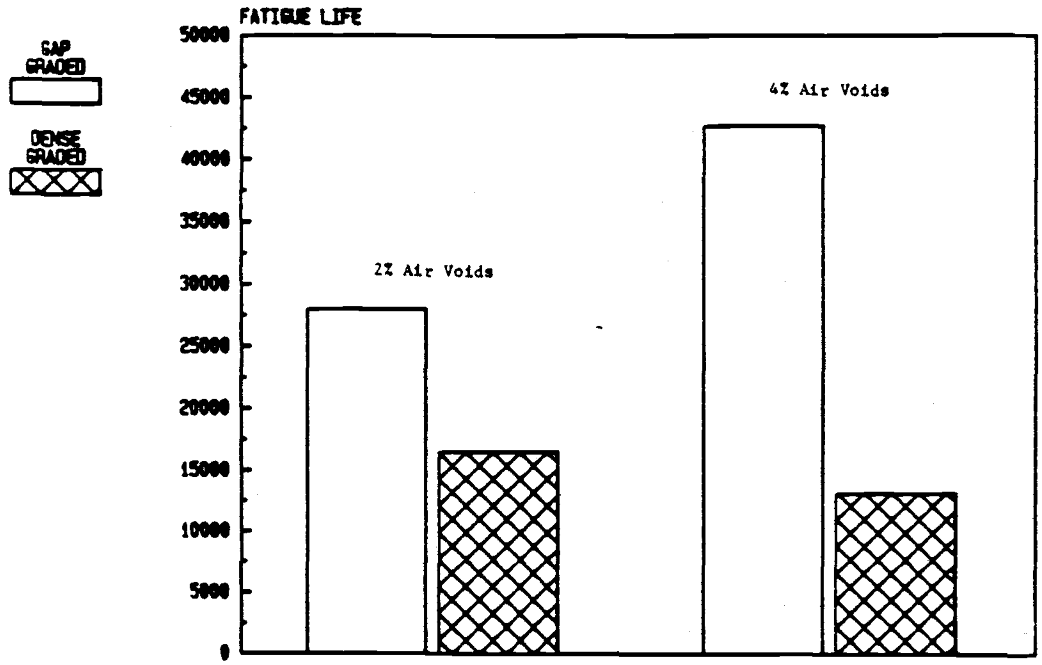


Figure 4.20. Effect of Air Voids on Fatigue Life at +10°C (3% Rubber 80/20 Blend).

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.

The fatigue life of both the dense-graded and gap-graded mix were reduced with an increase in air voids (Figure 4.20). This behavior is similar to that of conventional dense-graded mixes. The fatigue life for the gap-graded rubber mix was reduced by 50 percent with an increase in air voids. Also, the fatigue life of dense-graded rubber mix was reduced by 67 percent when air void content increased from 2 to 4 percent. These results show the dense-graded rubber mix is a very sensitive mix.

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 4.21). This relates directly to the 9.3-percent asphalt used in gap-graded rubber mix versus 7.5 percent in dense-graded rubber and 5.5 percent in conventional mix.

The fatigue life for each mix type corresponds to the modulus values (Figure 4.22): the higher the modulus, the lower the fatigue life.

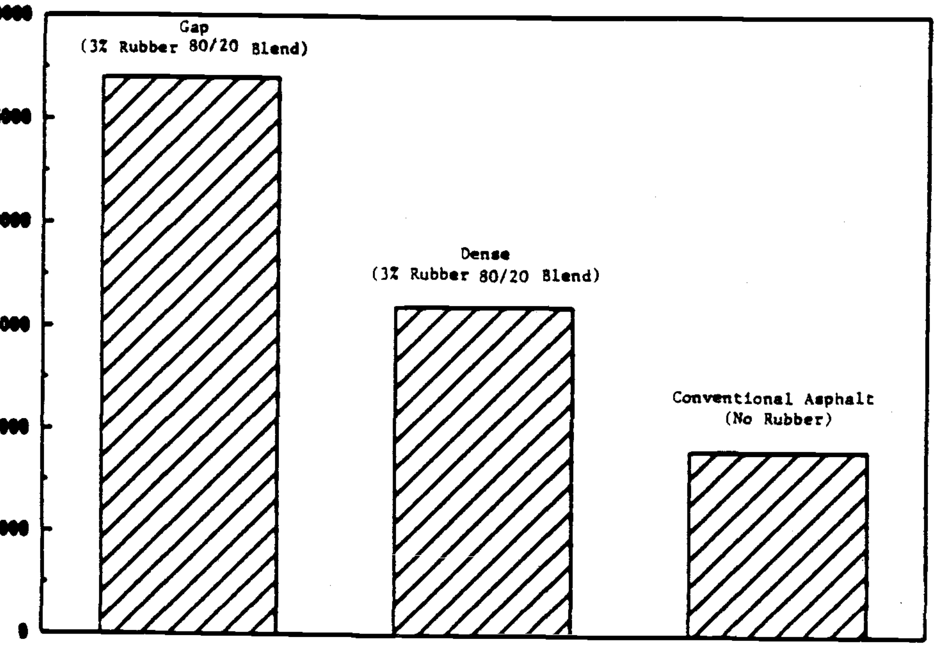


Figure 4.21. Effect of Rubber Content and Aggregate Gradation on Resilient Modulus at +10°C.

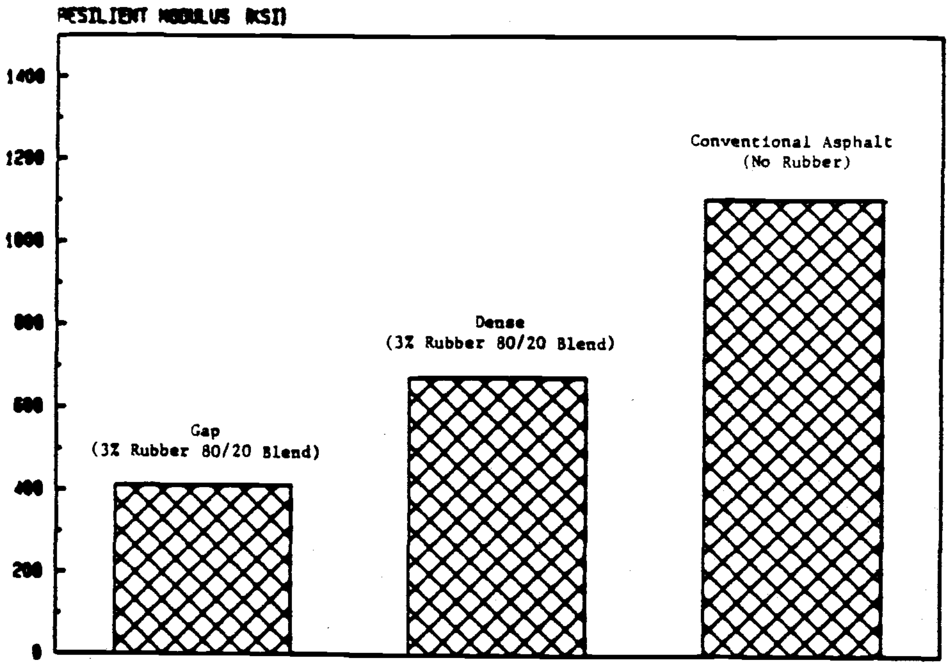


Figure 4.22. Effect of Rubber Content and Aggregate Gradation on Fatigue Life at +10°C.

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 (62):

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

where

ε_t = initial tensile strain, in./in.,

a = antilog of the intercept of the logarithmic relationship, and

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 4.16. The averaged logarithm fatigue life values versus logarithm of strains are shown as a linear relationship in Figure 4.23. 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 4.23 together with R^2, or coefficient of determination. R^2 values tend to be greater than 0.95. This is attributed to

Table 4.16. Summary of Fatigue Lives 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

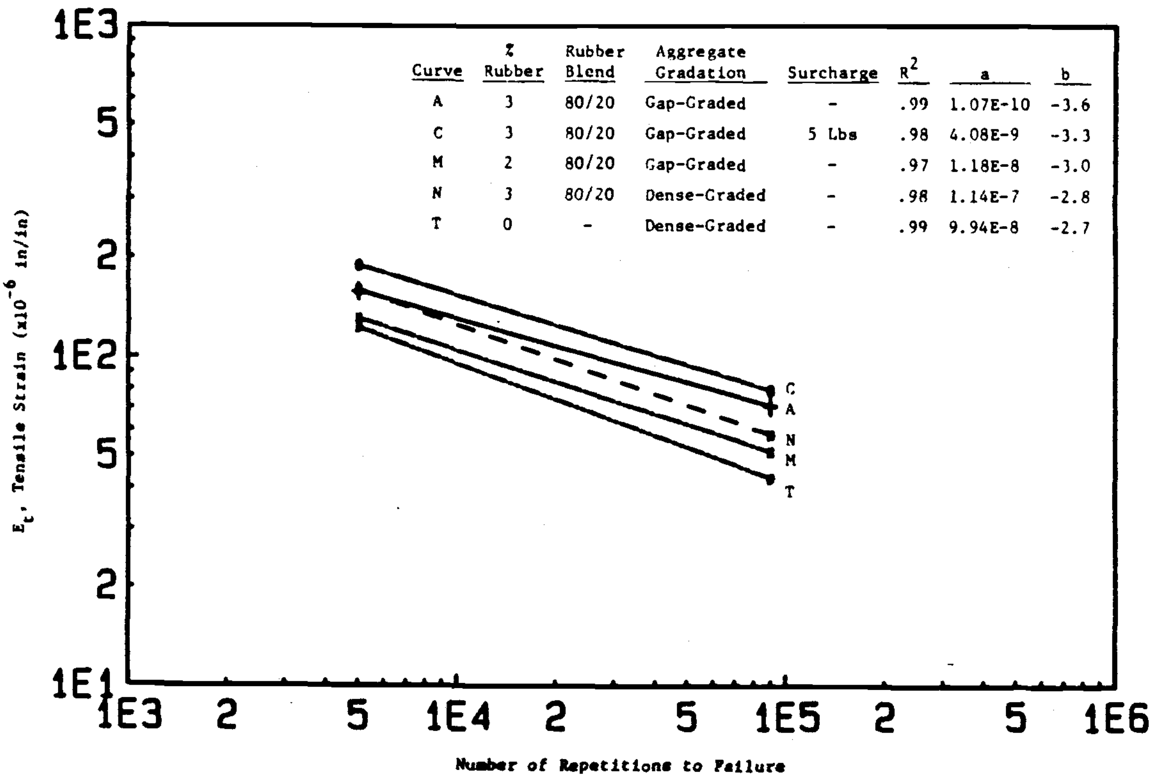


Figure 4.23. Laboratory Fatigue Curves at 10°C.

the precise testing techniques at 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 4.23 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 4.14). For all dynamic tests, samples were subjected to a constant load, applied at sixty cycles per minute, with a load duration of 0.1 s. A fifty-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 F. The results of resilient modulus and fatigue for twenty different mixes are summarized in Table 4.17.

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

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 4.24 and 4.29. These figures show that the mixture with gap-graded aggregate in all three mixing conditions had lower resilient modulus and lower fatigue life than the mixtures with dense-graded aggregate.

Table 4.17. 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	4.05	0.15	1,512	70	16,822	2,670
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	4.17	0.12	1,825	76	17,262	2,120
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	4.35	0.18	1,621	192	62,251	26,720
T*	3	2.25	0.13	3,163	133	15,536	2,562

*Specimens used to establish fatigue curves.

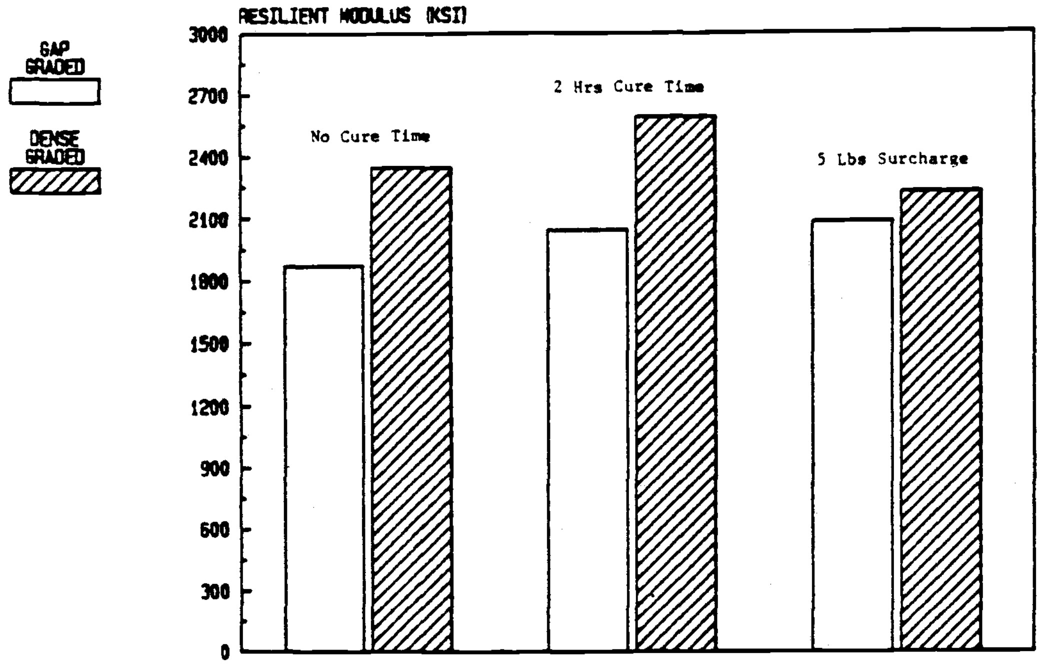


Figure 4.24. Effect of Aggregate Gradation, Cure Time, and Surcharge on Resilient Modulus at -6°C (3% Rubber 80/20 Blend).

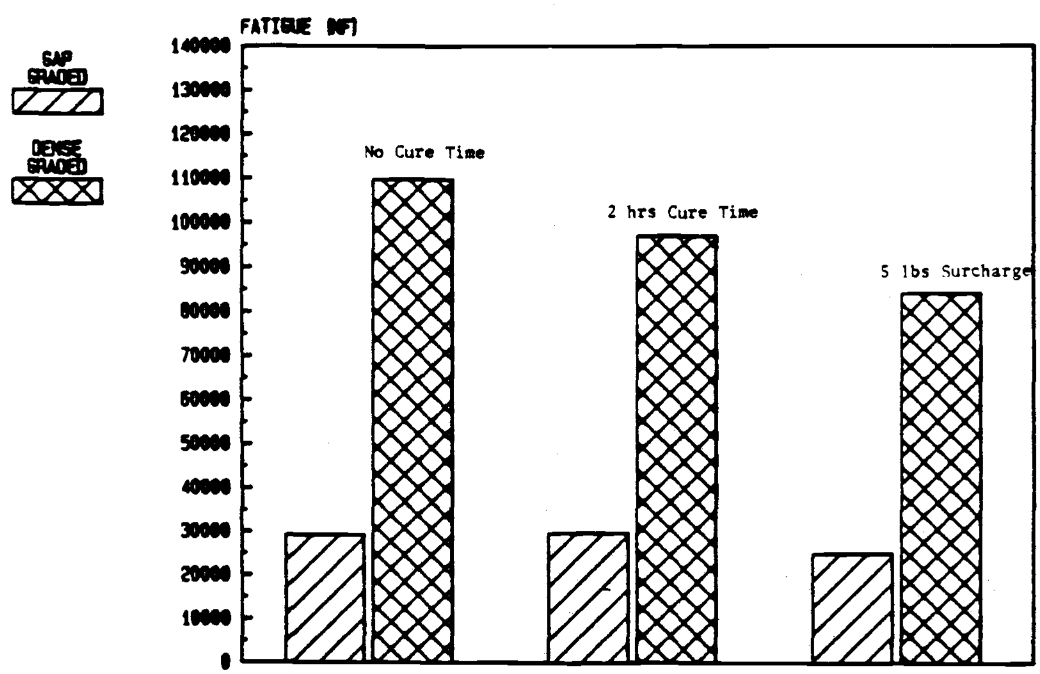


Figure 4.25. Effect of Aggregate Gradation, Cure Time, and Surcharge on Fatigue Life at -6°C (3% Rubber 80/20 Blend).

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 failed by deformation failure. 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 had the lowest modulus and highest fatigue life. This is shown in Figures 4.26 and 4.27. The results at +10°C had 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 4.28 and 4.29. The samples with 3-percent rubber generally had a lower resilient modulus than the samples with 2-percent rubber (Figure 4.28). The rubber content reduction (3% to 2%) increased the fatigue life by two to three times. These results compare directly with those found at +10°C.

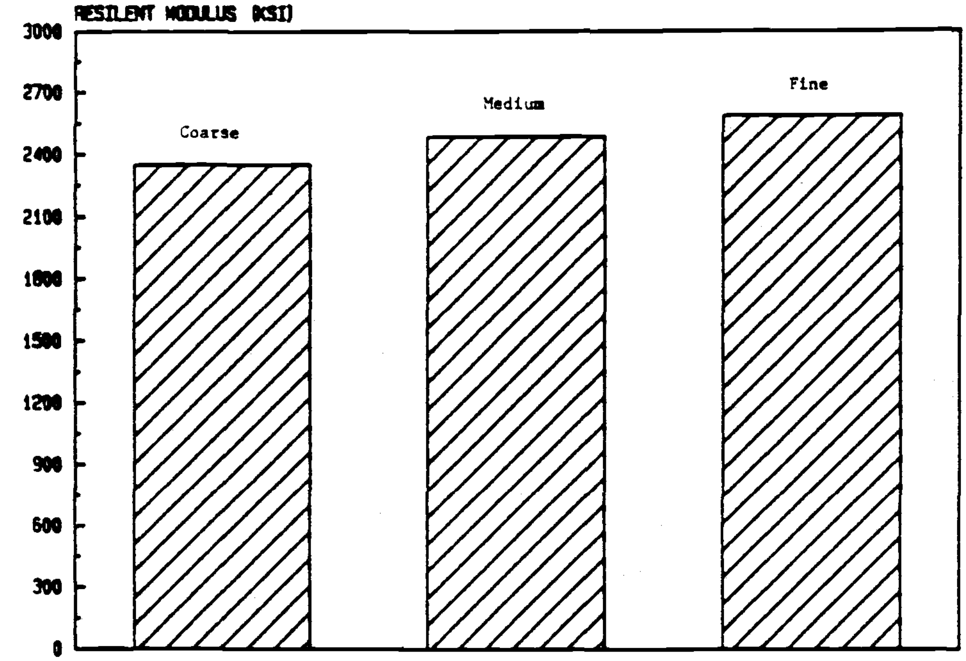


Figure 4.26. Effect of Rubber Gradations on Resilient Modulus at -6°C (Gap-Graded Aggregate, 2% Rubber).

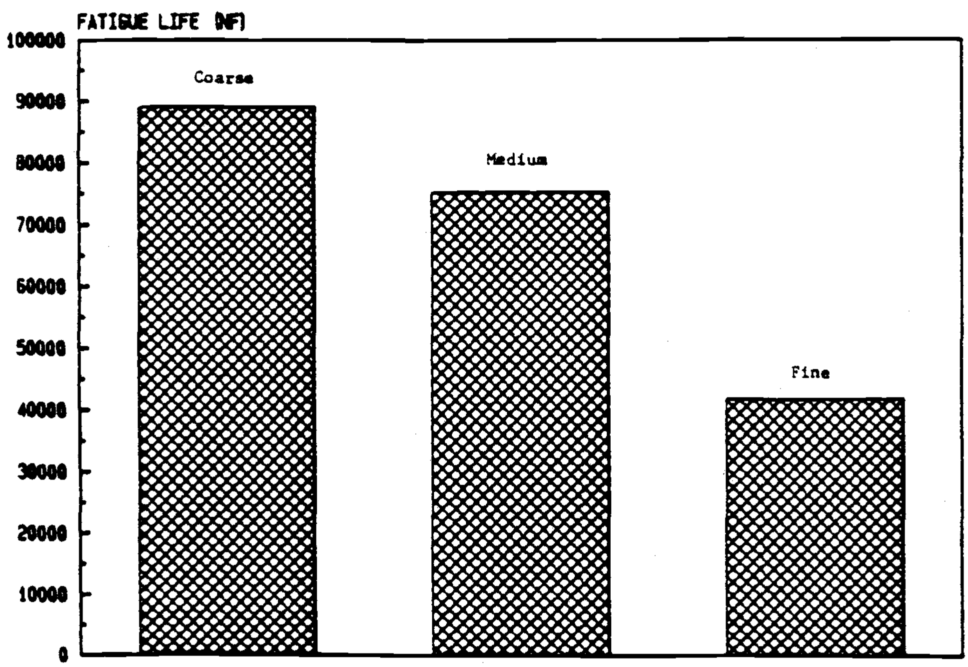


Figure 4.27. Effect of Rubber Gradations on Fatigue Life at -6°C (Gap-Graded Aggregate, 2% Rubber).

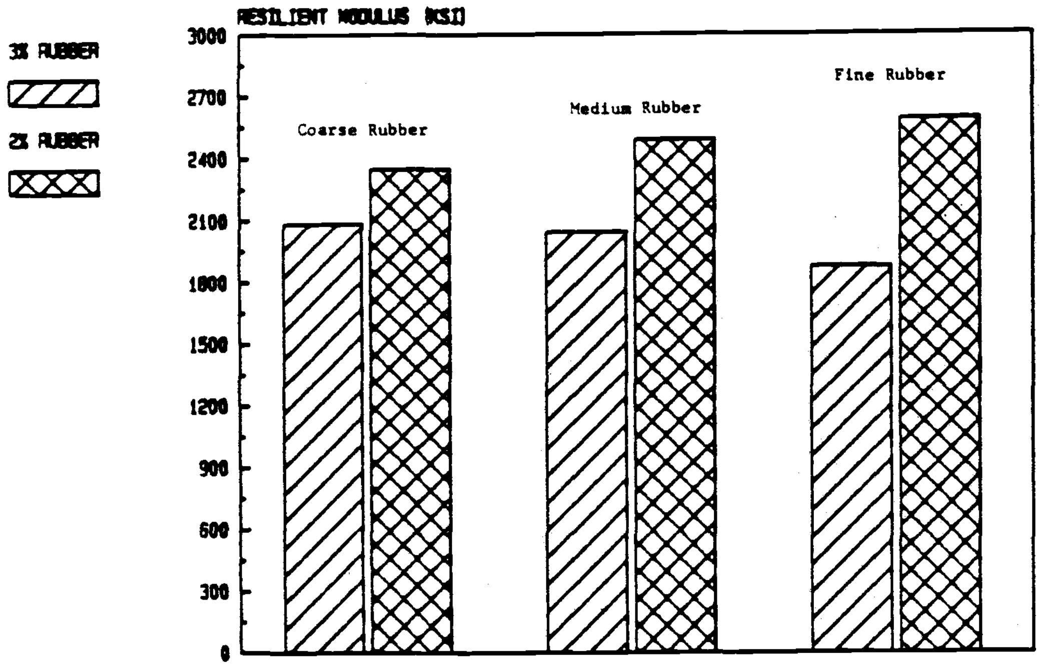


Figure 4.28. Effect of Rubber Content and Grading on Resilient Modulus at -6°C (Mixes with Gap-Graded Aggregate).

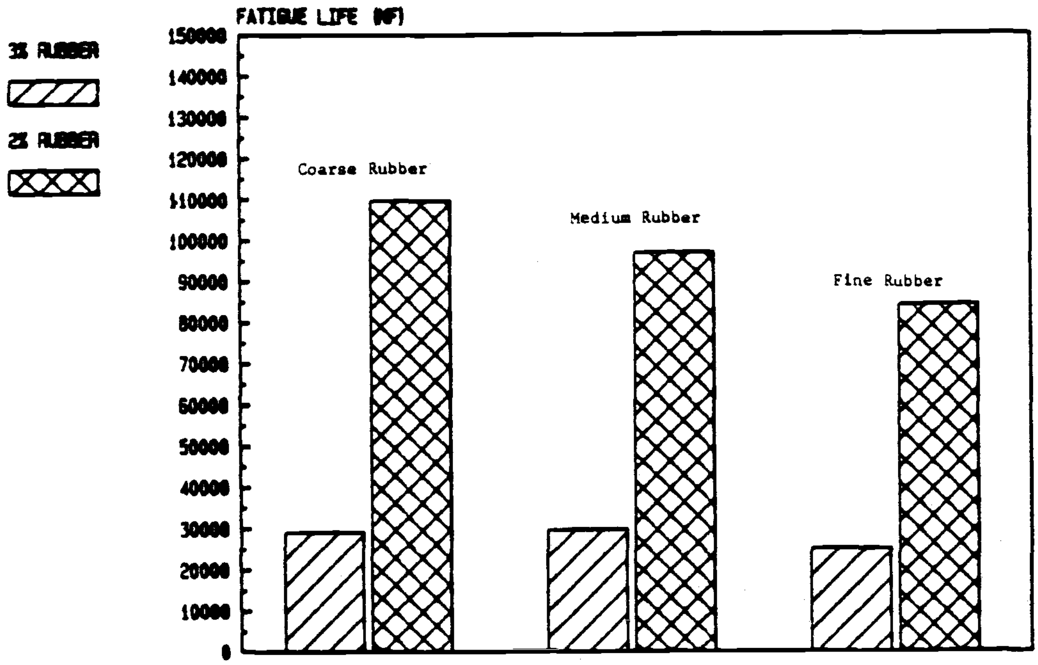


Figure 4.29. Effect of Rubber Content and Grading on Fatigue Life at -6°C (Mixes with Gap-Graded Aggregate).

4.3.1.4 Effect of Mixing Temperature (375°F vs. 425°F). The effect of mixing temperature on resilient modulus and fatigue life is shown in Figures 4.30 and 4.31. 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 results at +10°C had 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 two 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 4.32 and 4.33. These figures show that the effect of cure time on resilient modulus and fatigue was 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 4.34 and 4.35. These figures show that the effect of surcharge on resilient modulus was slight, but the samples with surcharge have a lower fatigue life than the samples with no surcharge. These results are contrary to those found at +10°C. This is due to a change of

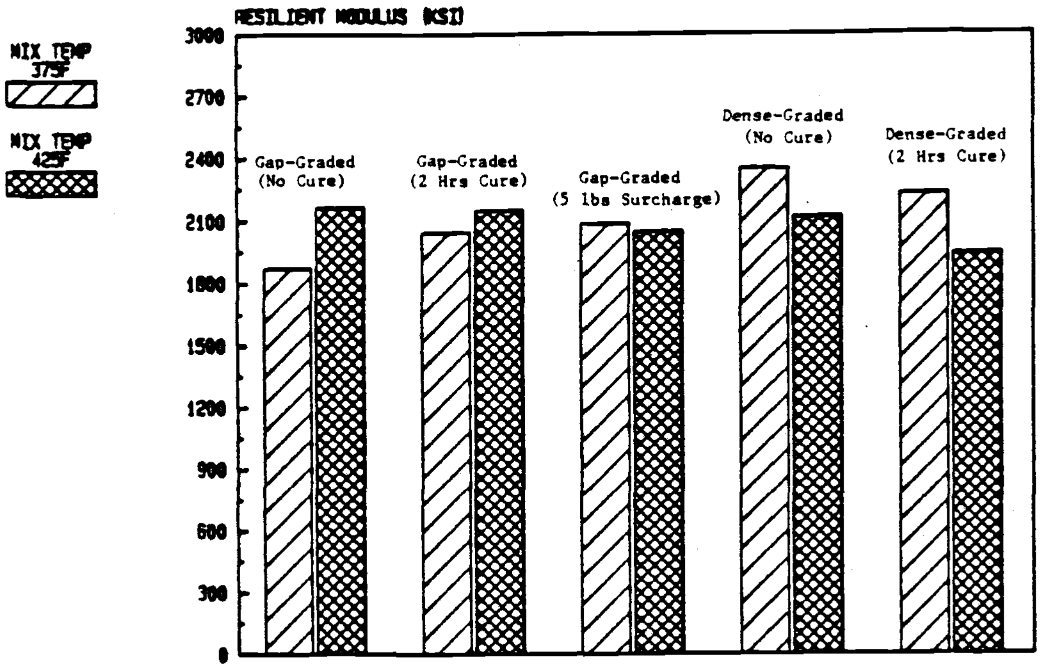


Figure 4.30. Effect of Mixing Temperature on Resilient Modulus at -6°C (3% Rubber 80/20 Blend).

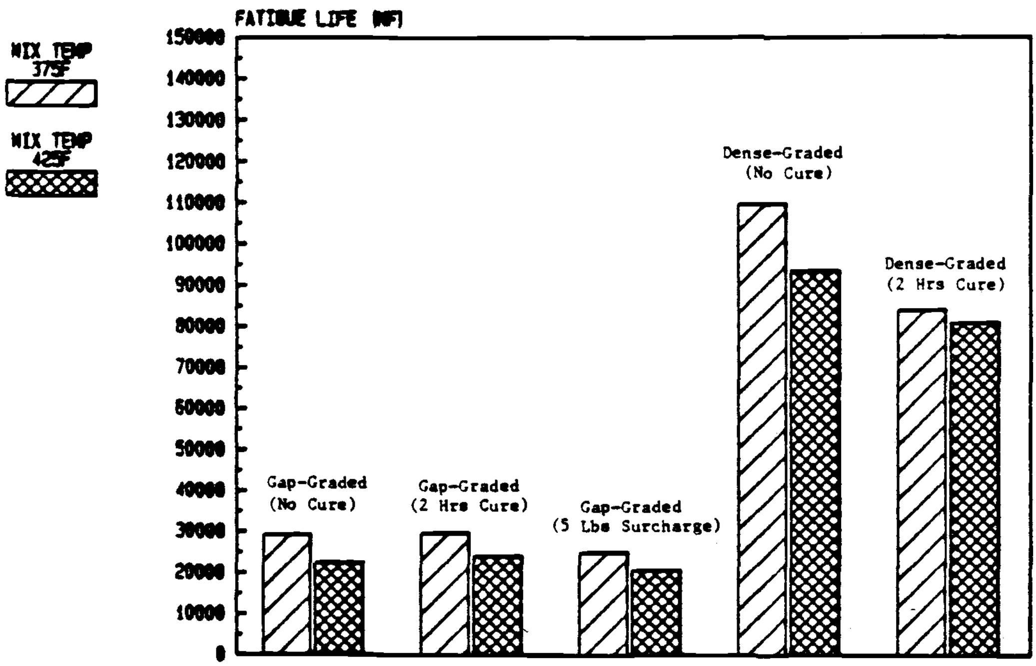


Figure 4.31. Effect of Mixing Temperature on Fatigue Life at -6°C (3% Rubber 80/20 Blend).

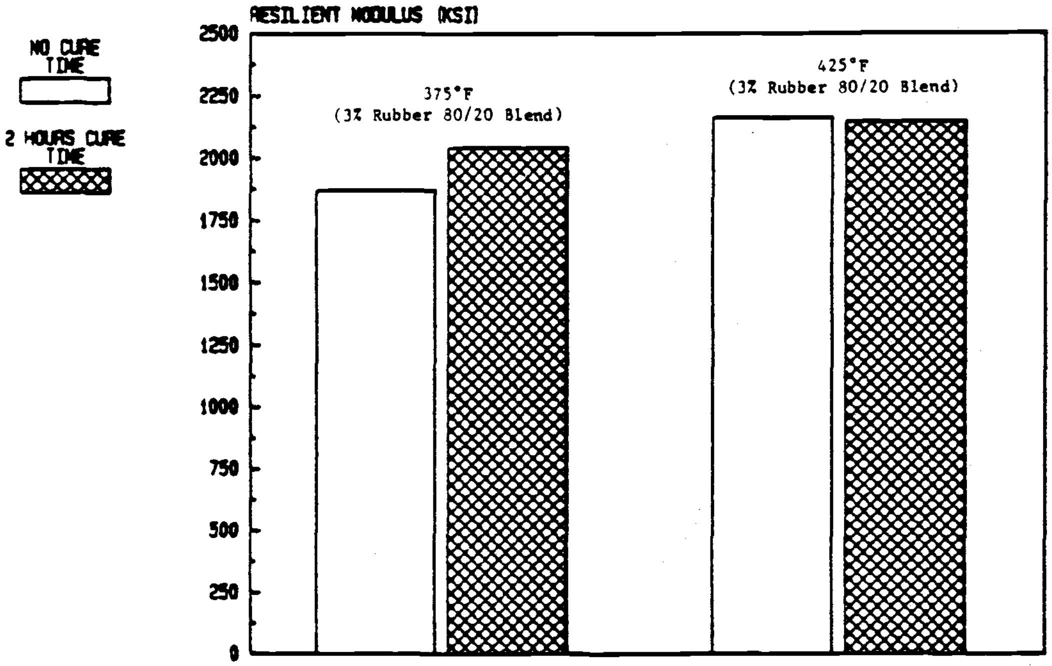


Figure 4.32. Effect of Cure Time at 375°F and 425°F with Gap-Graded Aggregate at -6°C.

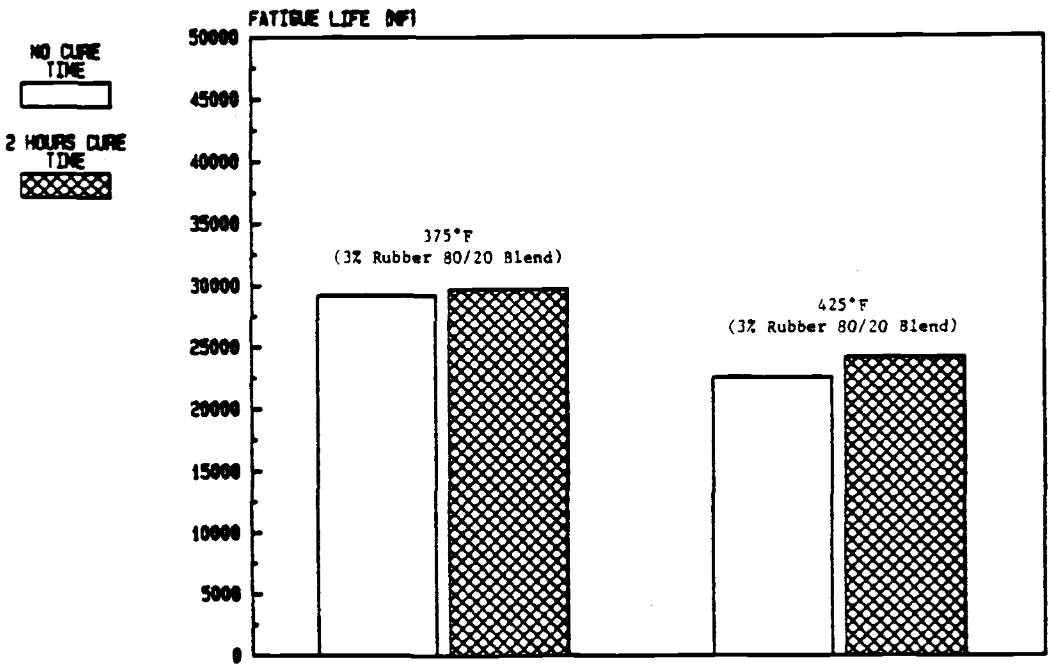


Figure 4.33. Effect of Cure Time at 375°F and 425°F with Gap-Graded Aggregate at -6°C.

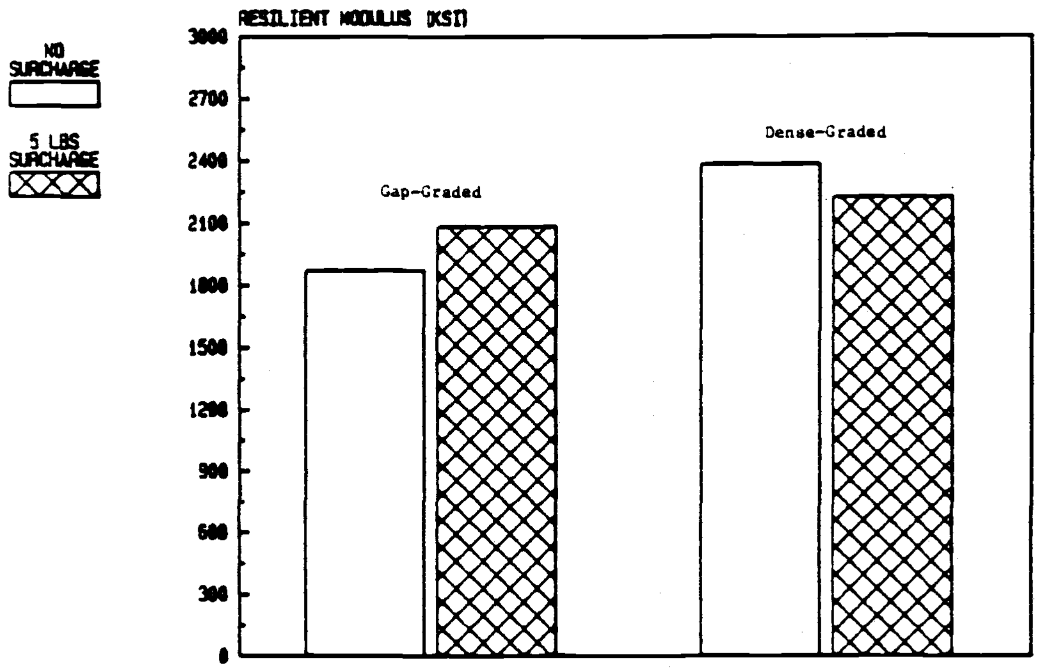


Figure 4.34. Effect of Surcharge on Resilient Modulus at -6°C (3% Rubber 80/20 Blend).

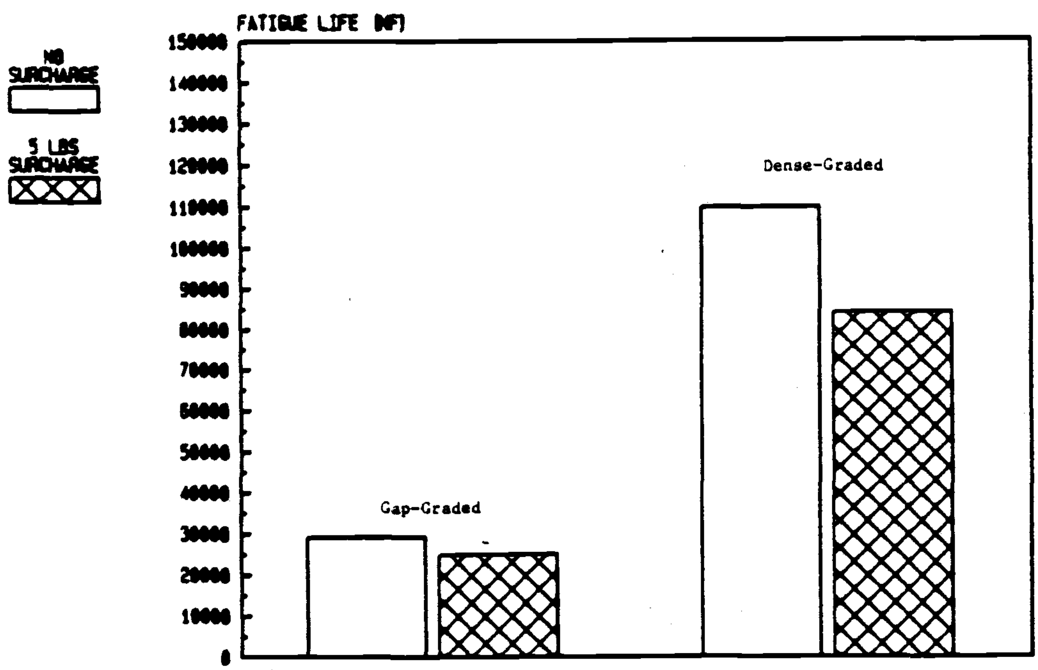


Figure 4.35. Effect of Surcharge on Fatigue Life at -6°C (3% Rubber 80/20 Blend).

behavior of the rubber at low temperature. Generally rubber lost its elasticity 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 2-4 percent for the gap-graded aggregate mix (Figure 4.36). However, the modulus of the dense-graded aggregate mix was reduced by 40 percent 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 decreased with an increase in air voids (Figure 4.37). These results compare directly with those found at +10°C.

4.3.1.8 Comparison of Rubber-Modified vs. Conventional Mix. The resilient modulus of conventional asphalt mix was approximately 40 percent higher than gap-graded rubber mix and 25 percent higher than dense-graded rubber mix (Figure 4.38). This relates directly to 9.3 percent asphalt used in gap-graded rubber mix versus 7.5 percent in dense-graded rubber and 5.5 percent in conventional mix.

The fatigue life of conventional asphalt mix is approximately 600 percent lower than dense-graded rubber mix and 88 percent lower than gap-graded rubber mix (Figure 4.39). 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

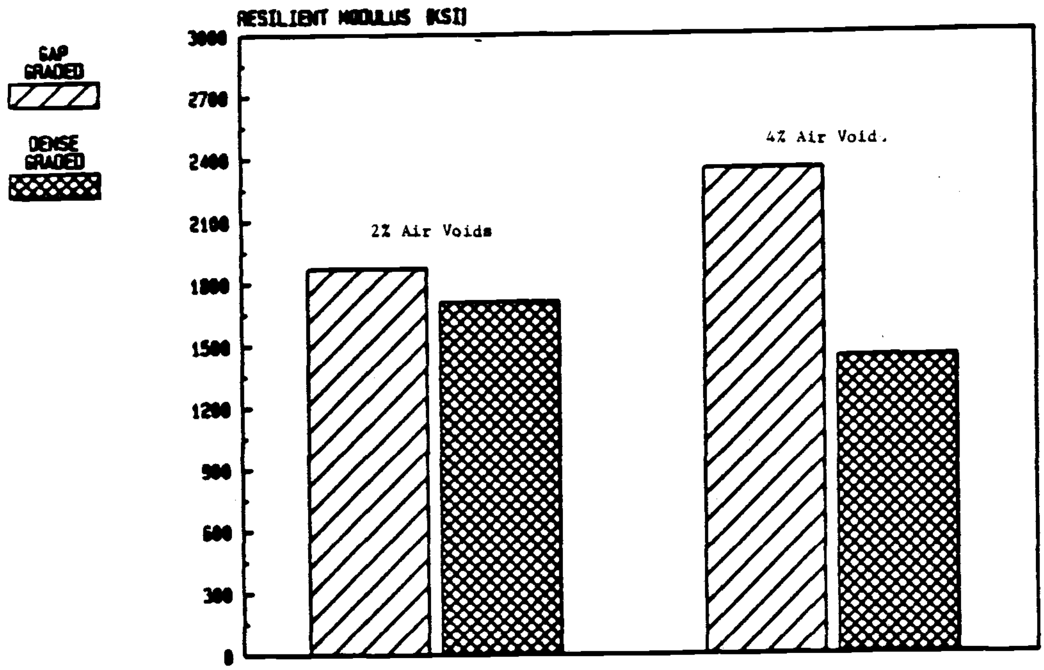


Figure 4.36. Effect of Air Voids of Resilient Modulus at -6°C (3% Rubber 80/20 Blend).

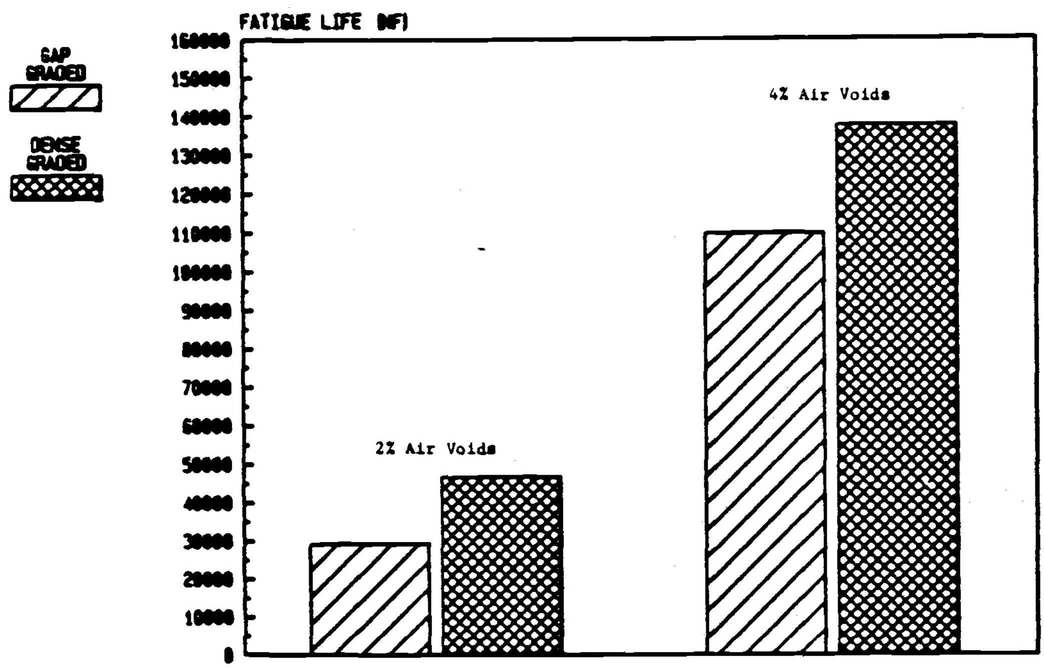


Figure 4.37. Effect of Air Voids of Fatigue Life at -6°C (3% Rubber 80/20 Blend).

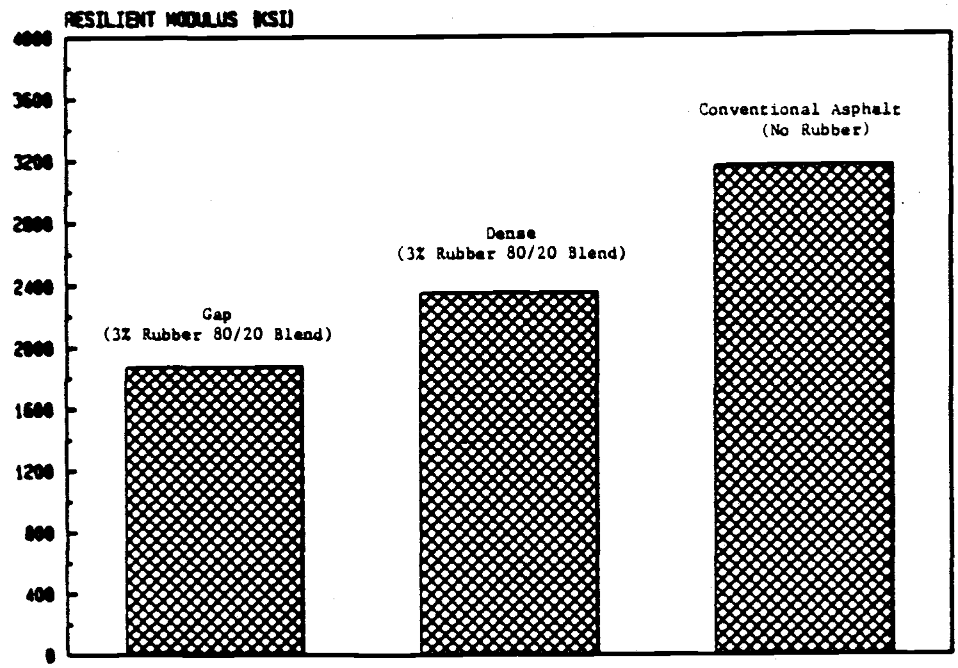


Figure 4.38. Effect of Rubber Content and Aggregate Gradation on Resilient Modulus at -6°C.

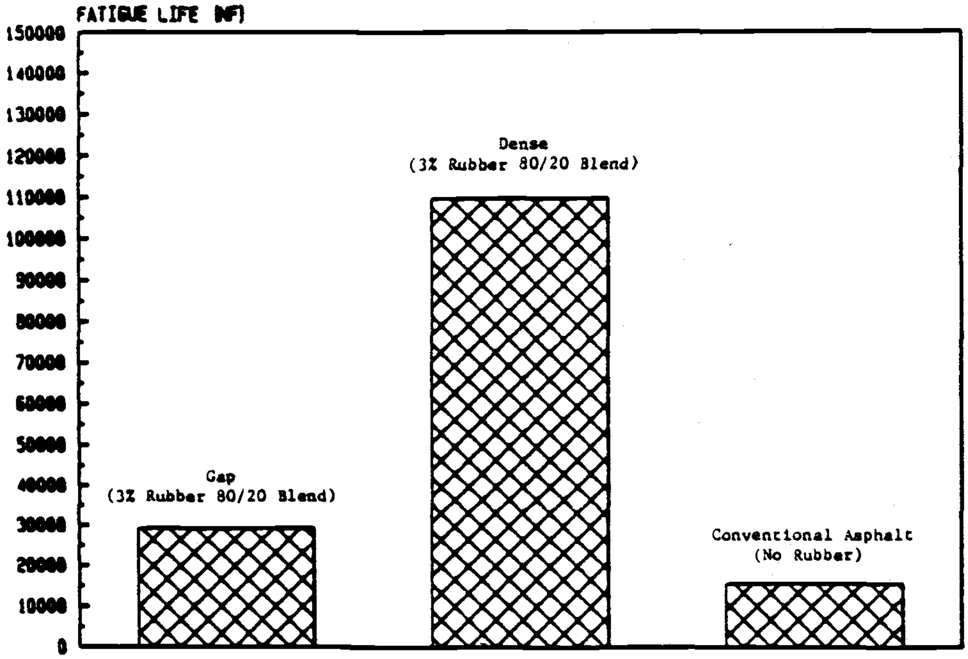


Figure 4.39. Effect of Rubber Content and Aggregate Gradation on Fatigue Life at -6°C.

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 combination--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 4.18. The averaged logarithm fatigue life values versus logarithm of strains are shown as a linear relationship in Figure 4.40.

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 4.19 summarizes the results of resilient modulus at different temperatures for all twenty mix combinations. The effect of temperature on resilient modulus for all rubberized asphalt mixture combinations are shown in Figures 4.41 through 4.47. 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.

To evaluate the time it takes the rubber-asphalt sample to reach a stable temperature (inside, outside), a small study was undertaken.

Table 4.18. Summary of Fatigue Lives at Different Strain Levels (-6°C).

Sample Identification	Fatigue Life Micro-strain Level 85	 100	 150
A	48,752	29,237	19,263
N	199,227	118,186	73,262
T	14,250	8,526	2,526

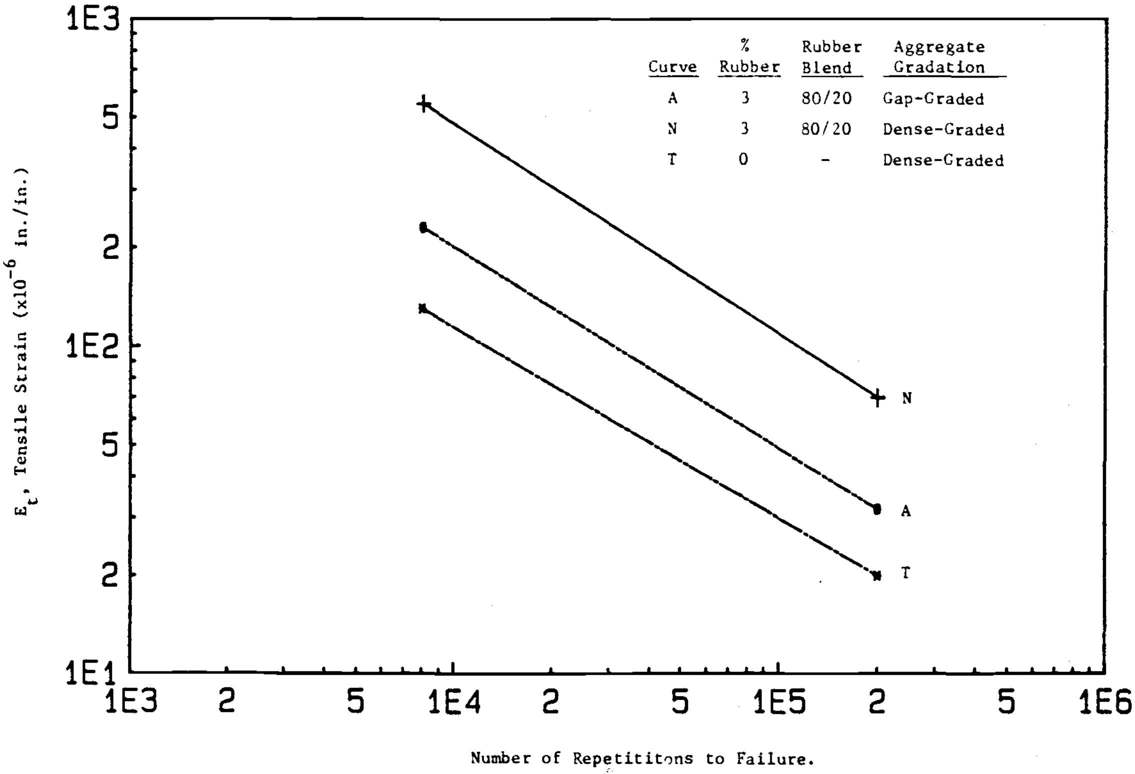


Figure 4.40. Laboratory Fatigue Curves at -6°C.

Table 4.19. Summary of Resilient Modulus at Three Different Temperatures.

Sample ID	Resilient Modulus (ksi)	Temperature (°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

Table 4.19. Summary of Resilient Modulus at Three Different Temperatures. (Cont.)

Sample ID	Resilient Modulus (ksi)	Temperature (°C)
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

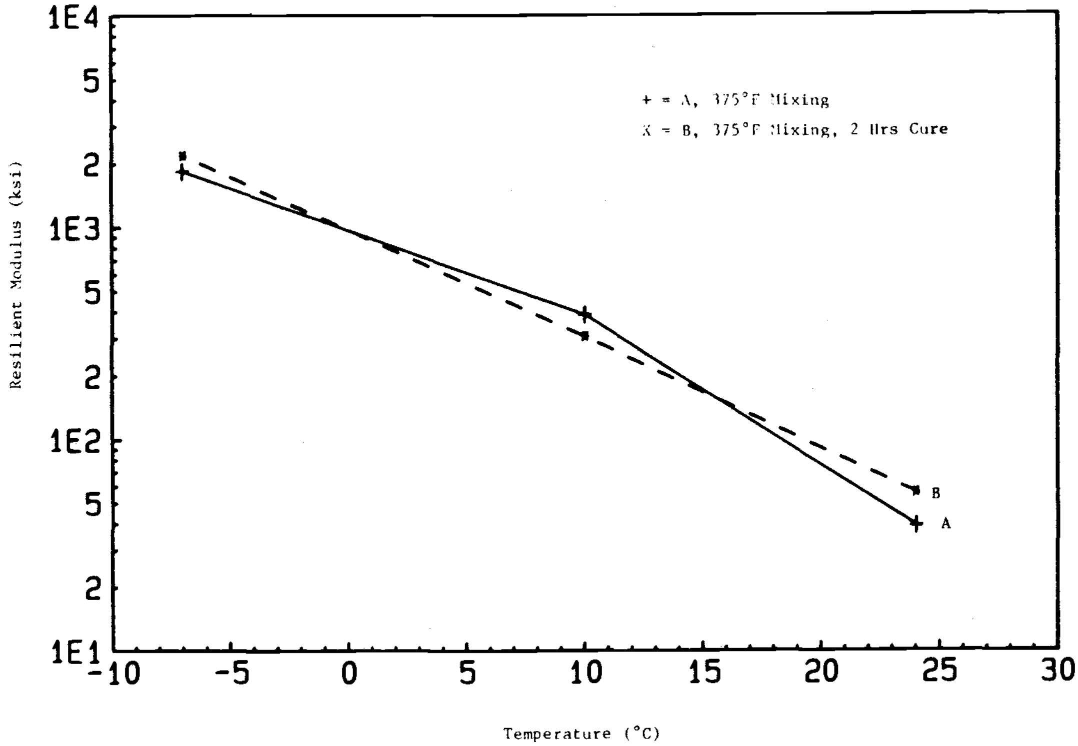


Figure 4.41. Effect of Temperature on Resilient Modulus for Mixes with Gap-Graded Aggregate (3% Rubber 80/20 Blend).

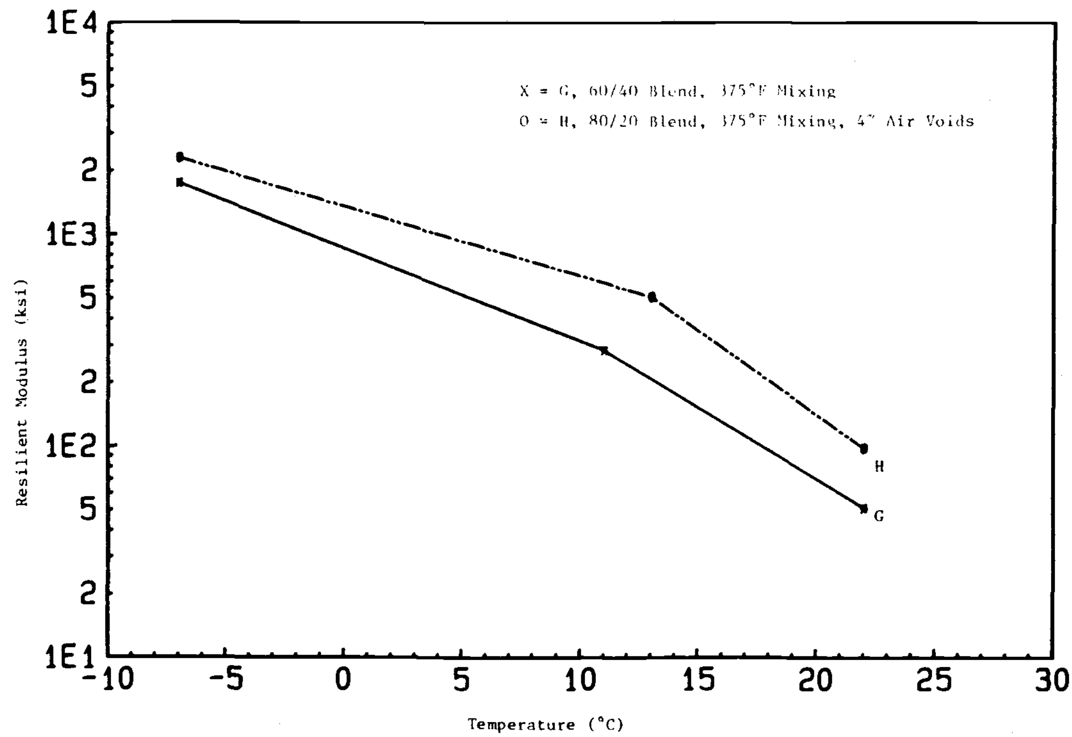


Figure 4.42. Effect of Temperature on Resilient Modulus for Mixes with Gap-Graded Aggregate (3% Coarse and Medium Rubber).

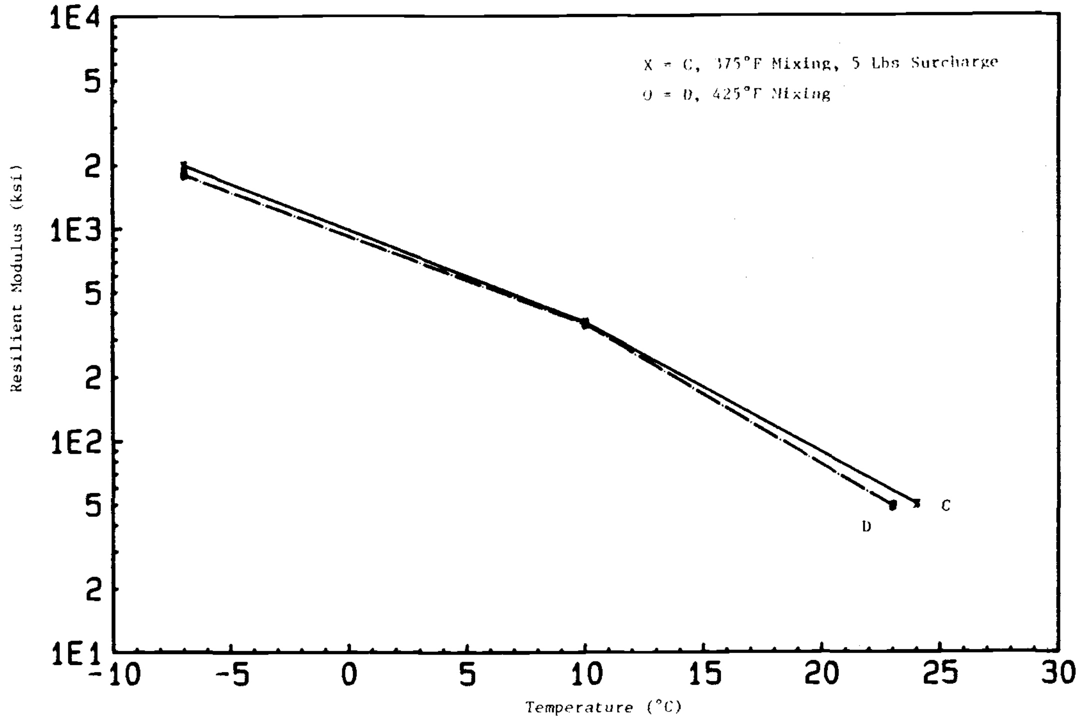


Figure 4.43. Effect of Temperature on Resilient Modulus for Mixes with Gap-Graded Aggregate (3% RUbber).

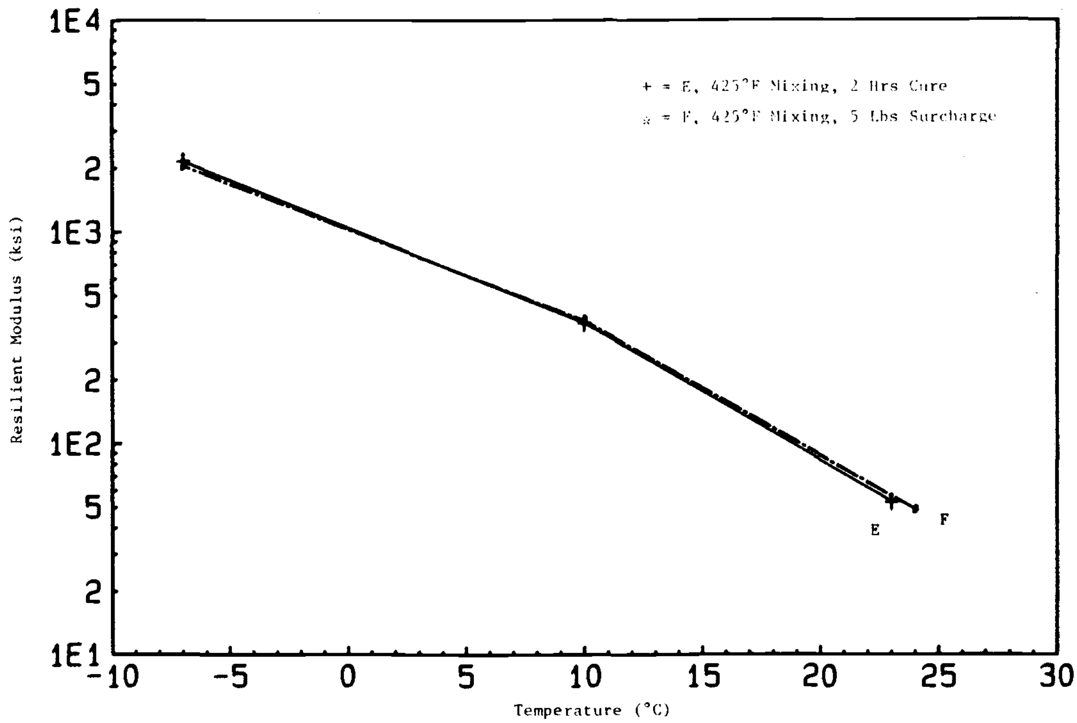


Figure 4.44. Effect of Temperature on Resilient Modulus for Mixes with Gap-Graded Aggregate (2% Rubber).

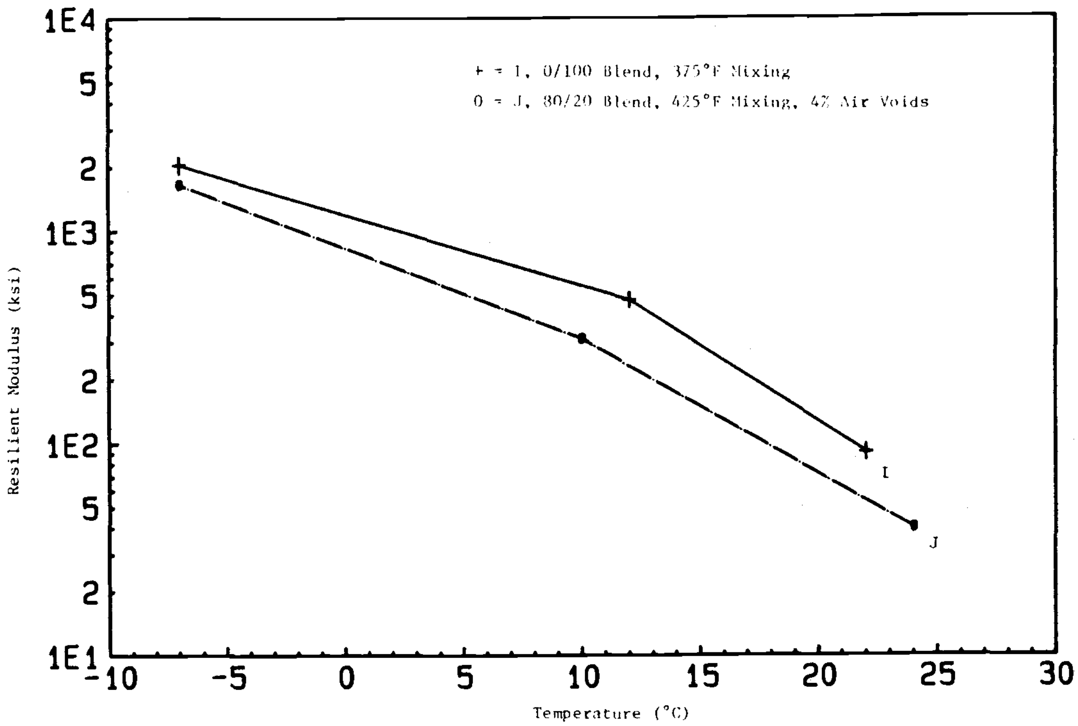


Figure 4.45. Effect of Temperature on Resilient Modulus for Mixes with 375°F Mixing Temperature.

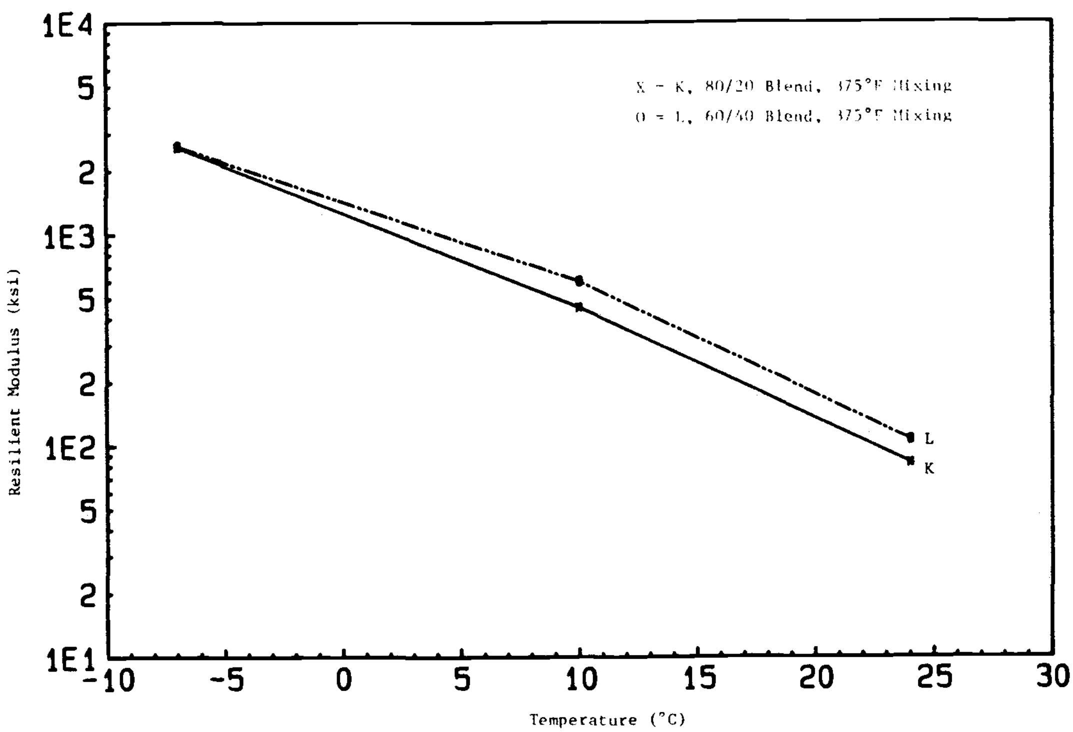


Figure 4.46. Effect of Temperature on Resilient Modulus for Mixes with Dense-Graded Aggregate (3% Rubber 80/20 Blend).

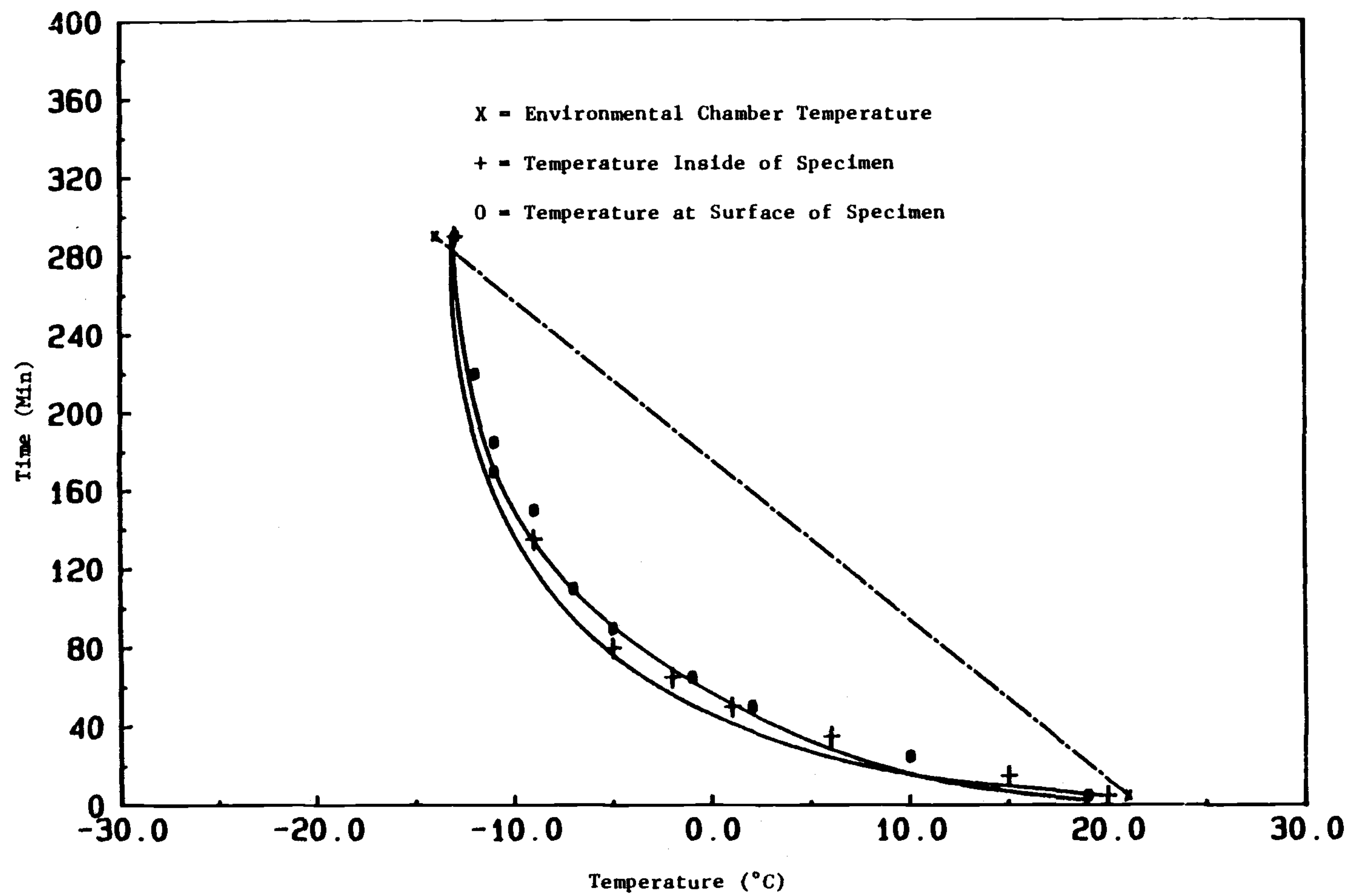


Figure 4.47. Time Required for Sample to Stabilize at Test Temperature of -13°C.

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 4.20 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 (Centigrade) 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 recorded 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

Table 4.20. Summary of Temperature Drop in Rubberized Asphalt Specimen at Different Time Intervals

Time Interval (Minute)	Temperature Inside of Specimen (°C)	Temperature at Surface of Specimen (°C)	Environmental Chamber Temperature (°C)
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
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

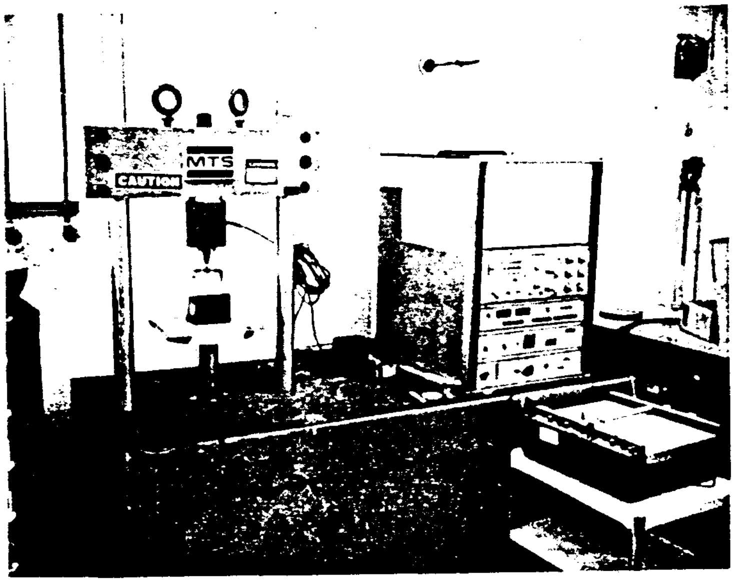


Figure 4.48. Load Application Device (MTS).

Figure 4.49. Rubber Cube Testing Setup.

(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 ten seconds per cycle.

The summary of the sample measurements and the modulus of elasticity test results obtained at different temperatures are presented in Tables 4.21 and 4.22, respectively. To calculate the resilient modulus, the displacement was divided to total sample height to obtain strain and load divided by cross-stress over strain. Figure 4.50 shows the resilient modulus at different temperatures 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 was 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 4.14) 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 F and summarized in Table 4.23.

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

Table 4.21. 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 4.22. 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	0.7856	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

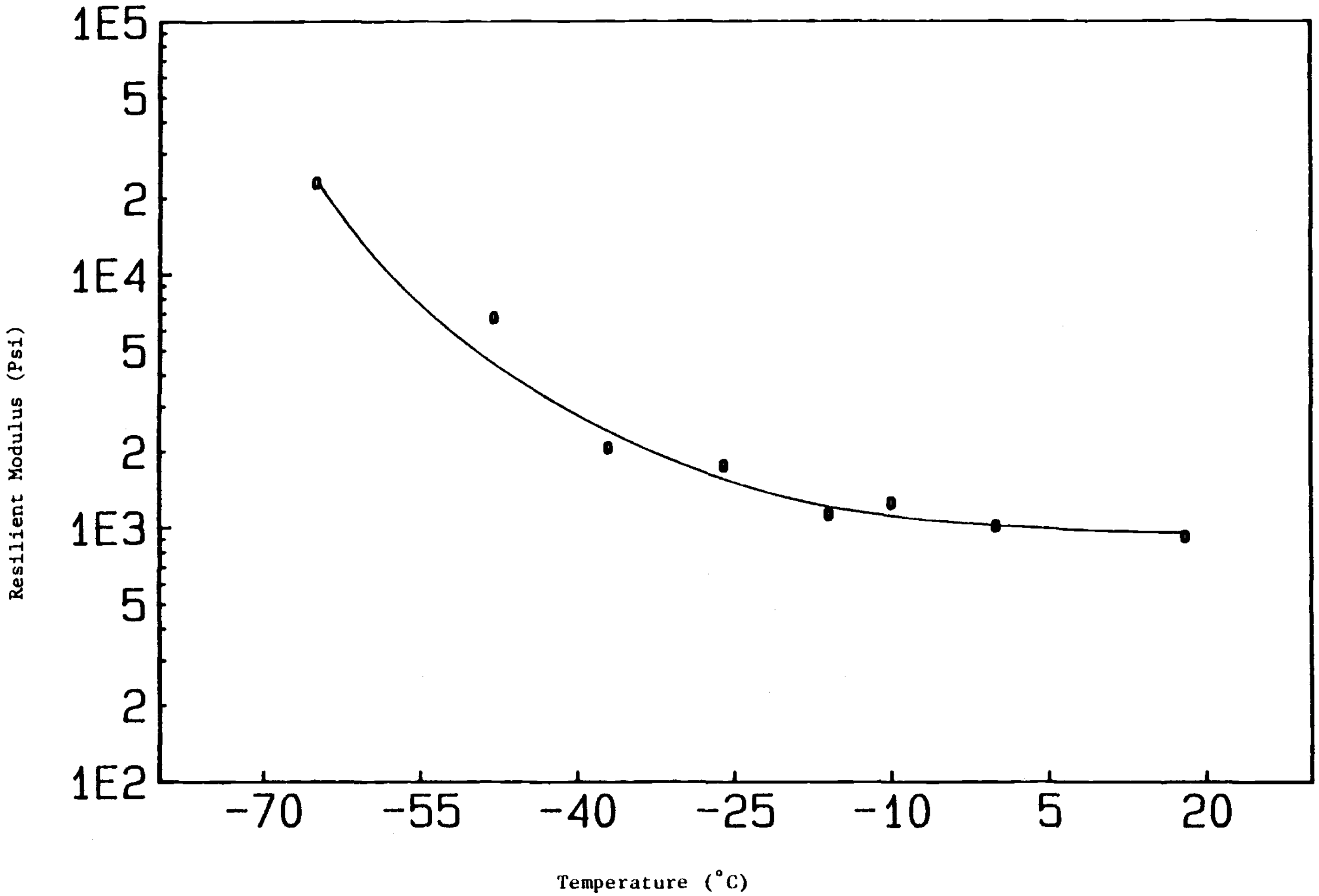


Figure 4.50. Resilient Modulus vs. Temperature for Reclaimed Rubber.

Table 4.23. 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

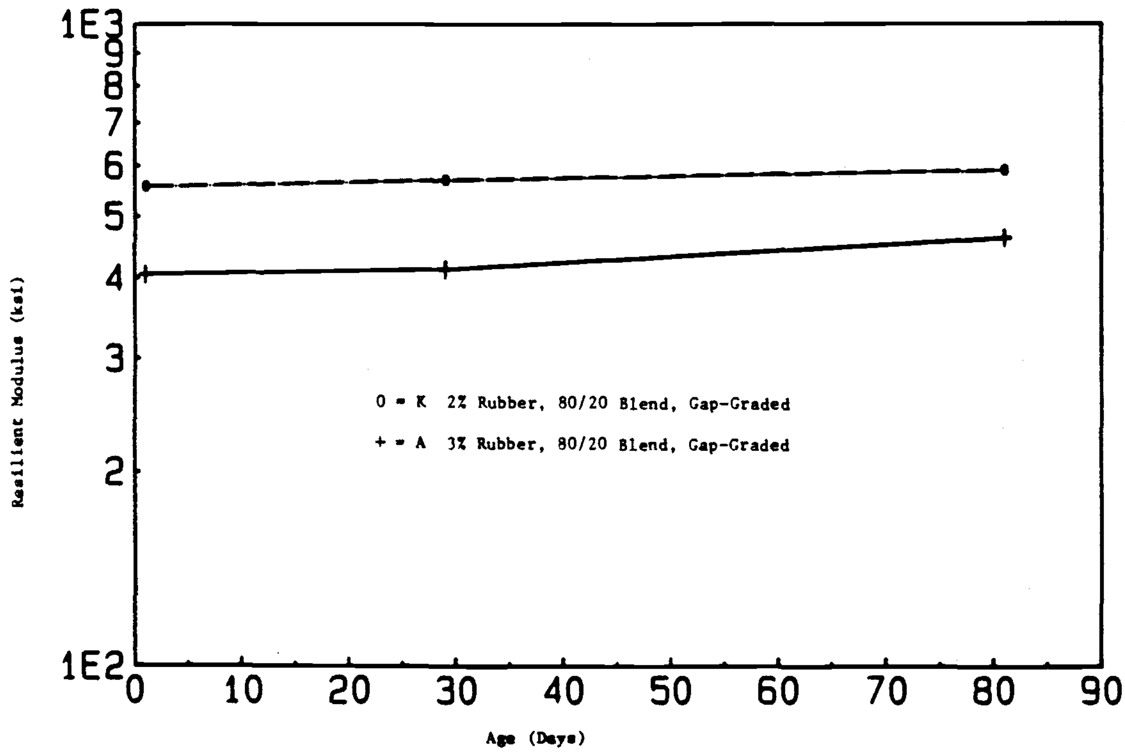


Figure 4.51. Effect of Aging on Resilient Modulus.

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 Creep Behavior of Rubber-Modified Mixtures

Creep behavior of five different mix combinations at 40°C and 25°C were evaluated. Tables 4.24 and 4.25 present the sample identification and the creep test results, including the intercept (I) and slope (S) after regression analysis and creep stiffness at 60 minutes. The coefficients of determination (R^2) are also presented. The regression analysis was performed in the range from 1 minute to 90 minutes.

$$\log \text{strain} (\%) = \log (I) + S \log \text{time (sec)} \quad (4\text{-}2)$$

or

$$\text{strain}, \% = (I)\ (\text{time, sec})\ S \quad (4\text{-}3)$$

Creep strain and creep stiffness was determined using the following equations:

$$\varepsilon = \frac{\Delta h}{h} \quad (4\text{-}4)$$

where ε = creep strain,

Δh = deformation at time t, and

h = thickness of specimen.

and,

$$S_{mix}\ (T,t) = \frac{\sigma}{\varepsilon\ (T,t)} \quad (4\text{-}5)$$

where S_{mix} (T,t) = creep stiffness at temperature T and time t,

σ = compressive stress, and

ε (T,t) = creep strain at temperature T and time t.

Table 4.24. Specimen Identification.

Specimen Identification	Rubber Content (%)	Rubber Blend (% Fine/% Coarse)	Mixing/Compaction Temperature (°F)	Aggregate Gradation
A	3	80/20	375/265	Gap
I	3	0/100	375/265	Gap
N	3	80/20	375/265	Dense
T	-	No rubber	375/265	Dense
U	3	0/100	375/265	Dense

Table 4.25. Creep Test Results

Sample Identification	S mix (ksi)[1]	I[2]	S[3]	R^2[4]
		Tested at 40°C (104°F)		
A	71.0	0.0078	0.1263	.99
I	107.0	0.0084	0.0598	.93
N	101.0	0.0081	0.0729	.96
T	195.0	0.0053	0.0467	.98
U	50.0	0.0148	0.0408	.91
		Tested at 25°C (77°F)		
A	132.0	0.0054	0.0904	.95
I	128.0	0.0051	0.0744	.95
N	148.0	0.0058	0.0832	.94
T	203.0	0.0044	0.0510	.96
U	156.0	0.0051	0.0801	.94

(1 S_{mix} = predicted creep stiffness at 60 minutes after regression

(2 I = intercept; strain, % at 1 sec.

(3 slope; strain, % = Ix (time, sec)^S

(4 R^2 = coefficient of determination

The creep behavior of an asphalt mixture can be interpreted by the slope obtained after regression analysis and creep strain or creep stiffness. To analyze the effect of mix variable, including aggregate gradation, rubber gradation on creep behavior, the regression lines for all five mix combinations were compared (Figure 4.52). In general, the slope of the regression lines for mixes containing rubber are steeper than the mixes with no rubber. Also, the intercepts for all rubber-asphalt mixes are higher values than for mixes with no rubber at both temperatures. As these results indicate, the rubber-asphalt mixes had lower stability than the mixes with no rubber.

Among rubber-asphalt mixes, the mix with gap-graded aggregate and coarse rubber (80/20) has the sharpest slope, and the dense-graded mix with fine rubber (0/100) has the smallest slope value at 40°C. This indicates the fine rubber improved the stability of rubber-asphalt mixtures. However, there are slight differences among the slopes of all rubber-asphalt mixes. This indicates the rubber asphalt mixes showed high elasticity behavior.

4.8 Permanent Deformation Results

Permanent deformation was determined for five different mix combinations--samples with identification symbols A, I, N, T, U (Table 4.24). Specimens were tested at 100 microstrain in the control environment of 15°C. Total vertical deformation was measured using a dial gauge accurate to 10^{-3} inches. Table 4.26 presents the permanent deformation test results, including the intercept (I) and slope (S) after regression analysis at 3600 repetitions. The coefficients of determination (R^2) are also presented.

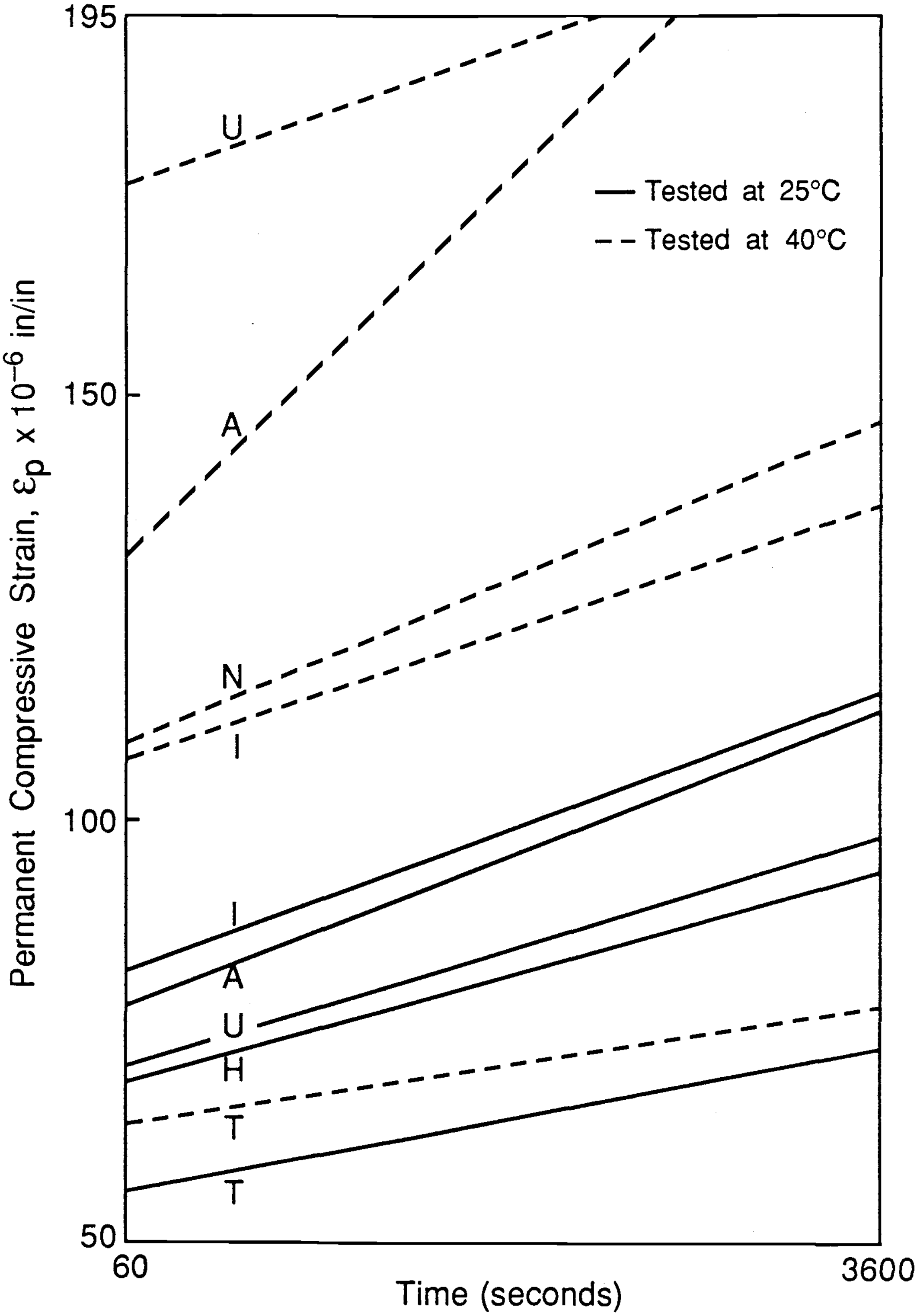


Figure 4.52. Creep Behavior of Rubber-Asphalt Mixes.

Table 4.26. Diametral Vertical Deformation Results

Sample Identification	M_R[1] (ksi)	I[2]	S[3]	R^2[4]
A	120	0.0023	0.4024	.99
I	281	0.0006	0.6842	.91
N	283	0.0005	0.6249	.97
T	414	0.0020	0.6293	.90
U	157	0.0006	0.5400	.97

(1 M_R = Diametral resilient modulus (ksi)

(2 I = Intercept; strain, % at 1 sec.

(3 Slope; strain, % = Ix (number of repetitions)^S

(4 R^2 = coefficient of determination

The test results indicate that the control mix (mix with no rubber) has steepest slope and the gap-graded mix with 3-percent coarse rubber (80/20) has lowest slope value. In general, all rubber-asphalt mixes have lower slope than the control mix (Figure 4.53). This indicates that the rubber-asphalt mixes showed very high elastic behavior.

4.9 Summary

This chapter included a summary of mix design results, resilient moduli and fatigue values for various mixes, and results of tests to evaluate the effects of temperature and aging on resilient moduli of rubber-modified asphalt mixes. Also, the creep behavior and permanent deformation for various mixes were evaluated.

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 increased resilient modulus also increased. Samples with 2-percent fine rubber had the highest stability and modulus. The reverse relation was true for flow results: As flow increased, the resilient modulus decreased.

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-percent rubber 80/20 blend, and surcharge had 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,

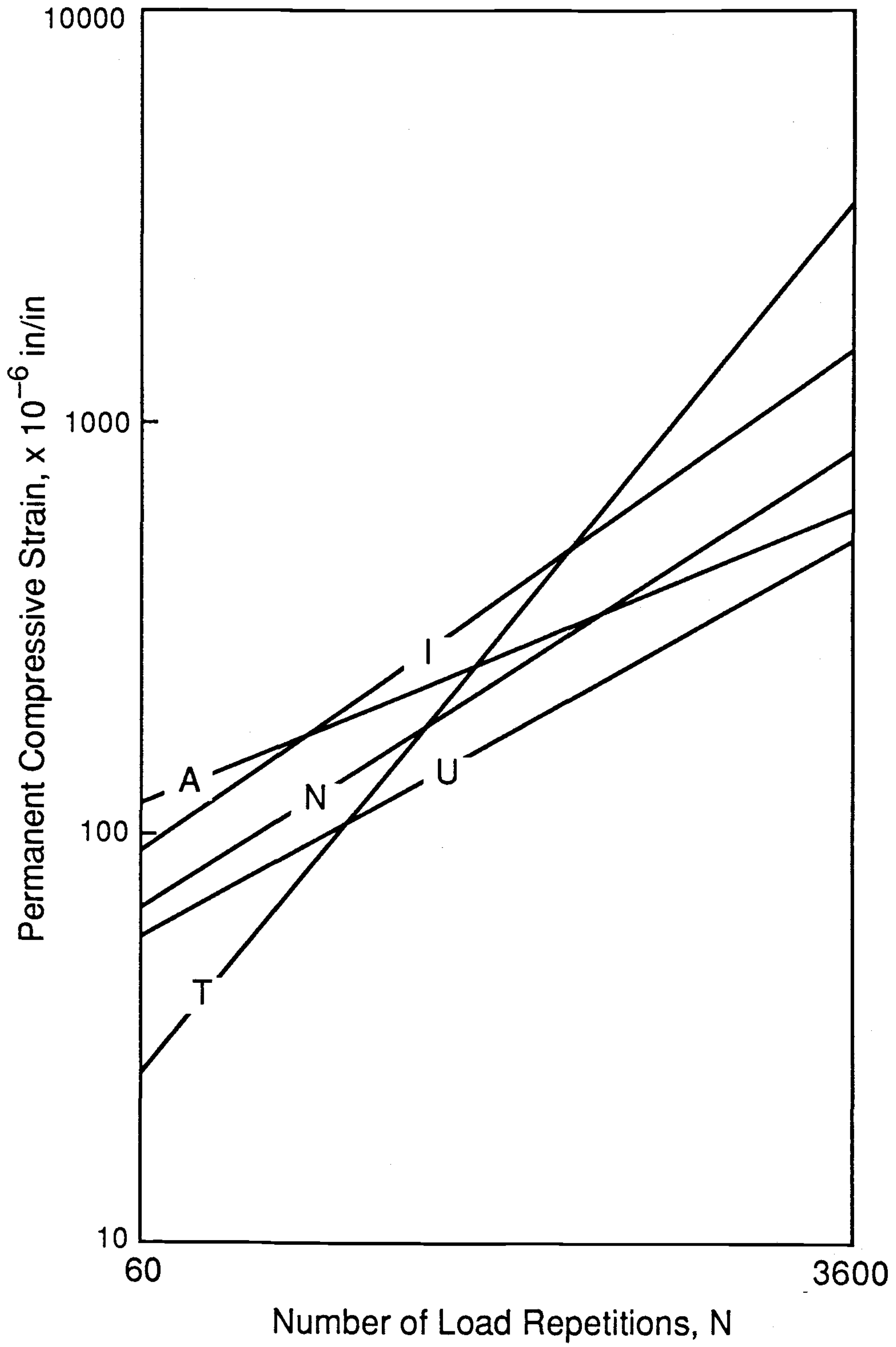


Figure 4.53. Relation Between Number of Load Repetitions and Vertical Strain.

3-percent 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) was similar. The dense-graded aggregate had 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 for mixes with dense-graded aggregate.

The effect of rubber gradation on resilient modulus at both temperatures was consistent. The mixture with coarse rubber had the lowest modulus and highest fatigue life. The higher mixing temperature increased 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 may have been a strong factor in this behavior.

The effect of cure time on mix properties at both temperatures was 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 indicate, as increasing the air voids in the mix from 2 percent to 4 percent decreased the fatigue life at both temperatures.

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 decreased, as expected, with increasing temperature.

The effect of temperature on modulus of compacted rubber buffings was analyzed. The reclaimed rubber cubes were tested at eight different temperatures. The results show that stiffness increased, as expected, with decreasing temperature. However, the rate of increase of stiffness as temperature decreased 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.

The results of creep and permanent deformation tests indicate that the rubber asphalt mixes had low stability and high elasticity.

5.0 ANALYSIS OF DATA

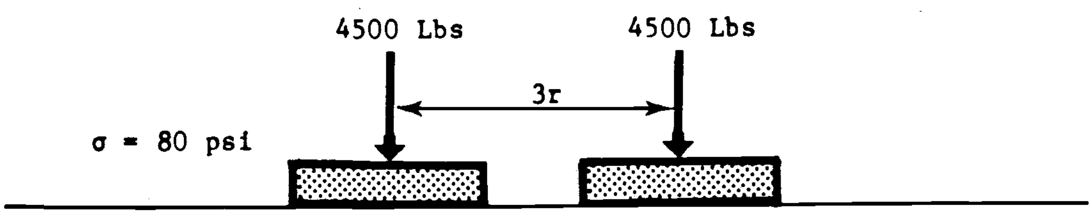
The purpose of this chapter is to bring together selected test data and project information to estimate the effects of mixture variables on pavement life. Layered elastic theory was used with the material properties developed and project information supplied to evaluate the effects of mix variations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



Wearing Course

E_1 = 3200, 1900, 1100, 350 ksi

ν_1 = 0.4

t_1 = 2, 4, 6 inch

Base

E_2 = $1.5E_3$

ν_2 = 0.35

t_2 = 24 inch

Subgrade

E_3 = 50000, 10000, 2000 psi

ν_3 = 0.4

1 in. = 25.4 mm
1 lb = .454 kg
1 psi = 6.894 kPa
1 ksi = 1000 psi

Figure 5.1. Pavement Structures Used for ELSYM5 Analysis (63).

from this program includes stresses, strains, and displacements. For a more complete description of ELSYM5, the reader should refer to reference 64.

As seen in Figure 5.1, three pavement structures were evaluated using ELSYM5 computer program. The layer equivalencies for three seasons (winter, spring thaw, spring/fall) were evaluated for three different surface thicknesses (two, four, and six inches). The modulus for the surface and subgrade varied for each seasons. The base modulus was assumed to be 1.5 time 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 modulus values for subgrade were obtained from Alaska DOT & PF (63). Table 5.1 shows the surface and subgrade resilient modulus for rubberized asphalt and conventional asphalt in these 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 (65) 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 $_{ac}$ 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.

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

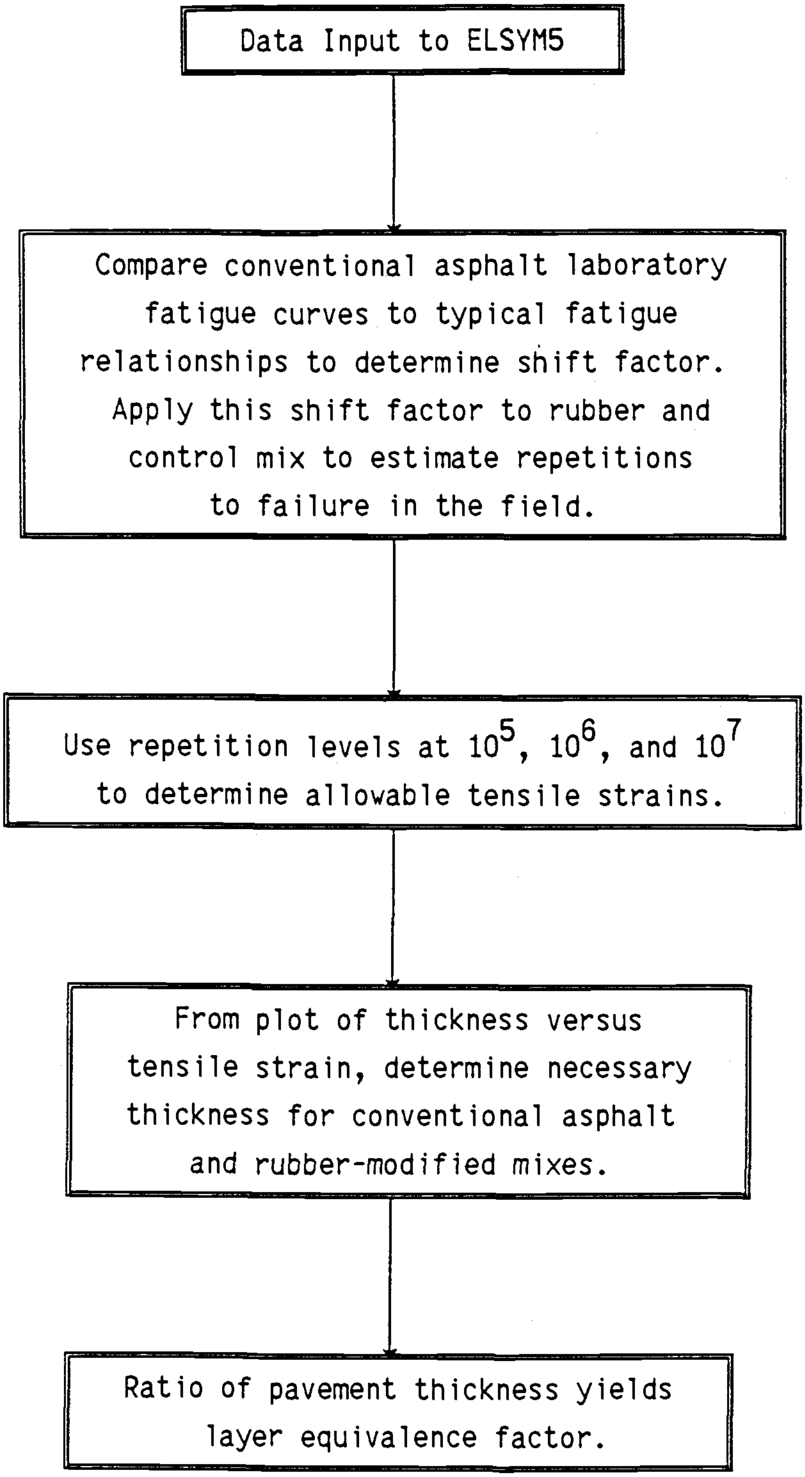
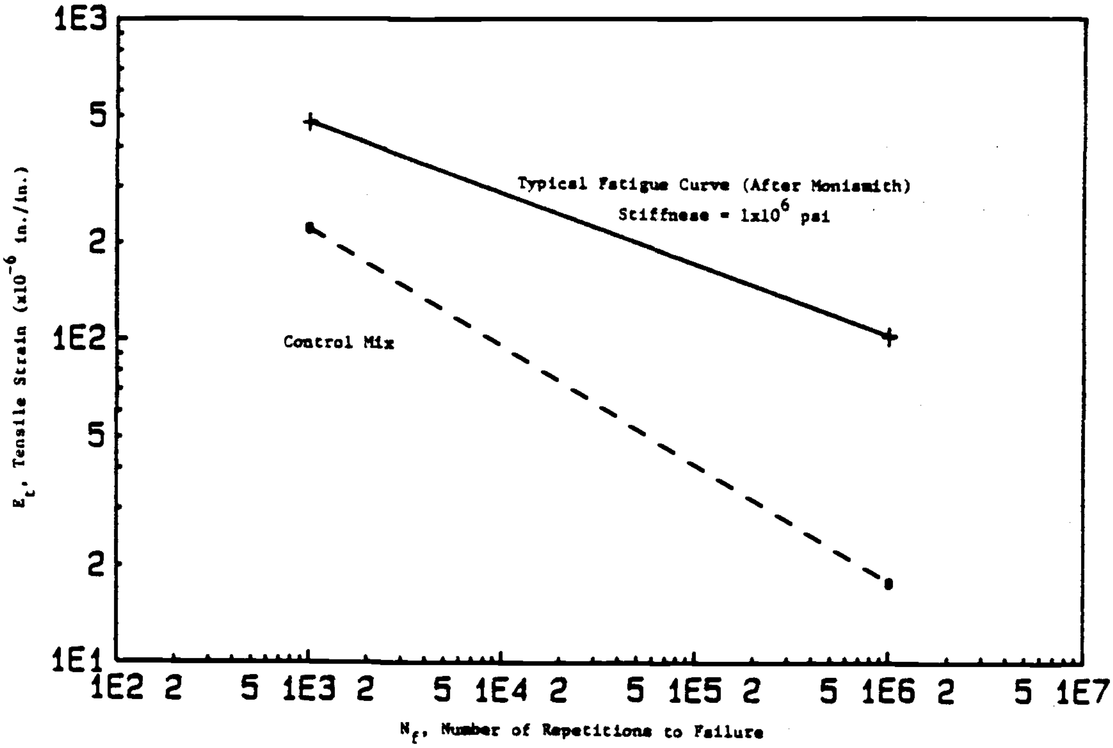
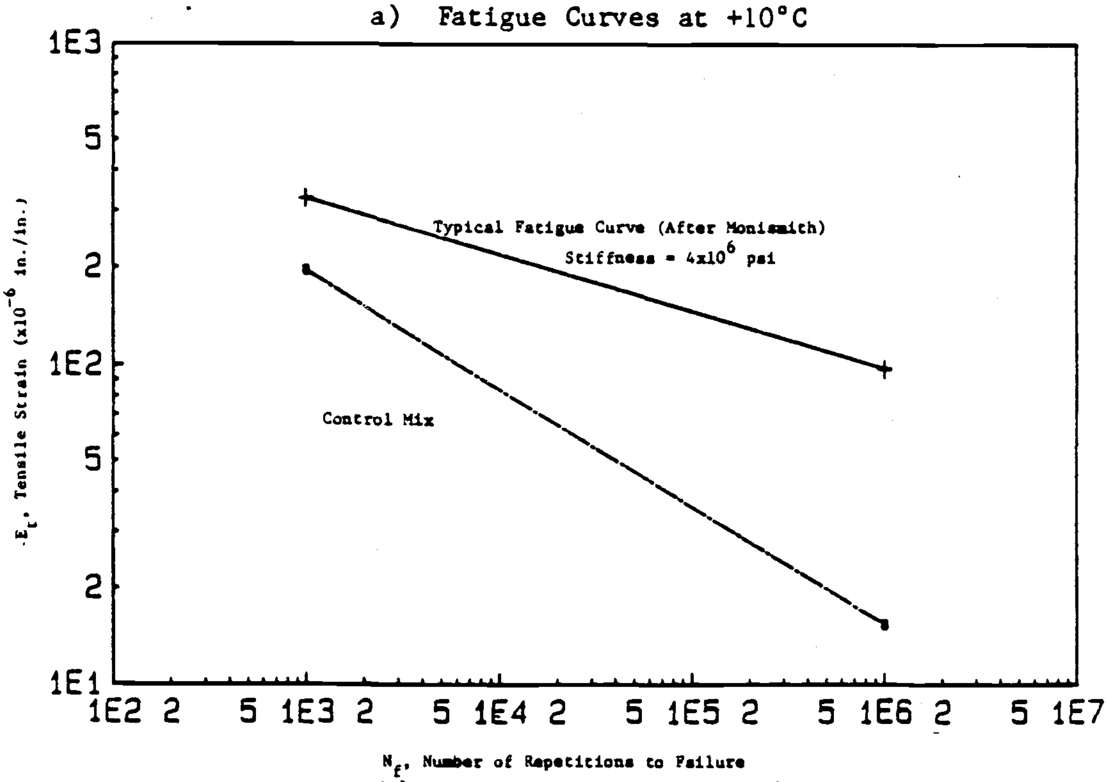


Figure 5.2. Flow Chart for Determination of Layer Equivalencies.



a) Fatigue Curves at +10°C



b) Fatigue Curves at -6°C

Figure 5.3. Comparison of Laboratory and Field Fatigue Curve.

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 (65). 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. The allowable tensile strain for conventional and rubber-modified mixes for each season was thereby determined. The allowable strains were used in 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).

Table 5.2. Summary of Data for Shift Factor Determination

Source of Data	Strain	Fatigue Life
	a) @ +10°C (E = $1x10^6$ psi)	
Yoder and Witzak (65)	100	1,000,000
	200	601,000
	400	2,000
Laboratory Data @ +10°C	85	12,997
	100	9,343
	159	2,826
	b) @ -6°C (E = $4x10^6$psi)	
Yoder and Witzak (65)	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, $_{ac}$, 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	Spring Thaw	3,000	2,000	320
4	AC	3,200,000	Spring Thaw	3,000	2,000	129
6	AC	3,200,000	Spring Thaw	3,000	2,000	69
2	AR	1,900,000	Spring Thaw	3,000	2,000	461
4	AR	1,900,000	Spring Thaw	3,000	2,000	197
6	AR	1,900,000	Spring Thaw	3,000	2,000	108
2	AC	1,100,000	Spring/Fall	15,000	10,000	348
4	AC	1,100,000	Spring/Fall	15,000	10,000	187
6	AC	1,100,000	Spring/Fall	15,000	10,000	118
2	AR	350,000	Spring Fall	15,000	10,000	591
4	AR	350,000	Spring/Fall	15,000	10,000	380
6	AR	350,000	Spring/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 (s)	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

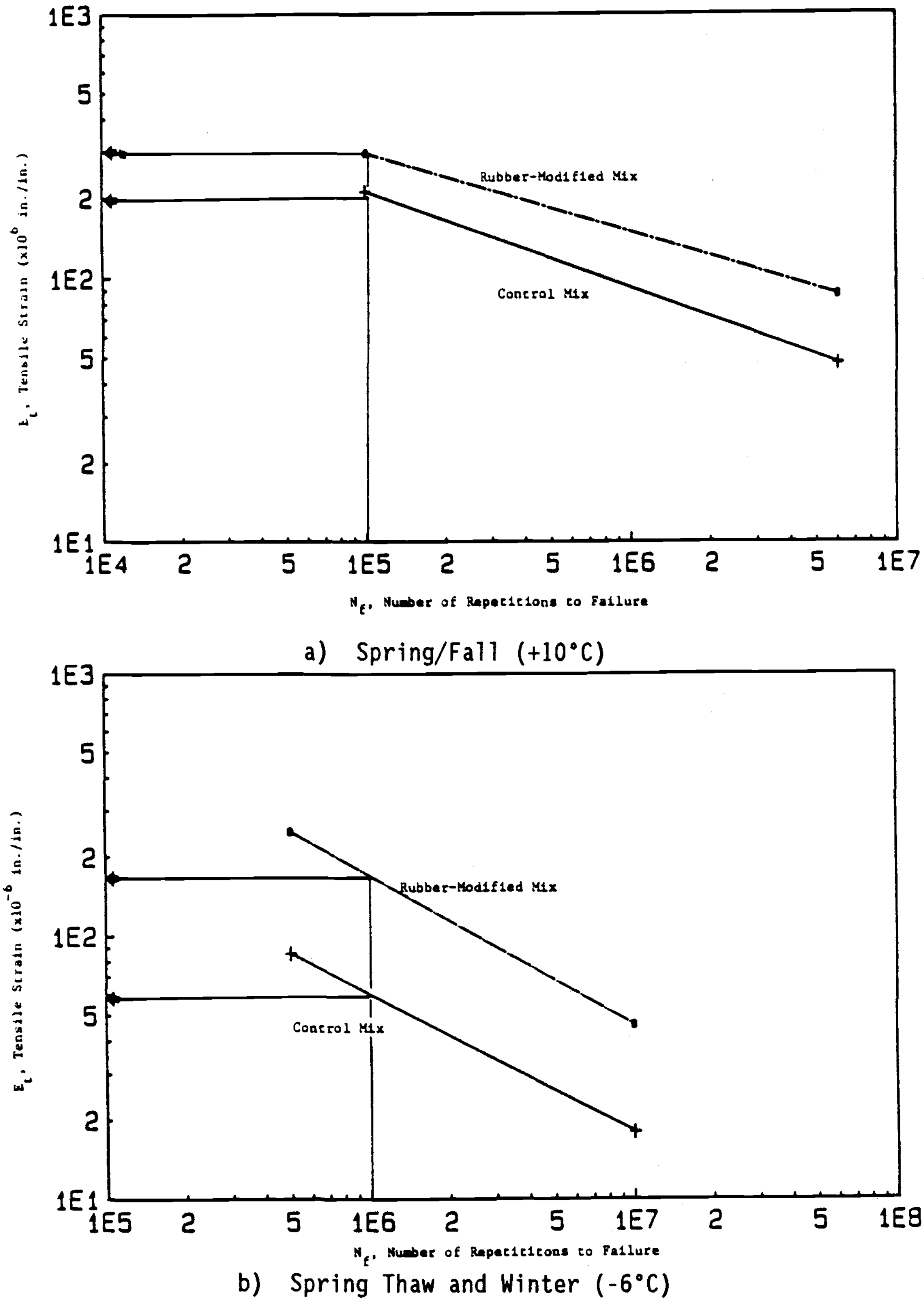
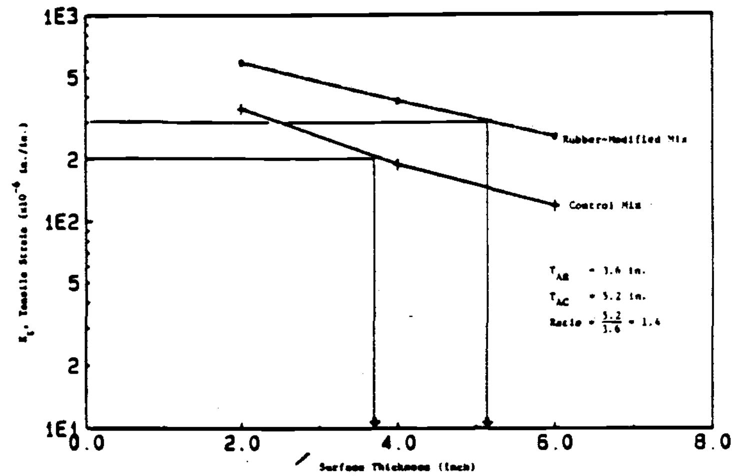
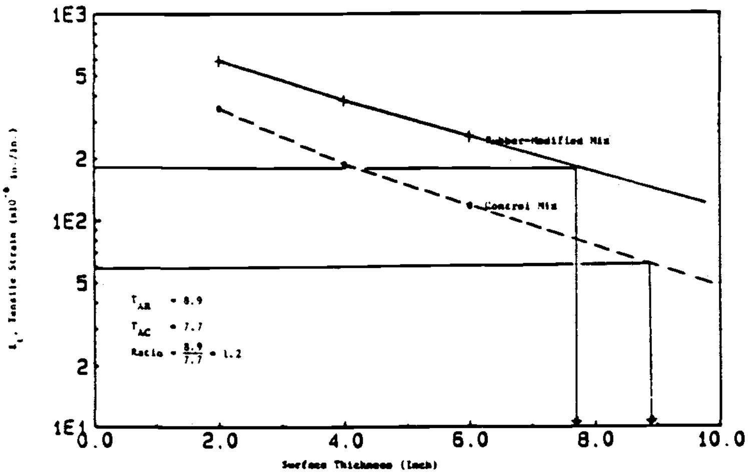


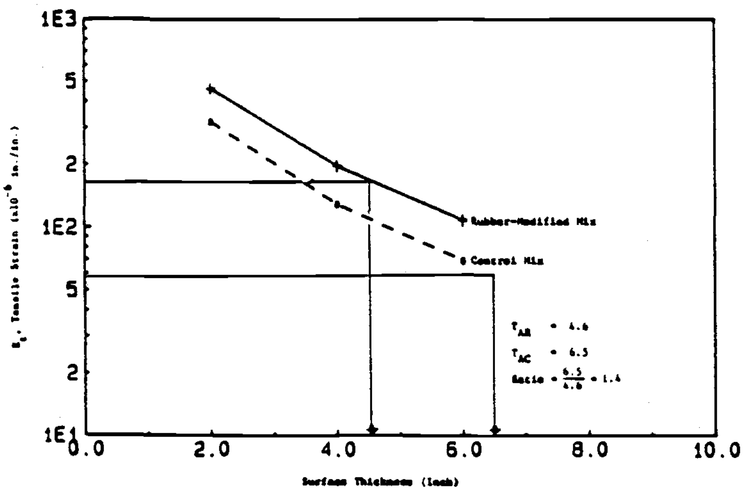
Figure 5.4. Shifted Laboratory Fatigue Curves



a) Spring/Fall



b) Spring Thaw



c) Winter

Figure 5.5. Required Thickness

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

The layer equivalency ratios correspond to an approximately 20- to 40-percent reduction in surface thickness versus that of conventional asphaltic concrete surface.

5.2 Material Costs

The purpose of this section is to identify the costs of rubber-modified asphalt pavements placed in various areas throughout Alaska and compare them with the costs of conventional forms 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 Alaska DOT & PF personnel from actual contract unit prices on project in Anchorage, Fairbanks, and Juneau areas (66). 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 (59). The quote used for rubber came directly from Rubber Granulators and was based on the equivalent price for an 80-percent coarse and 20-percent 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 PaveTech Corporation of Bellevue, Washington (34).

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 (68).

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

Component	Conventional Asphalt Cement Binder $/Ton	%	PlusRide[TM] Asphalt Rubber Binder $/Ton	%
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.

Component	Conventional Asphalt Cement Binder $/Ton	%	PlusRide™ Asphalt Rubber Binder $/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.

Component	Conventional Asphalt Cement Binder $/Ton	Conventional Asphalt Cement Binder %	PlusRide™ Asphalt Rubber Binder $/Ton	PlusRide™ Asphalt Rubber Binder %
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.

The component percentages for the PlusRide^{TM} 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 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 percent to 8.5 percent 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 percent 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 pavement 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 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 percent less than that of the conventional material. This means a ton of the asphalt-rubber material would cover about 8 percent 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.

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 pounds versus 10.5 cents per pound for coarse rubber (less than 4% passing the No. 20 screen). The price increase for a 3-percent 60/40 rubber blend mix versus 3-percent 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 Oregon State University 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 percent per ton ($19.13) for Alaska DOT & PF typical mix to 9.3 percent 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

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 8.5% 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.

	Conventional Asphalt Cement Binder		Rubber-Modified with 8.0% Asphalt Binder	
Component	$/Ton	%	$/Ton	%
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.

	Conventional Asphalt Cement Binder		Rubber-Modified with 7.0% Asphalt Binder	
Component	$/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 Mix, 80/20 Blend, 3% Rubber, Dense Aggregate Grading - Anchorage Area.

Component	Conventional Asphalt Cement Binder $/Ton	Conventional Asphalt Cement Binder %	Rubber-Modified with 7.5% Asphalt Binder $/Ton	Rubber-Modified with 7.5% Asphalt Binder %
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.

thicknesses to calculate the life required for equivalent annual costs. The second analysis method uses equal surfacing thicknesses of rubber-modified and conventional asphalt pavements 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 asphalt based on unequal thickness.

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 fifteen 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 percent,
2. crack seal maintenance cost = $0.10/yd^2,
3. chip seal maintenance cost = $0.40/yd^2,
4. conventional mix cost without 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 (66), and
9. unit weight = 142 pcf.

Table 5.13 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

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.

Table 5.13. Life Cycle Cost Comparisons with Equivalent Annual Costs (Cont'd.)

c) Alternatives 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.

a conventional mix. Table 5.13 includes a maintenance scenario that 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 that is assumed by the information 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, three), but the difference in time (t) increases with the use of typical curves. As t 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 use 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 by Alaska DOT & PF to reduce stopping distances in adverse conditions. This characteristic of the rubber-modified surfaces adds to roadway safety; therefore, 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 night-time visibility. The effect of these benefits of rubber-modified asphalt should be considered when comparing with conventional asphalt for the selecting of the best alternative.

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

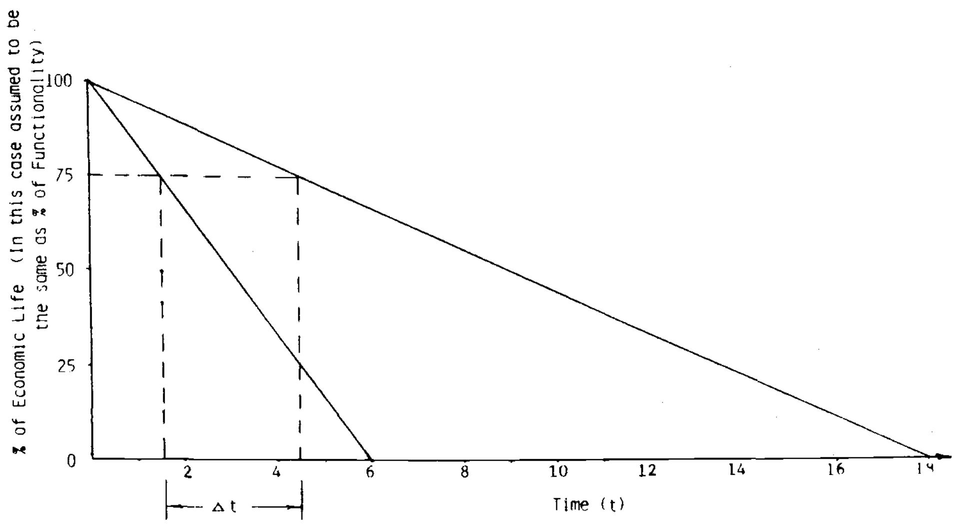


Figure 5.6. Straight Line Deterioration with Time.

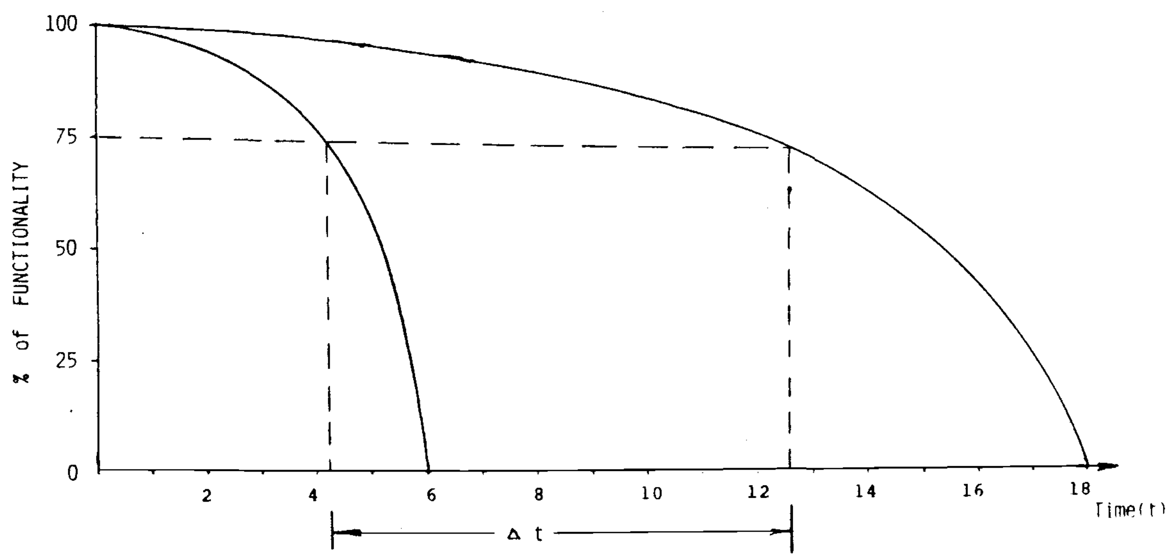


Figure 5.7. Typical Shapes for Pavement Deterioration Curves (40).

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 = $\frac{i(1+i)^n}{(1+i)^n-1}$

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

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

----

*X and Y must be in the same units.

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 percent, 4.0 percent, and 4.5 percent. The discount rate was based on the real cost of capital as used in 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 percent and 4.4 percent nationally (69).

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 H 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 inches and the expected fatigue life would be the same as a 3-inch 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

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 Costs				
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

Table 5.15. Capital Cost Comparison Considering Layer Equivalencies.

Surfacing Alternative	Capital 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

rubber-modified mixes would not be economically acceptable since the laboratory results show 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. A small increase in the capital cost may be justified if benefits, such as de-icing capabilities, reduced adverse-weather stopping distances, and 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 require a life-span of approximately 24 to 24 years to provide the same life cost as an equivalent thickness of conventional asphalt concrete 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-percent 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 percent. 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 in the United States Road Systems

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

5.4.1 Mix Design Guidelines

The mix design guidelines for pavements in hot, moderate and cold climates using rubber-asphalt mixture are presented in the following sections. The description of test methods for mix designs are provided in Appendix B.

5.4.1.1 Mix Design Guideline for Pavements in Hot Climates (Maximum Ambient Temperature Greater Than 100°F). For pavements in hot climates which are subjected to large numbers of heavy vehicles and/or vehicles operating at high tire pressures, rutting may be a controlling factor in mix design. Suggested steps in the design process to mitigate rutting are:

1. Use rubber-modified asphalt as an overlay layer, not a structural layer.
2. The minimum rubber-asphalt layer thickness should not be less than 1-3/4 inches nor greater than 2-1/2 inches.
3. Use AC-20 grade asphalt cement.
4. Use rough texture aggregate and PlusRide^{TM}8 aggregate gradation with maximum 9-percent #200 filler (Table 2.8).
5. Use 3-percent medium rubber (60% coarse/40% fine) (Table 3.6).
6. Mixing temperatures in the range of 350 to 375 °F and compaction temperatures of 300 to 330 °F are desirable.
7. Mix the rubber with aggregate before adding asphalt.
8. Cure the rubber-asphalt mixture before compaction in the oven (375-350 °F) for one hour.
9. A preliminary design asphalt content should be selected using the air voids. (NOTE: Mix should have an air void content of approximately 3 percent.)
10. Determine S_{mix} at short times of loading (0.1 S) for expected range in temperatures. Stiffness values in the range of 300,000 to 350,000 psi at 77°F and 0.1 sec loading time are desirable.
11. Perform creep tests on representative specimens to define S_{mix} a function of time at 25°C (77°F) and 40°C (100°F). Use 0.5 inches as criterion for rutting analysis.
12. If the analysis indicates that rutting is at an undesirable level for the expected conditions, the mix must be

redesigned and the analysis repeated. The use of fine rubber (0% coarse/100% fine) can be considered (Table 3.6).

13. If the mix is considered suitable, then its fatigue performance should be checked.

5.4.1.2 Mix Design Guidelines for Pavements in Moderate Climates (Maximum Ambient Temperature of 100°F). For pavements in moderate climates that are subjected to large numbers of heavy vehicles, fatigue may be a controlling factor in mix design. The following steps represent an approach that can be taken.

1. The minimum rubber-asphalt layer thickness should not be less than 1-3/4 inches nor greater than 3 inches.
2. Use AC-10 (AR-4000) grade asphalt cement.
3. Use gap-graded aggregate (PlusRide^{TM}12) (Table 2.8).
4. Use 3-percent coarse rubber (75% coarse/25% fine).
5. Mixing temperatures in the range of 320-350 °F and compaction temperatures of 300-320 °F are desirable.
7. A preliminary design asphalt content should be selected using the air voids. (NOTE: Mix should have an air void content of approximately 3 percent.)
6. Determine S_{mix} at short times of loading (0.1 S) for expected temperatures. Stiffness values in the range of 250,000 to 300,000 psi at 77°F and 0.1 loading time are desirable.
7. For expected traffic and temperature conditions, and for the anticipated range of stiffness characteristics of the other

rubber or aggregate gradations, perform a fatigue analysis using the procedure described in Appendix B.

5.4.1.3 Mix Design Guidelines for Pavement in Cold Climates (Minimum Ambient Temperature of 0°F). For cold climates, low temperature response will govern the initial selection of mix characteristics. The following steps are suggested for cold climates:

1. The minimum rubber-asphalt layer thickness should not be less than 2 inches.
2. The rubber-asphalt mixture can be used as an overlay as well as a structural layer.
3. The rubber-modified mixes have fatigue lives that range from two to seven 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 the cold climate design procedure.
4. Use AC-5 (AR-1000) grade asphalt cement.
5. Use gap-graded aggregate (PlusRide™12 or PlusRide™16) (Table 2.8).
6. Use 3 percent coarse rubber (80% coarse/20% fine) (Table 3.6).
7. Mixing temperatures in the range of 300-330 °F and compaction temperature of 265-300 °F are desirable.
8. A preliminary design asphalt content should be selected using the air void content. (NOTE: Mix should have an air void content of approximately 3 percent.)

9. Determine S mix at short times of loading (0.1 S) for expected range in temperatures. Stiffness values in the range of 180,000 to 230,000 psi at 77°F and 0.1 loading time are desirable.

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 Alaska DOT & PF. 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 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, based on results of this study, guidelines for use of rubber asphalt mixes in the United States road systems have been developed. These guidelines are in the form of suggestions of types of mixes to be used 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 the United States road systems. Based on the results of this study, the following conclusions appear warranted:

1. The 1984 and 1987 field survey indicated that most rubber-modified pavements placed to date have not failed due to fatigue or rutting. Where problems have been reported, they have generally been due to early raveling and are attributed to excessive voids resulting from poor compaction and/or low asphaltic content.
2. Rubber-modified asphalt mixtures are more susceptible than conventional mixtures to preparation and compaction problems when adverse weather or equipment problems occur. However, with adequate equipment and favorable weather conditions, the rubber-modified asphalt mixture placement is similar to conventional mixture placement.
3. The rubber-modified asphalt mixture wearing course has lower friction numbers compared to the conventional asphalt mixture course when tested during the summer periods. However, extensive measurements by Alaska DOT & PF showed an average

reduction in stopping distances of 20 percent for the rubber-modified pavements in icy conditions. These characteristics are best measured by testing under icy conditions.

4. De-icing benefits have been reported by several agencies (Minnesota DOT, City of Corvallis, and Alaska DOT & PF).
5. Deflection data indicate that the amount of surface deflection in the rubber-modified asphalt wearing course is not significantly different than that of the conventional wearing course.
6. The laboratory mix design results show that the asphalt content required 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-percent coarse rubber* required the highest design asphalt content (9.3%)*. The mixture with 3-percent coarse rubber* and dense aggregate grading required 7.5 percent*, and the conventional asphalt mix (no rubber) had the lowest design asphalt content (5.5%)*. The asphalt contents reported were for 2-percent air voids.
7. The resilient modulus for rubber mixes at +10°C and -6°C was generally higher for dense-graded aggregates than for gap-graded aggregates.
8. 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.

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*Based on dry aggregate weights.

9. The resilient modulus values for gap-graded and dense-graded aggregates increased at +10°C and -6°C as the rubber gradation became finer. The fatigue lives were reduced by about 20 percent as the rubber gradation got finer.
10. As the percent rubber by dry weight of aggregate increased from 2 to 3 percent, the modulus values generally decreased at +10°C and were unaffected by -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.
11. Gap-graded aggregate mixtures with a blend of 80 percent coarse and 20 percent fine rubber had the lowest modulus and highest fatigue life at both testing temperatures.
12. 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.
13. The effect of cure time after mixing on resilient modulus and fatigue life at both testing temperatures was not significant.
14. 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.

15. The fatigue life generally decreased as the air void content increased from 2 to 4 percent, regardless of the testing temperature. The resilient modulus values at both temperatures decreased as air voids increased, as would be expected.
16. The effect of temperature on resilient modulus appears to be linear within the range tested. As the temperature decreases, the resilient modulus increases.
17. 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 to -10°C were only 9 percent and 18 percent respectively.
18. The limited study of aging effects on resilient modulus showed a small increase of modulus with age when tested at +10°C.
19. The results of creep study indicate that the rubber asphalt mix with gap-graded aggregate and 3-percent coarse rubber (80% coarse/20% fine) have lowest stability at 40°C. However, the creep results at 25°C indicate all rubber asphalt mixes behave in the same manner.
20. The results of permanent deformation at 15°C indicate that the rubber-asphalt mix with gap-graded aggregate and coarse rubber has highest elasticity and the mix with no rubber has lowest elasticity characteristics.

21. 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. In view of the significant reductions in wintertime stopping distances under icy or frosty road surface conditions, the use of coarse rubber in asphalt pavements, such as in the PlusRide™ systems, should be seriously considered. This is particularly true for areas such as bridge decks, on and off freeway ramps or insulated roadway sections, which may occasionally result in slippery surfaces from differential surface icing.
2. 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.
3. Reduction of the 80:20 rubber content to 2 percent of dry aggregate and the use of a 60:40 blend of coarse rubber to fine rubber also shows promise and should be field tested. These changes could result in cost savings and less chance of early raveling.

4. 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.

6.3 Recommendations for Further Research

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

1. 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.
2. Quantify the de-icing and noise benefits of rubber-modified asphalt pavements.
3. Evaluate the application of rubber-modified asphalt for airport runways and taxiways.
4. Evaluate the construction procedure and cost of using a dense-graded aggregate with coarse rubber particles (80% coarse/20% fine).
5. Evaluate wetting agents for prevention of steel drum roller pick-up on rubber-modified asphalt mixes.
6. Evaluate the methods of introducing rubber particles to drum dryer plant.
7. Quantify user cost differences between rubber-modified and conventional asphalt pavements.

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APPENDICES

APPENDIX A

LIST OF PLUSRIDE^{TM} AND ARM-R-SHIELD^{TM} PROJECTS

APPENDIX A1

List of PlusRide^{TM} Projects (34)

TABLE A.1. PlusRide™ Hot Mix Projects

DATE	PROJECT	OWNER	CONTRACTOR	QUANTITY (TONS)
1979	Carnation Road	Alaska DOT & PF	---	90
1980	Old Seward Highway	Alaska DOT & PF	---	1,700
1981	Peger Road	Alaska DOT & PF	H&H Contractors	294
1981	Upper Huffman	Alaska DOT & PF	Central Paving	690
1981	Victoria Streets	City of Victoria, B.C.	Island Asphalt	1,522
1981	Tellico Plains, Tennessee	FHWA	Harrison Const. Co.	494
1982	Seiling, Oklahoma	Oklahoma DOT	Bruce Const. Co.	2,570
1981	Union Gap, Washington	Washington DOT	Yakima Asphalt	328
1981	Verdi, Nevada	Nevada DOT	Granite Const.	1,778
1982	B.C. Ferry Dock	B.C. Transportation	---	19
1982	Yakima River Bridge	Washington DOT	Yakima Asphalt	66
1982	110th Street	City of Bellevue, WA	Hi-Line Asphalt	200
1982	Auburn Interchange	Washington DOT	Lakeside Industries	465

(Continued)

TABLE A.1. PLUSRIDE™ HOT MIX PROJECTS (Cont'd.)

DATE	PROJECT	OWNER	CONTRACTOR	QUANTITY (TONS)
1982	St. Patrick Street	S.D. DOT	James E. Simon Co.	441
1983	Mt. St. Helens, WA	FHWA	Morrill Asphalt	2,570
1983	Lemon Road	Alaska DOT & PF	Associated S&G	2,279
1983	JFK Bridge	Ports and NY and NJ	Edenwald Contracting Co.	60
1983	MacDonald Pass	Montana Highway Dept.	American Asphalt	2,919
1983	Susanville	Caltrans	Frank W. Pozar	7,263
1983	Bellevue Streets	City of Bellevue	Watson Asphalt	795
1984	Route 41	New Jersey DOT	Trap Rock Industries	605
1984	Bellevue Streets	City of Bellevue	Watson Asphalt	2,724
1984	Strawberry	Utah DOT	Staker Paving	3,839
1984	St. Cloud	Minnesota DOT	Baverly Brothers	854
1984	Forest Lake	Minnesota DOT	Ashbach Construction	752
1984	Chama	New Mexico DOT	T. Brown Construction	9,775

(Continued)

TABLE A.1. PLUSRIDE™ HOT MIX PROJECTS

DATE	PROJECT	OWNER	CONTRACTOR	QUANTITY (TONS)
1984	"S" Curve	Washington DOT	Hi-Line Asphalt	334
1985	Lava Butte	Oregon DOT	R.L. Coats Const.	656
1985	Edson, Alberta	Alberta Transportation	PCL Road Const.	594
1985	A.C. Couplet	Alaska DOT & PF	Central Paving	3,205
1985	Richardson Highway	Alaska DOT & PF	Rogers & Babler	1,398
1985	New Seward Highway	Alaska DOT & PF	Wilder Const.	1,384
1985	Fauntleroy Ferry Terminal	Washington DOT	M.A. Segale, Inc.	561
1985	Arizona 260	Arizona DOT	Corn Const.	2,240
1985	Dahlgren Road	Washington DOT	Associated S&G	651
1985	Lamar Airport	City of Lamar	McAtee-Renquist Paving	610
1985	Peterson AFB	U.S. Air Force	Broderick & Gibbons	955
1985	Rawlins Airport	City of Rawlins	McMurry Brothers	5,619
1985	Des Moines	Iowa DOT	Grimes Asphalt	460

(Continued)

TABLE A.1. PLUSRIDE™ HOT MIX PROJECTS

DATE	PROJECT	OWNER	CONTRACTOR	QUANTITY (TONS)
1986	Airport Way, AK	Alaska DOT	---	14,114
1986	A/C Couplett, AK	Alaska DOT	---	1,829
1986	Monte Vista, CO	---	---	2,409
1986	Aurora, CO	---	---	450
1986	Arvada, CO	---	---	1,195
1986	Sand Point Way, WA	Washington DOT	---	1,274
1986	Bellevue, WA	City of Bellevue	---	4,086
1986	Brockton, MA	---	---	3,052
1986	Corvallis, OR	City of Corvallis	Morse Brothers Inc.	646
1986	Boulder Airport, CO (in progress)	---	---	
1986	Regina Hwy., Canada	---	---	1,000
1985	Northgate P&R Lot	Seattle Metro	Hi-Line Asphalt	296
1985	Highway 87, Mesa	Arizona DOT	Industrial Asphalt	1,685
1986	Minn Ave. Exit, AK	Alaska DOT	---	6,065

APPENDIX A2

List of Arm-R-Shield^{TM} Projects (51)

TABLE A.2

Arm-R-Shield™ Hot Mix Projects (Supplied by ARCO)

DATE	AGENCY	PROJECT/LOCATION	TONS OF BINDER
April, 1980	Arizona DOT	Mesa-Payson Highway	91
August, 1980	Caltrans	Route 80, Lake Tahoe	75
June, 1981	Caltrans	Route 50, Echo Summit, CA	761
Nov., 1981	City of St. George FAA	St. George Airport	133
May, 1982	City of Kanab, Utah FAA	Kanab Airport	11
June, 1982	Caltrans	I-80, Truckee, CA	83
June, 1982	Caltrans	Donner Pass, CA (continue job #8143)	149
July, 1982	Oklahoma DOT	U.S. 270, Seiling, OK (Woodward County)	221
July, 1982	Rock Springs, WY FAA	Rock Springs Airport	220
Sept., 1983	Caltrans	U.S. Route 395, Ravendale, CA	839
May, 1984	Caltrans	I-80, Placer City, CA	819
June, 1984	Salt Lake City, UT FAA	Salt Lake City Airport #2	501
August, 1984	Oregon DOT	Route 367, Linn County, Oregon	188
Oct., 1984	Minnesota DOT	Meeker County	252
August, 1985	Oregon DOT	Deschute & Klamath Counties	78
August, 1984	Illinois DOT	Route 5 Tollway, Aurora, Illinois	426
Sept., 1985	FHWA	Lake Cresent, Vancouver, Washington	30

APPENDIX B

EVALUATION OF CURRENT MIX DESIGN PROCEDURES

APPENDIX B

Evaluation of Current Mix Design Procedures

The purpose of this appendix is to evaluate the strength and weaknesses of present mix design procedures.

1.0 Evaluation of Current Mix Design Procedures

Many state highway agencies have experienced a number of problems with their asphalt concrete pavements over the past 15 years. These reportedly include:

1. raveling
2. tenderness
3. rutting
4. bleeding
5. segregation, and
6. low compaction.

The causes of these problems have generally been attributed to one or more of the following:

1. mix design
2. construction practices
3. asphalt cement, and
4. aggregate grading and quality.

The objective of this appendix is to develop a new mix design procedure for rubber-modified asphalt concrete mixes. Specifically, the objectives are:

1. Identify the strengths and weaknesses of present mix design techniques;

2. Develop an improved asphalt mix design;
3. Use improved material selection and mix requirement;
4. Develop design framework for an improved asphalt mix design.

1.1 Current Practices

The objective of asphalt paving mix design is to determine an economical blend and gradation of aggregates and asphalt to achieve those requirements of a mixture needed for it to fulfill its intended function. The design of asphalt-aggregate mixtures follows prescribed steps:

1. select type and grading of aggregates,
2. select type and grade and amount of asphalt.

This approach is applicable whether the engineer is designing seal coats and surface treatments, asphalt concrete (hot and cold mixes., and modified asphalt concrete (rubber and polymer., both new and recycled. The methods used in asphalt mix design can be categorized in three major areas:

1. preliminary tests on aggregates,
2. mixing and compaction techniques, and
3. tests on compacted samples.

Test of Aggregates. Most highway agencies are following the American Association of State Highway and Transportation Officials (AASHTO) recommendations for testing the specific gravity and absorption of aggregates (T-84, T-85). Some agencies such as CALTRANS and FHWA use AASHTO T-270 (Centrifuge Kerosene Equivalent Test) for preliminary determination of asphalt content (72).

Sample Preparation. Although each agency uses the Marshall or Hveem method of sample preparation, the mixing and compaction methodology specified by each agency varies. For example, ODOT, FHWA and CALTRANs closely follow the recommended procedures of AASHTO T-246 and T-247. WSDOT uses different mixing and compaction temperatures as well as compactive effort. Efforts should be made towards the adoption of more uniform procedures of preparing specimens.

Mix Tests. The tests performed on the compacted samples vary from agency to agency, with each laboratory facility emphasizing different tests in its design procedure. The stability test is considered to be the most important test in the determination of optimum asphalt content; however, there are definite differences in procedures used.

Mix Design Criteria. The criteria used in the determination of the optimum asphalt content vary from agency to agency. The two test results used by all agencies are the stabilometer and percentage of air voids. Although each agency uses these results, the minimum values required vary. This is obviously the result of differences in compaction equipment and test procedures.

1.2 Strengths and Weaknesses of Present Mix Design Techniques

Two of the most widely used mixture design methods are the Hveem stabilometer and the Marshall methods. At the present time (1987), 38 states are using the Marshall method, ten states are using the Hveem method, one state is using the Texas method, and one state is using the mix design method based on aggregate gradation, as shown in the map (Figure B.1). These procedures have been adopted by a number of

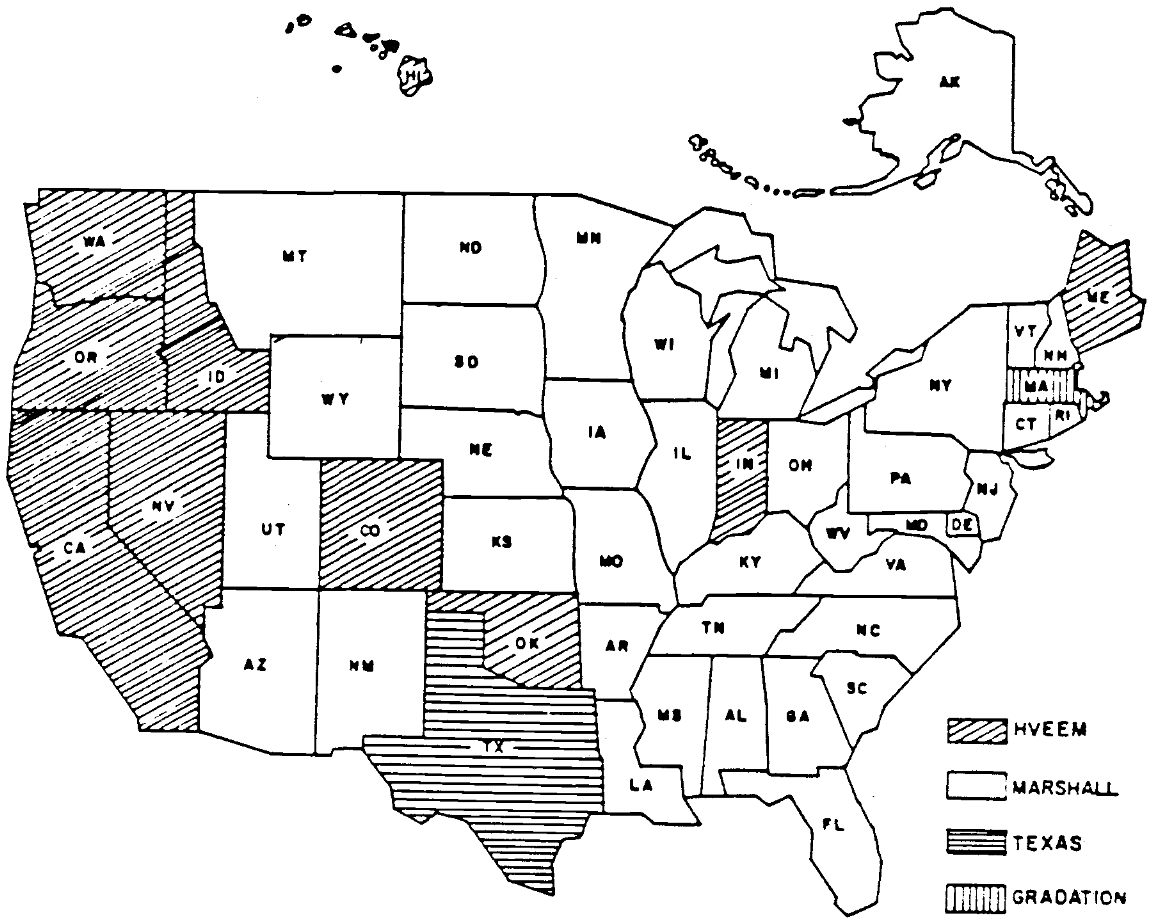

Figure B.1. Mix design methods used (77).

highway agencies around the world and modified to suit specific local requirements. One such adaptation is that recommended by The Asphalt Institute. These methods have become widespread in use. However, because of some difficulties encountered with performance of mixes designed according to these procedures, a number of investigators have begun to identify the weaknesses of the current procedures. Also, they have begun to look to other test procedures to either supplement or to replace a current procedure. In this section the weaknesses and strengths of these procedures are discussed.

Both of these procedures are empirical methods. Empirical methods are correlated with performance under certain field conditions and with certain procedures in the laboratory. As soon as the conditions or the procedure is varied, the correlation is no longer valid and recorrelation must be done. Therefore, every government or private laboratory that changes the procedure must recorrelate to its conditions. It is highly unlikely, with an empirical procedure such as either the Marshall or the Hveem, that one method will ever be used universally with the same empirical correlation. In the Hveen method, for example, the state of Washington changed the kneading compaction pressure from 500 to 350 psi and developed its own correlation. As mentioned above, the criteria for current mix design procedure was developed under certain conditions. For instance, either 50-blow criteria compaction or the 75-blow compaction may be adequate. However, fifty-blow criteria has been developed for 500 to 1400 passes of vehicles across a point on the pavement. This indicates the magnitude of the difference and is one of the weaknesses of the empirical method.

The other weakness of the current procedures is the validity of the various test methods in producing results indicative of the response of asphalt/aggregate paving mixtures to vehicular traffic loadings. The results obtained in the 1978 mix exchange which was carried out in 22 Canadian laboratories and is reported in the proceedings of the C.T.A.A., Volume SSV, November 1980, shows the average asphalt content recommended by 22 laboratories was 5.88 percent with a standard deviation of 0.35 percent, and varied from 5.3 to 6.7 percent. This wide variation is another example of the weakness of the current mix design methods.

The current procedures (Marshall and Hveem) are useful, especially to identify very stable or very unstable mixes. Apart from screening out these two extremes, highway agencies' experiences have shown that these methods do not provide a safety factor in terms of asphalt deformation, raveling, bleeding, etc., for average mixes. Also these methods have become widespread because of relative simplicity and low cost as well as over 40 years of research and experience that were invested to improve them. Also, the National Bureau of Standards through the AASHTO Materials Reference Lab (AMRL) has, in 1984, initiated a Marshall correlation program with standard mixes that is being sent to the various states and other laboratories that are participating in the program. In this way, standardization of some of the laboratories and their test procedures for asphalt mix design will occur. Therefore, the advantages of these methods are low cost, widespread use, and an investment of over 40 years of research and experience.

In summary, since the current procedures are empirical and rely on previous experience in the use of certain materials, the use of new and lower quality materials such as rubber-modified asphalt and recycled mixes may exceed the scope of this previous experience. Therefore, it may be necessary to supplement an existing design procedure with additional tests. However, what is needed are test methods and procedures which will eliminate empiricism and will give fundamental properties that can be applied to any conditions encountered.

APPENDIX C

CASE HISTORIES

APPENDIX C

Case Histories

To aid in developing guidelines for use of rubber-modified asphalt in cold regions, the information on the design, construction, and performance of rubber modified asphalt (PlusRide^{TM}) pavements constructed in the states of Alaska, Minnesota, and Washington are summarized.

1.0 Minnesota Department of Transportation (70)

One of the Minnesota DOT priorities is to reduce the amount of chemicals used for ice and snow control without reducing the level of service. The rubber-modified pavement was selected for experiment as an alternative method to control the accumulation of ice on Minnesota roadway surfaces.

Two construction projects were selected as sites for the evaluation of rubber-modified asphalt (PlusRide^{TM}). Both test projects are four-lane divided highways and have a two-way average daily traffic of 10,000 with 17 percent being truck traffic. These projects were constructed during the month of September, 1984 and are approximately 0.7 of a mile in length.

Preconstruction Evaluation. The job mix formula for both projects are summarized in Table C.1. Tests were conducted to determine the diametral modulus of the Marshall compacted specimens. The testing was performed using a test machine manufactured by Materials Testing System (MTS). At room temperature, the resilient modulus value was found to be between 126,000 and 188,000 psi. Typical

Table C.1. Job Mix Formula for Minnesota Experimental Projects (70).

Project No.	Aggregate Sieve Size	Aggregate Formula % passing	Aggregate Working Range % passing	Rubber Sieve Size	Rubber Formula % passing	Rubber Working Range % passing	Asphalt Cement % of Total Mixture (120/150 pen)	Granulated Rubber %	Density Results (pcf)
(1)	5/8 in.	100	100-100	1/4 in.	100	100	7.5 ± .3	3.0 ± .15	•Maximum theoretical 146
	3/8 in.	78	70-80	No. 4	99	76-100			•Marshall Density 143.4
	No. 4	36	30-40						•Target Density 138.7 to 143.1
	No. 10	29	25-32	No. 10	37	28-42			
	No. 30	21	17-25	No. 20	19	16-24			
	No. 200	9*	8-11						
(2)	5/8 in.	100	100-100	1/4 in.	100	100	7.8 ± .3	3.0 ± .15	•Maximum Theoretical 145.1
	3/8 in.	76	70-80	No. 4	99	76-100			•Marshall 142.4
	No. 4	32	30-38						•Target Density 137.9-142.2
	No. 10	26	22-30						
	No. 30	20	16-24						
	No. 200	--	8-12	No. 20	19	16-24			

*5% Mineral filler added.

conventional bituminous mixtures tested with the same procedure show a general range of resilient modulus values between 250,000 and 600,000 psi withsome samples with higher values.

Construction. Both test sections were completed during September 1984. Project No. 1 is an overlay on an existing bituminous overlay on a PCC concrete pavement. The thickness of the rubber modified asphalt mixture (PlusRide^{TM}) is 1-1/4", which was placed over a 1" leveling course. The construction of the project No. 2 consisted of milling the existing bituminous pavement to a depth of 2-3/4", and then resurfacing with 1-1/2" of asphalt concrete leveling course and 1-1/2" of rubber-modified asphalt mixture (PlusRide^{TM}).

Dryer drum asphalt mixing plants were used on both projects. The granulated rubber material was added to the mixture at the center of the drum where salvaged materials are commonly added. After mixing, the granulated rubber, aggregate and asphalt cement were separated using vacuum extraction procedures. The test results indicate that some of the fine rubber particles may have been lost during production. It is not known if the loss of rubber material was due to the production process, absorption into the asphalt cement, or from the testing procedures.

Field compaction consisted of rolling the mixture with vibratory steel drum rollers. The same paving equipment was used to place the rubber modified mixture as paved the conventional mixture. On both projects roller pickup was a problem. Density of the compacted mixture was measured using nuclear density tests. The density test results show that the nuclear test values are lower than the values obtained from roadway core samples. This indicates a need for a correction factor on the rubber-modified asphalt (PlusRide^{TM}) mixture. Field cores show that this correction is as much as four pounds per cubic foot. The core samples were also tested for their modulus values (diametral method), and the results were similar to the values determined during trial mix testing. The resilient modulus values varied from 114,000 to 121,000 psi (70).

Post Construction Evaluation. After construction of the rubber-modified test sections was completed, friction, roughness, noise, and deflection measurements were taken on the projects. The lock-wheel pavement friction test (ASTM E-274) at 40 mph was utilized to determine friction numbers. The test results show that the skid numbers for rubber-modified asphalt test sections were lower than those on the conventional sections.

The Mays meter mounted in a car was utilized to obtain serviceability ratings of the surface roughness on both projects. The tests were conducted only in the driving lane and run at 50 mph. A section of conventional mixture as well as the rubber modified asphalt mixture was measured. The rubber-modified asphalt mixture had a slightly lower serviceability rating on both projects.

The model 8000 Dynatest Falling Weight Deflectometer was used to gather surface deflection data on both projects. The testing was done to determine the amount of increase in surface deflection, if any, because of the use of rubber granules. The deflection at the center of the load was used to compare the deflection before and after application of the rubber-modified asphalt and the conventional mixtures. The measurements indicate that the difference in deflection between the rubber-modified mixture section and the conventional mixture section was small.

The noise unit of MN/DOT conducted tests on the amount of tire noise generated from the rubber-modified asphalt mixture surface versus the conventional asphalt mixture surface on both projects. Both surfaces were approximately one month old at the time of first testing. The results indicated that there was no significant difference in noise level between the two test sections.

The raveling occurred in the passing lane which was the first lane constructed in the project No. 1. However, the latest condition survey conducted in 1986, on Project No. 2 indicates that this project is in good condition and no raveling has occurred. Therefore, the condition survey results show that, when placement problems occur, there is a high probability of surface raveling; otherwise, there is not.

To evaluate the ability of the rubber-modified asphalt wearing course to reduce the amount of snow and/or ice adhering to its surface, the test sections were observed during occurrences of snow and ice. These observations were conducted during the winter of 1984-1985 and the winter of 1985-1986. The results of observations indicate that the rubber-modified test section performed better than the conventional pavement section on some occurrences of compacted snow or ice. Field inspectors also noted that the rubber-modified asphalt test section appears to absorb more solar energy which causes the snow to melt faster. The evaluators indicated only a marginal improvement in most cases.

2.0 FHWA-Western District Federal Division (71)

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^{TM}) of various thicknesses (1-3/4", 2-1/2", and 3-1/2") placed to determine the deicing effect and compare the fatigue life of rubber-modified asphalt (PlusRide^{TM}) section with an adjacent conventional pavement section.

This test section was expected to receive heavy log hauling due to planned sales of timber blown down during the May 18, 1980 eruption of Mt. St. Helens. This traffic was to have helped define the fatigue life of PlusRide^{TM} within three years; however, delays prevented construction until after the majority of timber had been removed.

Preconstruction Evaluation. The job mix formulas for both the rubber-modified and conventional mixes are given in Table C.2. Tests were conducted to determine the resilient moduli of the Marshall compacted specimens. All tests were run using the diametral test at 23°C (load, 0.1 sec., 20 per minute) results. The resilient modulus values were found to be lower than conventional bituminous mixtures tested with the same test procedure.

Construction. The construction of the rubber-modified asphalt pavement took place in the latter part of August 1983. The total rubber-modified pavement placed during the four days was 2569 tons.

A drum-type plant was used on this project. The rubber was added to the drum mixer by means of a conveyor. The conveyor was supplied from a bin filled by two workers who "broke" open the

Table C.2. Job Mix Formula for FHWA Experimental Projects (71).

Type of Mix	Aggregate			Rubber			Asphalt Cement % by weight of total mixture (AR 4000 W)	Granulated Rubber % by weight of total mixture	Air Voids %
	Sieve Size	Formula % passing	Working Range % passing	Sieve Size	Formula % passing	Working Range % passing			
Rubber	3/4 in.	100	---	1/4 in.	100	100	7.8	3.0	3.7 ± 0.1
Modified	5/8 in.	94	100-100	No. 4	90	76-92			
Mix	1/2 in.	74	---						
(PlusRide[TM])	3/8 in.	---	70-80	No. 10	35	28-36			
	1/4 in.	37	---						
	No. 4	34	30-40	No. 20	18	10-24			
	No. 8	---							
	No. 10	24	25-32					(coarse 2.3%)	
	No. 40	14	---					(fine 0.7%)	
	No. 200	8	8-11						
Conventional	3/4 in.	100	---				5.5	0.0	3.7 ± 0.1
Mix	5/8 in.	94	100-100						
	1/2 in.	---	---						
	3/8 in.	84	70-80						
	1/4 in.	---	---						
	No. 4	---	---						
	No. 8	38	30-40						
	No. 10	---	25-32						
	No. 40	14	---						
	No. 200	6	8-11						

granulated rubber bags. Also, mix temperature of the rubber asphalt mixture was approximately 340°F.

The rubber-modified asphalt was placed using conventional paving equipment. Two Tampo vibrating steel wheel rollers were used for compaction. The mixture was hauled approximately six miles from the plant in seven end dump trucks. Density of the in-place mix was determined using a Campbell nuclear field density guage. The following average densities were established:

Mix Thickness (in.)	Average % Compaction	Target Density, PCF
1-3/4	97.8	147.6
2-1/2	97.8	147.6
3-1/2	95.2	147.6

Aside from the problems with variations in aggregate gradation and its effect on resulting asphalt content to be used, the construction process was without major problems. However, the rubber asphalt mixture, because of its extremely "sticky" nature, precluded the use of pneumatic compactors.

Post Construction Evaluation. Laboratory tests were conducted on cores obtained by the Federal Highway Administration - Western District Federal Division (FHWA-WDFD). Coring took place shortly after construction in September 1983 and subsequently in November 1984, July 1985, and June 1986. Cores were secured from both the rubber-modified and adjacent conventional mix overlays. Testing of the cores was performed at Oregon State University. The results of tests conducted on these samples are presented below.

The diametral resilient modulus tests were performed using ASTM-D4123 at 22.5 ± 1°C. The diametral resilient modulus test shows both materials (rubber asphalt and conventional mixes) to be increasing in stiffness with time. The rate of increase is decreasing for both materials, with the rubber-modified material showing a slightly greater overall increase compared to the control mixture. It should, however, be noted that the rubber-modified mixture is considerably more flexible, as determined by modulus testing, than the conventional mixture. Also, the diametral fatigue test results indicate the rubber asphalt mixture cores were subjected to higher strain levels so that failure would occur in a reasonable length of time.

Hveem stabilometer tests were performed using ASTM-D1560. Stabilometer testing shows the control mix to be more stable; however, the test was not designed for rubber-modified materials. The low (unacceptable) values do not necessarily mean the material should be rejected as an acceptable surfacing. Furthermore, field surveys to date (February 1987) show no rutting apparent in either mix after 402,636 EALS. Additionally, the control mixture stability has increased with time whereas the stability of the rubber-modified material has remained constant.

Tensile strength was measured at 22.5°C using an MTS electro-hydraulic testing device. The test results show the control mix to have greater strength when tested at high deformations. Apparently, the high deformation rate limits the increased cohesion of the rubber-modified material from coming into action, thus indicating low strength.

Deflection measurements were taken using Road Rater equipment in September 1983 and June 1986. The tests results show there was very little difference in deflection between the various test sections in

September 1983 or in June 1986. This could indicate that all the sections are currently providing about the same structural capacity.

Roughness data were obtained for rubber asphalt test sections in February 1984 and August 1986. Roughness measurements were also taken on adjacent conventional mixture. Comparison of the February 1984 Mays ride meter data shows the rubber-modified section to be slightly rougher than the control. The data obtained in August 1986 indicate the roughness to be about the same for both material types.

The K.J. Law Friction tester (ASTM E-274) was utilized in July 1984 and August 1986 to determine friction numbers at 40 mph. The test results show the control mix has slightly better friction properties than the rubber-modified section in both test cases. However, macro-testure testing indicates the rubber-modified material to have better texture characteristics. This feature should allow shorter stopping distances by draining the surface.

An attempt was made to evaluate the de-icing characteristics of the rubber-modified asphalt through site visits by Forest Service and FHWA personnel. The results of these visits are not conclusive because of lack of ice at the time of the visits.

Visual condition surveys to determine the presence of cracking, raveling, or rutting were conducted in November 1983, March 1984, June 1985, and June 1986. Both surfaces were found to be in good condition.

3.0 Alaska Department of Transportation (35).

The Alaska Department of Transportation and Public Facilities has installed twelve experimental pavement sections totaling 34.11

lane-miles in Fairbanks, Anchorage, and Juneau between 1979 and 1986, utilizing different pavement mixtures to analyze the benefits of rubber-asphalt pavements.

Preconstruction Evaluation. The job mix formula for both the rubber-modified and conventional mixes are given in Table C.3. Tests were conducted to determine the resilient modulus of the Marshall compacted specimens. Also, the specimens with different contents of coarse and fine rubber and aggregate gradations were tested for fatigue.

Construction. The most common problem with project batching of acceptable rubber-modified asphalt mixes has been in achieving the proper gap in the grading curve, and obtaining sufficient fines (No. 200) to serve as a void filler. Both problems may come from contractor inexperience in producing aggregate to the unusual gradation requirements. In the preparation of rubber-modified asphalt mix, use of a "batch" plant is preferred because the required quantities of rubber, asphalt, and aggregates can be exactly measured and added separately to the "pugmill" or mixing chamber. However, both continuous mix and drum-dryer mix asphalt paving plants have been used without difficulty. Mixing temperatures and asphalt grades used have been similar to those for normal paving mixes.

Post Construction. Results of all stopping distance tests made on the Fairbanks area rubber-modified sections from 1980 to 1983 are shown by Table C.4. Test results for this test series, performed under icy road conditions with some roadway sand occasionally present, indicate an average reduction of 25 percent in stopping distance is achieved from the use of rubber in the paving mix. By comparison,

Table C.3. Job Mix Formula for Alaska Experimental Projects.

Project:	Carnation 1979	Seward Highway 1980	Peger 1981	Huffman 1981	Lemon Road 1983	Richardson Hiway 1985	New Seward Hiway 1985	A. St.-Anchorage 13th to Firewood Drive 1985	C. St.-Anchorage 15th to Firewood, Drive 1985	O'Malley Rd. Anchorage 1986	Minn. Ext. Anchorage 1986	Airport Rd. Fairbanks 1986
SIEVE SIZES:												
3/4"	100	100	100	---	---	---	100	100	100	100	100	---
5/8"	---	---	---	---	100	100	---	---	---	---	---	100
1/2"	---	78-94	---	---	---	---	---	---	---	---	---	---
3/8"	60-77	43-57	53-67	100	62-76	64-76	50-62	50-62	50-62	50-62	50-62	61-73
1/4"	---	---	---	---	32-42	30-44	30-44	30-44	30-44	30-44	30-44	30-40
# 4	45-59	29-43	28-42	47-60	---	49-63	---	---	---	---	---	---
#10	29-41	22-34	20-32	30-42	22-32	19-32	21-29	20-32	20-32	22-30	20-30	20-26
#30	12-20	15-23	14-22	15-24	20-25	13-25	16-23	12-23	12-23	13-21	13-21	13-21
#200	4-10	5-22	5-11	5-11	8-12	8-12	7-11	7-11	7-11	7-11	7-11	8-11
ASPHALT												
(% Total Mix)	7.0-8.0	6.1-7.1	7.0-9.0	9.0-10.0	8.1-9.1	7.0-8.0	7.3-8.1	7.0-8.0	7.1-7.9	7.1-7.9	7.1-7.9	7.0-8.0
Rubber (%) % specified of total mix	3.0-3.5	3.0-3.5 & 4.0	3.0	3.0	3.0	3.0	2.5	2.5	2.5	2.5	2.5	3.0
Asphalt Type	AC-5	AC-5	AC-2.5	AC-5	AC-5	AC-2.5	AC-5	AC-5	AC-5	AC-5	AC-5	AC-2.5
Thickness (Avg.)	2.25"	1.50"	1.70"	.75"	1.50"	2.0"	1.75"	2.0"	2.0"	1.50"	2.0"	1.50"
Base	2" AC	3" AC	Gravel	1-1/2" AC	7" ATB	8" DI Base	2" AC	3" ATB	3" ATB	2" AC & 3" ATB	2" AC & 3" ATB	1.5" AC
Length of Paving Lane - Ft.	212'	6,792'	649'	5,330'	5,075'	5,597'	10,243'	12,322'	9,610'	5,808;	22,176'	78,144'
MIX PROPERTIES:												
Marshall Stability	320 lbs	440 lbs	270 lbs	370 lbs	820 lbs	350 lbs	800 lbs	870 lbs	870 lbs	870 lbs	870 lbs	330 lbs
@ % Asphalt	@7.5%	@7.0%	@8.5%	@8.5%	@8.6%	@7.5%	@7.7%	@7.5%	@7.5%	@7.5%	@7.5%	@7.5%
% Voids	3.0	2.3	1.7	3.0	1.1	2.1	1.8	1.4	1.4	1.1	1.1	1.8
CONDITION-1987:	Good condition	Overlayed 1982	Seal coated 1986	Good condition	Good condition minor pot-holes at one intersection	Very good condition	Very good, 1 thermal crack in 1/2 mile after 2 winters	Very good condition	Very good condition	Minor intersection rutting	Good condition	Slight to moderate flushing in mainline wheel

Table C.4. **Stopping Distance Test Comparisons 1980-1984**

Date	Pavement Temperature (°F)	Site	Stopping Distance ft @ 25 mph Rubber Modified Asphalt	Normal	Percent Reduction with rubber
01/22/81	-13	Carnation	91	114	20
01/22/81	-13	Fairhill	64	129	50
01/30/81	+27	Fairhill	75	113	34
02/02/81	+27	Carnation	98	101	3
02/05/81	+27	Carnation	53	91	42
02/06/81	+21	Carnation	52	64	19
12/10/81	+13	Peger Road	61	66	7
12/11/81	+ 6	Peger Road	43	49	12
12/16/81	+ 6	Peger Road	58	90	36
12/18/81	+18	Peger Road	63	77	18
01/11/82	- 9	Peger Road	82	97	15
01/14/82	-11	Peger Road	82	100	18
01/29/82	0	Peger Road	55	109	50
02/02/82	10	Peger Road	80	93	14
02/03/82	17	Peger Road	48	55	13
02/04/82	25	Peger Road	65	80	19
02/09/82	21	Peger Road	70	87	20
12/10/82	14	Peger Road	94	123	24
12/11/82	6	Peger Road	62	124	50
11/29/83	+24	Peger Road	62	87	29
12/02/83	+12	Peger Road	45	53	15
		Avg. Values	67	91	25

tests of bare pavements at these air temperatures indicate minimum stopping distances of 25 to 30 feet. The use of coarse sands for ice control in similar areas would normally result in reduced stopping distances for only a short period of time, as the sand rolls off under traffic action.

Following the 1984 season, in which no new PlusRide™ section were constructed, seven new installations were placed by the end of 1986. These installations totaled 27.26 lane-miles as detailed in Table C.3. Most of these sections were constructed without significant problems, with Anchorage area work using a specified rubber content of 2.5 percent as compared to 3 percent in the Fairbanks area. It is the opinion of the author that the 2.5 percent rubber content provides for a better end-product, as significantly higher stabilities can be attained at lower asphalt contents. A decrease in rubber of 0.5 percent typically lowers the asphalt demand by a similar amount.

Minor construction problems occurred on the 1986 Minnesota-O'Malley project as a result of initial asphalt contents which proved too high, resulting in flushing and rutting of the mix at intersections. This was subsequently corrected by lowering the asphalt content from 7.5 to 7.0 percent, and dropping the mixing temperature from 325 to 290 °F. On the Airport Road project in Fairbanks, slight to moderate flushing of the asphalt was noted within a few days after placement, during unusually warm weather. This effect was first noted, and became most excessive, at the intersections. In these areas, the traction and braking forces caused increased mixture densification and the excess asphalt was flushed to the surface. Subsequent core testing revealed that the asphalt contents and aggregate gradations were well within specifications. However, the rubber contents appeared to average only about 2.1 percent as compared to the 3 percent specified. This resulted in a significantly reduced asphalt demand for the mix, and was considered to be the cause for the flushing. The principal effect has been increased slipperiness when wet and a reduction in the wintertime traction benefits which normally results from the use of rubber granules in a paving mix. At this time (1987), it appears that traffic action and studded tire wear will serve to remove most of the excess surficial asphalt within the first two winters, and that the long-term durability will be very good.

Stopping distance tests on Airport Road were done on six test dates with an average of sixteen tests per date. Airport Road is a four-lane divided urban collector route, with signalized intersections at frequent intervals. The primary purpose was to evaluate the icy-road friction aspects of the newly placed Airport Road rubber-modified pavement. Tests were performed in a 1984 Chevrolet station wagon, using a Bowmonk (brand) Brake-Meter. This meter is functionally similar to the Tapley (brand) Meter used in previous tests, and results should be directly comparable.

In all tests performed on Airport Road during area-wide icy road conditions, the stopping distances were noted to be variable with traffic levels and with the degree of surface flushing. Tests on November 28, 1986, focused on the moderate and severe flushing areas, compared them with nonflushed areas. Stopping distances at 25 mph averaged 91, 150, and 81 feet, respectively, for these three conditions. Comparisons between nonflushed and moderately flushed areas on December 5, 1986, showed an increase of 37 percent in stopping distances resulting from the flushing of excess asphalt to the surface of the pavement during construction. On this date, Airport Road was also compared with College Road which had a normal asphalt pavement. Stopping distances were found to average 133 feet on College Road and only 81 feet on the nonflushed areas of the Airport Road PlusRide^{TM} project, an improvement of 39 percent.

Stopping distance tests on Airport Road generally demonstrated that braking efficiencies were affected by traffic volumes and speeds and by the degree of flushing, as well as by the presence of the granulated rubber in the mix. While no extensive tests were done to investigate the effects of traffic levels and speed, it was noted that stopping distances were as much as 30 percent greater in the highest traffic sections of this route. These high-traffic sections typically have lower average speeds, more stop-and-go movements, and possibly more extensive asphalt flushing than other portions of the route. The effects of traffic on icy road surface slipperiness appear to result from the polishing action of sliding tires during braking and acceleration at stoplights, and possibly also from the condensation of exhaust water vapor onto the cold pavement surface. In Fairbanks, the most common cause of icy roads is the formation of surface frost during almost every atmospheric warming cycle. Under these conditions, the combination of relatively warm moist air with cold pavement surfaces results in the condensation of moisture to form a thick frost layer. Traffic action then polishes the frost layer and further reduces the skid resistance. This condition commonly exists over a four-month period during the winter season. It typically ends in

Table C.5. Stopping Distance Test Comparison (1987)

Date (1987)	Air Temp. (°F)	Site	Stopping Distance Ft. @ 25 mph PlusRide	Nov. 1	Percent Reduction with Rubber
1/20	32°	Minnesota - N. Bd.	83	87	4
1/20	32°	Minnesota - N. Bd.	73	74	1
1/20	32°	A-Street	42	60	30
1/20	32°	C-Street	32	59	46
1/21	32°	Minnesota - F. Rd.	89	130	32
1/21	32°	Minnesota - N. Bd.	46	52	12
1/28	16°	Minnesota - F. Rd.	84	120	30
2/02	26°	Minnesota - N. Bd.	71	70	(-1)
2/02	26°	Minnesota - S. Bd.	116	116	0
2/02	26°	Seward Highway	68	80	15
2/02	26°	C-Street	77	87	12
2/02	26°	A-Street	72	76	5
2/02	26°	Minnesota F. Rd.	68	72	5
		Average Values	70.7	83.4	14.8

Legend: N. Bd. - Mainline on North-Bound Lanes
S. Bd. - Mainline on South-Bound Lanes
F. Rd. - West Side Frontage Road at Dimond Road Intersection

March when the increasing solar radiation begins to warm the pavement surface.

Measurements were made of stopping distances on normal and PlusRide^{TM} rubber-modified pavements in early 1987, on four different paving projects in the Anchorage urban area. These tests were performed with a Tapley meter in a full-size pickup truck equipped with Uniroyal brand mud and snow tires. Testing on four different days when area roads were generally icy, showed an average reduction in stopping distances of 15 percent for the rubber-modified pavements. The values ranged from no improvement to a 46 percent reduction in stopping distance, as shown by Table C.5.

From these comparative tests, it can be seen that stopping distance reductions achieved with the rubber-modified asphalt pavements were lasting and quite significant in magnitude, while roadway sanding was of only temporary and minor benefit.

APPENDIX D

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

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

Project ID: Agency:	1983 Overlay Program City of Bellevue, Washington	FR 282 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.

Table D.1. Rubber-Modified Asphalt Project Information. (Cont.)

Project ID: Agency:	1983 Overlay Program City of Bellevue, Washington	FR 282 Oklahoma Department of Transportation
	b) Follow-Up Questionnaire	
Present Condition		
Raveling	None	None
Bleeding	None	Moderate
Potholding	None	Moderate-None
Wheel Track Rutting	None	None
Cracking	None	None
Overall	--	Moderate-None
Effectiveness 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.

Table D.2. Rubber-Modified Asphalt Project Information.

Project ID: / Agency:	SR 3437 South Dakota DOT	SPI-080-1 Nevada DOT
	a) Initial Questionnaire	
General		
Date Constructed	9/1/82 to 4/8/82	8/82
Tons Mixed	448	1,778
Mix Thickness	1-1/2 inches	1/1-2 inches
Mix Design		
Rubber Content	3%	3%
Asphalt Content	6.5-6.8%	8.6%
Construction		
Mix Temp., °F	320-335	330
Mixing Time, Sec.	-	15 dry-15 wet
Compaction Temp., °F	-	320-330
Voids in Mix, %	3%	7.5% (range 0.5-12.0%)
Problems		Asphalt draining in trucks, rubber tire roller left marks which did not iron out.
Mix Performance		
Types of Problems	Raveling (moderate to severe).	Raveling, mix too coarse.
Causes of Problems	Poor bond between RA and underlying pavement. Cool loads, lack of density, high voids?	Open mix allowed excess water intrusion which separated and lifted the pad.
Reason for Use	Experimental, de-icing.	De-icing, performance evaluation.

Table D.2. Rubber-Modified Asphalt Project Information. (Cont.)

Project ID: Agency:	SR 3437 South Dakota DOT	SPI-080-1 Nevada DOT
	b) Follow-Up Questionnaire	
Present Condition		
Raveling	Severe	Moderate
Bleeding	None	Moderate-None
Potholding	Moderate-None	Moderate
Wheel Track Rutting	None	None
Cracking	None	None
Overall	Severe	--
Pavement Performance	**Effective**	
Ice Control	No	No
Noise Control	No	No
Reflective Crack Control	No	--
Skid Resistance	No	--
Fatigue Resistance	No	--
Comments	Poor performance has been attributed to asphalt content being too low.	Asphalt failures in the pavement occurred immediately after the first rain. Maintenance is scheduled to remove the Plusride from the roadway and replace it with a a conventional Type 2 plant mix.

Table D.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

Table D.3. Rubber-Modified Asphalt Project Information. (Cont.)

Project ID: Agency:	F8-2(22)28U-2 MDOH	02-189504 CALTRANS
b) Follow-Up Questionnaire		
Present Condition		
Raveling	None	None
Bleeding	None	None
Potholding	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.

Table D.4. Rubber-Modified Asphalt Project Information.

Project ID: / Agency:	Mt. St. Helens / FHWA - WDFD	Lemon Road / Alaska DOT & PF
a) Initial Questionnaire		
General		
Date Constructed	August 1983	1983
Tons Mixed	2570	2462
Mix Thickness	1-3/4, 2-1/3, 3-1/2 inches	
Mix Design		
Rubber Content	3%	3%
Asphalt Content	7.8%	design 8.6%
Construction		
Mix Temp., °F	350	275
Mixing Time, Sec.	-	-
Compaction Temp., °F	320	-
Voids in Mix, %	4%	2%
Problems	-	Some shoving in control strip
Mix Performance		
Types of Problems	Too early to determine	Too early to determine
Causes of Problems	-	-
Reason for Use	Experimental	Experimental, de-icing

Table D.4. Rubber-Modified Asphalt Project Information. (Cont.)

Project ID: Agency:	Mt. St. Helens FHWA - WDFD	Lemon Road Alaska DOT & PF
b) Follow-Up Questionnaire		
Present Condition		
Raveling	None	Less than 5%
Bleeding	None	None
Potholding	None	2 Potholes/mile
Wheel Track Rutting	None	None
Cracking	None	None
Overall	None	None
Pavement Performance	Effective	
Ice Control	--	No (very mild winter)
Noise Control	Yes	No (industrial area)
Reflective Crack Control	--	No (new section)
Skid Resistance	--	No
Fatigue Resistance	--	No (raveled areas appear more permeable)
Comments	--	--

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

Project ID: Agency:	Upper Huffman Road Anchorage, Alaska / ADOT&PF	Upper Carnation Drive Fairbanks, Alaska / ADOTP&F
	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

Table D.5. Rubber-Modified Asphalt Project Information. (Cont.)

Project ID: Agency:	Upper Huffman Road Anchorage, Alaska / ADOT&PF	Upper Carnation Drive Fairbanks, Alaska / ADOTP&F
	b) Follow-Up Questionnaire	
Present Condition		
Raveling	None	Less than 1%
Bleeding	None	None
Potholding	None	Less than 1%
Wheel Track Rutting	None	None
Cracking	None	Similar to Conventional Asphalt
Overall	Acceptable	Acceptable
Pavement Performance	Effective	
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 D.6. Rubber-Modified Asphalt Project Information.

Project ID: Agency:	Fairhill Access Road Fairbanks, Alaska / ADOT&PF	Old Seward Highway Anchorage, Alaska / ADOT&PF		
	a) Initial Questionnaire			
General				
Date Constructed	September 1979	1981		
Tons Mixed	-	-		
Mix Thickness	1.5 inches	1-1/4 inches		
Mix Design				
Rubber Content	-	3	3.5	4
Asphalt Content	-	6.6	6.6	6.6
Construction				
Mix Temp., °F	-	285	285	285
Mixing Time, Sec.	-		-	
Compaction Temp., °F	-	±260	±260	260
Voids in Mix, %	9	7.5	7.5	12
Problems	Blade placement too sticky, cooled too quickly.	Construction delays due to traffic.		
Mix Performance				
Types of Problems	Minor raveling	Raveling	Raveling	Raveling
Causes of Problems	1) High voids 2) Incomplete compaction	P200 level too low 1) Full vibratory screed not used 2) Aggregate out of specifications		
Reason for Use	Experimental, to judge with mix could be for maintenance control, skid comparison	Experimental, to determine effects of varying rubber content.		

Table D.6. Rubber-Modified Asphalt Project Information. (Cont.)

Project ID: Agency:	Fairhill Access Road Fairbanks, Alaska / ADOT&PF	Old Seward Highway Anchorage, Alaska / ADOT&PF
	b) Follow-Up Questionnaire	
Present Condition		
Raveling	Less than 5%	Moderate-Severe
Bleeding	None	None
Potholding	None	Moderate
Wheel Track Rutting	None	None
Cracking	None	None
Overall	Acceptable	Not acceptable
Pavement Performance	Effective	
Ice Control	Not Evaluated	Not Evaluated
Noise Control	Not Evaluated	Not Evaluated
Reflective Crack Control	Not Evaluated	Not Evaluated
Skid Resistance	Not Evaluated	Not Evaluated
Fatigue Resistance	Not Evaluated	Not Evaluated
Comments		

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

Project ID: / Agency:	Peger-Van Horn Intersection / Fairbanks, Alaska / ADOT&PF	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

Table D.7. Rubber-Modified Asphalt Project Information. (Cont.)

Project ID: Agency:	Peger-Van Horn Intersection Fairbanks, Alaska / ADOT&PF	Victoria Street City of Victoria, British Columbia
	b) Follow-Up Questionnaire	
Present Condition		
Raveling	Less than 15%	No response received
Bleeding	None	
Potholding	Less than 15%	
Wheel Track Rutting	None	
Cracking	None	
Overall	Not Acceptable	
Pavement Performance	Effective	
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 D.8. Rubber-Modified Asphalt Project Information.

Project ID: Agency:	TN FLH 1-1 FHWA-EDFD	First Kingsway Trial Country Roads Board of Victoria, Austrailia
	a) Initial Questionnaire	
General		
Date Constructed	1981	1/10/77
Tons Mixed	460	-
Mix Thickness	1.5	1 to 1-1/2 inches
Mix Design		
Rubber Content	3%	3%
Asphalt Content	7.5%	7.5%
Construction		
Mix Temp., °F	325	360-400
Mixing Time, Sec.	45-60	10 to 12 dry, 35 wet
Compaction Temp., °F	235	-
Voids in Mix, %	5.5	9.2
Problems	None	-
Mix Performance		
Types of Problems	None	Rutting, raveling, stripping
Causes of Problems		Wet weather after laying
Reason for Use	Experimental - reflective crack control, skid resistance comparison	Experimental

Table D.8. Rubber-Modified Asphalt Project Information. (Cont.)

Project ID:	TN FLH 1-1	First Kingsway Trial
Agency:	FHWA-EDFD	Country Roads Board of Victoria, Austrailia

b) Follow-Up Questionnaire

Present Condition	
Raveling	None
Bleeding	None
Potholding	None
Wheel Track Rutting	None
Cracking	None
Overall	Acceptable
Effectiveness of Rubber Mix	
Ice Control	Not Evaluated
Noise Control	Not Evaluated
Reflective Crack Control	Not Evaluated
Skid Resistance	Not Evaluated
Fatigue Resistance	Not Evaluated
Comments	The pavement durability to date has been excellent.

Table D.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 D.9. Rubber-Modified Asphalt Project Information. (Cont.)

Project ID:	Mordialloc Road Trial	Second Kingsway Trial
Agency:	Country Roads Board of Victoria, Australia	Country Roads Board of Victoria, Australia

b) Follow-Up Questionnaire

Present Condition	
Raveling	Moderate
Bleeding	Severe
Potholding	Moderate
Wheel Track Rutting	Moderate
Cracking	None
Overall	Acceptable
Effectiveness of Rubber Mix	
Ice Control	Weather not conducive to check this portion
Noise Control	No
Reflective Crack Control	No
Skid Resistance	No
Fatigue Resistance	No
Comments	The rubberized mix had too much asphalt and shows flushing in wheel paths.

Table D.10. Rubber-Modified Asphalt Project Information.

Project ID:	SR-97 Constr. 2229
Agency:	WSDOT

a) Initial Questionnaire

General	
Date Constructed	5/25/82
Tons Mixed	400
Mix Thickness	2 inches
Mix Design	
Rubber Content	3% by wt. of total mix
Asphalt Content	8%
Construction	
Mix Temp., °F	330
Mixing Time, Sec.	15 pre-mix, 30 wet mix
Compaction Temp., °F	330-200
Voids in Mix, %	3.5%
Problems	Very sticky mix. Fines would collect in augers and flight bars, then drop in mix to form fat spots.
Mix Performance	
Types of Problems	Flushing
Causes of Problems	Partially due to excess A/C; reduced 0.3%.
Reason for Use	Experimental, for fatigue resistance and de-icing.

* 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 D.1. Initial Questionnaire Form.

Follow-Up Questionnaire on PLUSRIDE

Project Identification ______________ Location: ______________

Agency: ______________ Date Constructed: ______________

Tons Mix: ______________ Mix Thickness: ______________

CONDITION	DEGREE (check one)				
% of Section	Severe 100-75	75-50	Moderate 50-25	25-10	None 10-0
Raveling	___	___	___	___	___
Bleeding	___	___	___	___	___
Pot Holing	___	___	___	___	___
Wheel Track Rutting	___	___	___	___	___
Cracking	___	___	___	___	___
Overall	___	___	___	___	___

When compared to conventional mixes, were any of the attributes listed below noted in the rubber modified test section?

	YES	NO	COMMENTS
Ice Control	/__/	/__/	______________
Noise Control	/__/	/__/	______________
Reflective Crack Control	/__/	/__/	______________
Skid Resistance	/__/	/__/	______________
Fatigue Resistance	/__/	/__/	______________

Additional Performance Comments: ______________

____

____

____

* * * * * * * * * * * * * * * * *

Figure D.2. Follow-up Questionnaire Form.

APPENDIX E

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

APPENDIX E

Description of Lemon Road Project (RS-0955(1))

1.0 WORK PLAN

1.1 Objective

The objective of this project was 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, Alaska within the flood plain of Lemon Creek. A quantity of 2,279 tons of rubberiuzed 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. Observations included 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.

1.4 Rubber-Asphalt Cost

The cost for supply and placement of the rubberized asphalt paving mix and binder was $82.30 per ton, with the quantity approximately 2,279 tons. AC-5 asphalt cement for the mix had been determined to be approximately 8.5% (195 tons) of total mix at $280.00 per ton.

2.0 MIX DESIGN RESULTS

A Marshall (Alaska method T-17) mix design was prepared on the aggregates obtained from Lemon Road. The results given below show the optimum asphalt content to be 8.6% by weight of aggregate. The PlusRide criteria was used for selecting the mix characteristics. The target values for the mix are as follows:

Gradation, % Passing	Target Value	Range
5/8 inch	100	100
1/2 inch	-	
3/8 inch	69	62-76
1/4 inch	39	32-42
No. 10	28	22-32
No. 30	9	8-12
Asphalt content, % Dry Wt. Agg.	8.6	8.1-9.1
Rubber content % Total Mix	3.0	2.85-3.15

The rubber gradation specification for the project was as follows:

Gradation, % Passing	Specifications
1/4	100
No. 4	76-100
No. 10	28-36
No. 20	10-24

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 palnt. 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 fairly well, but compaction did not. The mix was tender and shoved on both the treated and untreated bases. This resulted in limiting the passes of the vibratory compactor to two maximum. There was concern on the part of the engineer that even though the material was in specification, the mix behavior was not acceptable. Paving was temporarily stopped.

Another meeting was held on August 22, 1983 with representatives of the state and the contractor. The results were as follows:

1) The minimum mix discharge temperature should be reduced to 275°F for use of a drum dryer plant.
2) A 10-ton Hyster roller should be used for breakdown.
3) An 8-ton Dynapac roller should be used as the finish roller.
4) The asphalt content should be increased to 9.5% to fill air voids.
5) The CSS-1 tack coat should have an application rate of .05 gal/yd^2 (residual).

On August 24, 1983, All Seasons Surfacing personnel indicated the asphalt content should not be increased; therefore, the initial value of 8.6% was continued.

3.2 Construction Observations

The project engineer made several remarks concerning project construction in his report. The remarks are summarized below:

1) The production of gap-graded aggregates was difficult for the contractor, because the stockpiles used for blending contained a considerable amount of fines.
2) The drum-dryer plant used by the contractor produced an extremely opaque smoke which caused the Department of Environmental Control to shut the project down for a short time period.

3) Raking the mix on the longitudinal joint proved to be more difficult than normal.
4) Rubberized mix placed around concrete manhole adjustment rings caused the ring joint to separate.
5) Typical paint pavement stripes appeared to weaken in intensity more quickly than normal.
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 E.1 and E.2 summarize results of Alaska DOT & 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.

Table E.1. Properties for the Rubber Asphalt Mix - Lemon Road (Date Tested 8/30/83).

Property	Lab No. 83A-1455 Field No. 3	Lab No. 83-1456 Field No. 4	Project Specification
Asphalt content, % Dry Wt. Aggregate	9.8	8.9	8.1-9.1
Gradation, % passing			
5/8 inch	100	100	100
1/2 inch	91	91	-
3/8 inch	69	64	62-76
1/4 inch	46	42	32-42
No. 10	32	29	22-32
No. 30	27	25	20-25
No. 200	9	8	8-12
Rubber content, % Total Mix	2.82	2.53	2.85-3.15
Voids, total mix, %	1.3	1.9	-
Unit weight, pcf	142.5	143.1	-

Note the circled sample properties which mean the value does not meet the project specification.

Table E.2. Lemon Road Conformance Sampling.

Property	Sample Location Sta. 269+70 Rt. Date: 8/29/83	Sample Location Sta. 264+20 Lt. Date: 8/30/83	Sample Location Sta. 264+20 Lt. Date: 8/30/83	Project Specification
Asphalt content, %	8.79	9.34	9.11	8.1-9.1
Gradation, % passing				
5/8 inch	-	100	100	100
3/8 inch	-	62	66	62-76
1/4 inch	-	41	43	32-42
No. 10	-	28	39	22-32
No. 30	-	24	24	20-25
No. 100	-	15	16	-
No. 200	-	9	9	8-12
Rubber Content, $	2.80	2.70	2.76	2.85-3.15
Voids total mix, %	2.4	1.4	1.8	-
Voids filled, %	73.0	77.3	75.5	-
Stability, lbs	600	540	595	-
Flow, 1/100 inch	23	26	30	-
Unit weight, pcf	141.0	141.5	141.3	-
Aggregate fracture	-	-	87	70 min.

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

4.1 Test Summary and Economic Analysis of Fatigue Results

Table E.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 E.1. Evaluating the curves at 100 and 200 microstrain values gives fatigue lives for the rubber asphalt mixes three times and two 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 E.5. This table was constructed using the same assumptions as section 5.2.1 in the report. No intangible cost benefits (or costs) have been added to the present worth values.

The annualized equivalent cost for the Plusride material is \$0.36 per square yard versus \$0.42 per square yard for the conventional asphaltic concrete. These costs assume rubber-modified the pavement will fail in fatigue, and therefore, last approximately forty years.

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

Sample Identification	Strain (s)	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

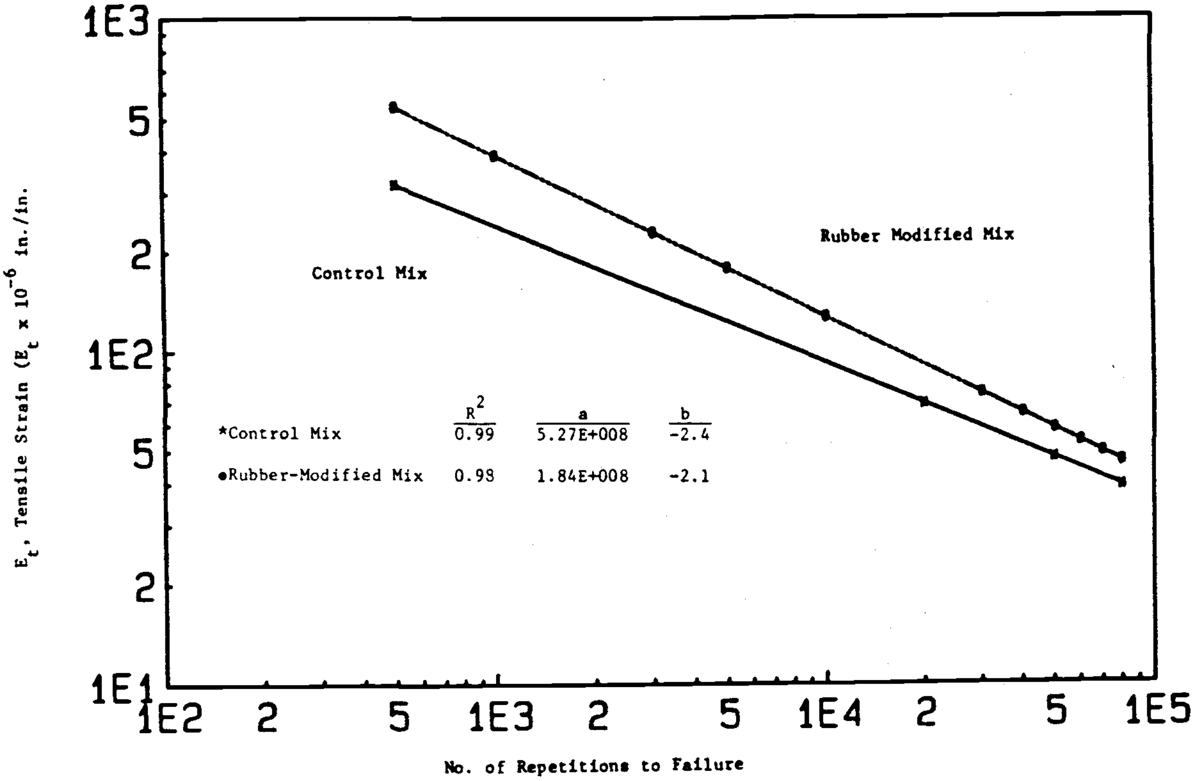

Figure E.1. Laboratory Fatigue Curves

Table E.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 = \$33.60/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, & 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.

APPENDIX F

CREEP TEST PROCEDURE AND COMPUTER PROGRAMS TO MONITOR TEMPERATURE AND DEFORMATION OF A SPECIMEN (42)

APPENDIX F

Creep Test Procedure and Computer Programs to Monitor Temperature and Deformation of a Specimen

A. Apparatus

1. Loading device: a loading device for soil consolidation test was used.
2. Repeated Load Test Control Cabinet: to adjust the air pressure.
3. LVDT
4. Data Acquisition/Control Unit (Model No. 3421A or 3497A) and H.P. 85 Computer: to record the temperature and displacements of specimen automatically.
5. Environmental Cabinet: to control the test temperature.
6. Thermistor: to measure the temperature of a specimen.

b. Sample Preparation

1. Diameter of 4 inches, height of 2.5 inches.
2. Polish both sides of specimen on a glass plate by using aluminum dredge powder.
3. Thin silicone grease on both sides.

c. Test Temperature: 40°C or 25°C.

d. Compression Stress: 0.1 MPa.

e. Test Duration: 3 hours loading.

f. Test Procedure

1. Put a loading device in an environmental cabinet and connect to the repeated load test control cabinet.
2. Warm the inside of the environmental cabinet to 40°C or 25°C.

3. After the temperature reaches 40°C or 25°C, put a specimen on a load plate and tighten the upper plate. Attach LVDT on the bottom plate.
4. Attach a thermistor to the specimen.
5. Wait for 5 to 10 minutes after closing the environmental cabinet.
6. Apply a pressure of 2 kPa as a preloading for one minute.
7. Apply a pressure of 0.1 MPa and run the computer program.

```
  5  OPTION BASE 1
 10  DIM B(3), T(20,3)
 20  SETTIME 0,0
 30  Q1=0.00146668
 40  Q2=0.000238497
 50  Q3=0.000000100533
 51  IMAGE 3X,"TIME,",2X,"TEMP1,"
     ,2X,"TEMP2,",2X,"TEMP3,"
 52  PRINT USING 51
 53  IMAGE 3X,"SEC",4X,"DEG C",3X
     ,"DEG C",3X,"DEG C"
 54  PRINT USING 53
 60  FOR I=1 TO 20
 70  OUTPUT 709 ;"TWO3-5"
 80  FOR J=1 TO 2
 90  ENTER 709 ; B(J)
100  Q4=LOG(B(J))
110  T(I,J)=1/(Q1+Q4*(Q2+Q3*Q4*Q4
     ))-273.15
120  NEXT J
130  OUTPUT 709 ;"OPN"
135  BEEP
140  PRINT USING 150 ; T1,T(I,J-3
     ),T(I,J-2),T(I,J-1)
150  IMAGE 2X,5D,3X,2D.2D,3X,2D.2
     D,3X,2D.2D
160  T1=TIME
170  IF T1>20*I THEN 200
180  DISP "RUNNING NOW"
190  GOTO 160
200  NEXT I
210  END
```

Figure F.1. Computer Program to Record Temperature (HP Model No. 3421).

```
  5  OPTION BASE 1
 10  DIM B(3), T(181,3), D(181)
 15  CLEAR 709
 16  OUTPUT 709 ;"VR3AI10"
 17  ENTER 709 ; R0
 18  DISP R0
 20  SETTIME 0,0
 30  Q1=0.00146668
 40  Q2=0.000238497
 50  Q3=0.000000100533
 51  IMAGE 3X,"TIME,",2X,"TEMP1,"
     ,2X,"DEFORM"
 52  PRINT USING 51
 53  IMAGE 3X,"SEC",4X,"DEG C",3X
     ," in."
 54  PRINT USING 53
 60  FOR I=1 TO 181
 70  OUTPUT 709 ;"AF09AL10VR3VC2"
 80  FOR J=1 TO 2
 85  OUTPUT 709 ;"ASVT3"
 90  ENTER 709 ; B(J)
 94  IF J=2 THEN 111
 95  B(J)=B(J)*10000
100  Q4=LOG(B(J))
110  T(I,J)=1/(Q1+Q4*(Q2+Q3*Q4*Q4))-273.15
111  D(I)=(B(J)-R0)/21.63 ! DISPL
     ACEMENT CALIBRATION
112  OUTPUT 709 ;"VC0"
120  NEXT J
130  OUTPUT 709 ;"VC0"
135  BEEP
140  PRINT USING 150 ; T1,T(I,1),
     D(I)
150  IMAGE 2X,5D,2X,4D.1D,2X,2D.D
     DDD
160  T1=TIME
170  IF T1>60*I THEN 200
180  DISP "RUNNING NOW"
190  GOTO 160
200  NEXT I
210  END
```

Figure F.2. Computer Program to Record Temperature and Deformation of a Specimen (HP Model No. 3497A).

APPENDIX G

LABORATORY TEST DATA

Table G.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

Table G.2. Summary of Modulus and Fatigue Data at +10°C.

Sample Number	Air Voids (%)	Test Condition Load (Lb)	Test Condition Strain (10^{-6})	Resilient Modulus (ksi)	Fatigue Life
A-1	1.99	273	85	417	36,763
A-2	2.42	311	85	460	48,020
A-3	1.82	313	85	470	83,885
A-4	2.19	282	85	453	47,436
A-5	2.01	287	100	400	22,556
A-6	1.93	315	100	436	31,020
A-7	2.14	287	100	387	28,999
A-8	1.88	306	100	420	29,397
A-9	2.37	440	150	405	3,646
A-10	2.91	394	150	364	10,330
A-11	2.62	421	150	391	6,840
A-12	2.57	450	150	404	2,800
A-13	2.49	469	150	423	22,665
B-1	2.13	278	100	383	28,390
B-2	2.09	277	100	383	22,123
B-3	2.09	335	100	480	20,123
B-4	2.05	298	100	411	24,563
C-1	2.03	335	85	553	57,624
C-2	2.36	211	85	345	66,365
C-3	2.49	220	85	352	59,619
C-4	2.00	239	85	382	64,536
C-5	1.89	270	100	366	48,536
C-6	2.08	277	100	379	52,055
C-7	2.16	263	100	363	50,720
C-8	2.16	239	100	334	41,649
C-9	2.12	399	150	361	10,536
C-10	1.91	411	150	370	11,370
C-11	2.07	378	150	343	9,563
D-1	2.05	306	100	423	174,200
D-2	1.88	316	100	440	55,030
D-3	2.09	263	100	369	29,245
D-4	2.09	287	100	393	35,268
D-5	1.96	302	100	417	40,928
E-1	1.92	315	100	422	46,297
E-2	2.00	287	100	393	27,728
E-3	2.09	349	100	477	21,558
E-4	2.05	325	100	445	29,310
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

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

Sample Number	Air Voids (%)	Test Condition Load (Lb)	Strain (10^{-6})	Resilient Modulus (ksi)	Fatigue Life
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
L-1	1.86	491	100	711	9,751
L-2	2.28	478	100	687	10,308
L-3	2.44	532	100	761	19,534
M-1	2.47	383	85	617	14,579
M-2	2.38	402	85	656	34,766
M-3	1.89	388	85	639	13,627
M-4	2.75	397	85	649	20,967
M-5	2.67	488	100	689	14,519

Table G.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
M-6	2.59	593	100	842	7,101
M-7	2.80	651	100	911	6,987
M-8	2.26	766	150	714	5,390
M-9	1.56	823	150	734	35,823
M-10	2.18	785	150	728	2,423
M-11	2.22	815	150	752	2,836
N-1	2.05	344	85	557	31,328
N-2	1.65	479	85	700	32,454
N-3	2.35	398	85	650	38,771
N-4	2.13	405	85	658	27,264
N-5	2.67	530	100	732	22,042
N-6	2.82	446	100	677	28,814
N-7	2.95	520	100	722	12,283
N-8	3.09	440	100	609	14,642
N-9	3.15	488	100	677	8,747
N-10	2.13	641	150	545	6,247
N-11	2.43	756	150	686	7,084
N-12	2.47	737	150	610	5,410
O-1	2.18	747	100	955	4,117
O-2	2.46	584	100	801	16,115
O-3	2.29	624	100	850	8,831
O-4	2.19	693	100	827	17,417
P-1	1.92	417	100	577	28,332
P-2	2.03	450	100	622	18,211
P-3	2.01	513	100	705	13,139
P-4	2.08	505	100	691	13,562
Q-1	2.01	564	100	785	7,503
Q-2	2.14	631	100	877	8,417
Q-3	1.98	747	100	1060	8,341
Q-4	2.00	631	100	887	4,799
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

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

Sample Number	Air Voids (%)	Test Condition Load (Lb)	Strain (10^{-6})	Resilient Modulus (ksi)	Fatigue Life
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-12	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-17	2.29	768	150	707	2,250

Table G.3. Summary of Modulus and Fatigue Data at -6°C.

Sample Number	Air Voids (%)	Test Condition Load (Lb)	Strain (10^{-6})	Resilient Modulus (ksi)	Fatigue Life
A-14	2.23	1364	100	1842	25,567
A-15	2.16	1412	100	1879	28,321
A-16	2.11	1398	100	1894	32,824
A-17	2.19	1071	70	1918	65,620
A-18	2.07	1047	70	1984	61,566
A-19	2.27	1023	70	1975	65,503
A-20	2.01	1315	70	1812	82,319
A-21	2.12	1801	130	1847	19,536
A-22	2.22	1705	130	1787	22,320
A-23	2.16	1790	130	1801	24,232
A-24	2.25	1776	130	1894	14,964
B-5	2.32	1607	100	2191	26,422
B-6	2.08	1437	100	1953	30,551
B-7*	2.42	1412	100	1916	40,147
B-8	2.19	1461	100	1988	32,236
C-12	2.11	1583	100	2165	22,311
C-13	2.16	1485	100	2000	33,665
C-14	2.27	1534	100	2088	19,236
D-6*	2.34	1364	100	1809	38,562
D-7	2.23	1583	100	2185	21,006
D-8	2.07	1592	100	2151	24,014
D-9	2.12	1602	100	2158	22,526
E-6	2.49	1485	100	1976	34,655
E-7	2.06	1519	100	2094	26,090
E-8	2.11	1656	100	2196	24,326
F-7	2.21	1510	100	2049	22,057
F-8	2.11	1519	100	2085	16,640
F-9	2.24	1437	100	1965	25,549
F-10	1.96	1544	100	2089	18,826
G-4	3.93	1363	100	1747	33,000
G-5	4.40	1145	100	1505	70,100
G-6	3.92	1426	100	1889	37,154
H-9*	2.14	1680	100	2301	68,890
H-10	2.06	1583	100	2161	27,875
H-11	1.97	1802	100	2499	47,743
H-12	2.12	1753	100	2409	48,254

*The results were not included in the statistical analysis.

Table G.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
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	86,851
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	82,943
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	41,321
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	1.92	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	78,557
P-6	2.22	1656	100	2268	85,622
P-7	2.11	1689	100	2296	88,262

*The results were not included in the statistical analysis.

Table G.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
Q-7	2.18	1461	100	2027	97,631
Q-8	2.09	1529	100	2107	94,060
Q-9	2.09	1617	100	2215	89,263
R-5	1.98	1412	100	1947	89,900
R-6	2.14	1330	100	1802	80,263
R-7	1.94	1509	100	2067	73,262
S-5	4.75	1120	100	1464	163,943
S-6	4.46	950	100	1256	134,910
S-7	4.29	1218	100	1610	114,193
T-19	2.16	2172	100	3263	9,224
T-20	2.40	2146	100	3214	9,362
T-21	2.08	2046	100	3070	5,256
T-22	2.19	2021	100	3012	10,262
T-23	2.42	2391	130	2753	1,425
T-24	2.39	2362	130	2767	3,228
T-25	2.23	2372	130	2842	2,925
T-26	1.96	1461	70	3256	18,526
T-27	1.52	1437	70	3092	10,236
T-28	2.17	1412	70	3060	13,988

Table G.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	29
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 G.5. Summary of Static Creep Data

Sample Number	Smix (ksi)	Interception	Slope	R^2	Temperature (°C)
A-1	50.5	0.0094	0.1356	0.97	40
A-2	90.3	0.0062	0.1170	0.88	40
I-1	100.1	0.0080	0.0723	0.89	40
I-2	123.0	0.0084	0.042	0.93	40
I-3	96.4	0.0088	0.065	0.98	40
N-1	106.0	0.0101	0.0371	0.89	40
N-2	100.7	0.0068	0.0907	0.99	40
N-3	93.9	0.0073	0.0909	0.99	40
T-1	164.5	0.0065	0.038	0.96	40
T-2	224.7	0.0041	0.055	0.99	40
U-1	24.2	0.0041	0.3267	0.71	40
U-2	49.4	0.0196	0.0492	0.94	40
U-3	111.6	0.0099	0.0324	0.87	40
A-1	142.9	0.0068	0.0492	0.93	25
A-2	54.2	0.0157	0.0650	0.92	25
A-3	121.9	0.0040	0.1316	0.95	25
I-1	165.8	0.0044	0.0845	0.94	25
I-2	146.4	0.0059	0.0642	0.93	25
I-3	88.4	0.0128	0.0296	0.92	25
N-1	226.5	0.0025	0.1174	0.91	25
N-2	137.9	0.0054	0.0823	0.98	25
N-3	118.5	0.0061	0.0841	0.92	25
T-1	209.4	0.0042	0.0621	0.94	25
T-2	196.3	0.0045	0.0598	0.98	25
T-3	169.7	0.0053	0.0592	0.98	25
U-1	147.1	0.0049	0.0853	0.92	25
U-2	81.0	0.0087	0.0882	0.90	25
U-3	149.7	0.0052	0.0749	0.96	25

Table G.6. Summary of Diametral Vertical Deformation Data

Sample Number	Smix (ksi)	Interception	Slope	R^2	Temperature (°C)
A-1	17.8	0.0029	0.4043	1.00	15
A-2	13.6	0.0009	0.5723	0.99	15
A-3	33.9	0.0016	0.4004	0.99	15
I-1	4.7	0.00002	1.1988	0.96	15
I-2	10.2	0.00031	0.7491	0.92	15
I-3	11.3	0.00881	0.6192	0.89	15
N-1	25.1	0.0011	0.4804	0.89	15
N-2	16.9	0.0007	0.5868	1.00	15
N-3	20.2	0.0003	0.6630	0.98	15
T-1	23.2	0.00391	0.3385	0.93	15
T-2	17.1	0.00005	0.9201	0.83	15
T-3	89.0	0.00249	0.2295	1.00	15
U-1	31.0	0.00379	0.1310	0.83	15
U-2	29.1	0.00084	0.4983	0.98	15
U-3	31.5	0.00039	0.5818	0.95	15

APPENDIX H

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

Example of "LIFECST" Program Output

Step	Description
1	XEQ "LIFECST"
2	Input costs for conventional asphaltic concrete. The units are irrelevant as long as they are consistent.
3	Input discount rate in decimal form.
4	Input assumed life for conventional asphaltic concrete.
5	The equivalent modified life is calculated.
6	To obtain different modified asphaltic concrete lives with new conventional life assumptions, place x = 0 when prompted. If the run is complete, place x = to any integer.

```
        XEQ "LIFECST"
CALCULATION OF
LIFE FOR EQUAL
ANNUAL COST
COST CONV AC=?
        43.2500    RUN
COST MOD.=?
        67.6500    RUN
DISCOUNT RATE=?
          .0350    RUN
CONV AC LIFE=?
         2.0000    RUN
LIFE MOD=3.1922
PLACE X=0 IF
IF MORE MOD
LIFES ARE
REQUIRED: IF
CALCS ARE
COMPLETE, PLACE
ANY INTEGER
EQUAL TO X
X=?
         5.0000    RUN
RUN COMPLETE
```

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

```
01♦LBL "LIFECST"
02 "CALCULATION OF"
03 AVIEW
04 "LIFE FOR EQUAL"
05 AVIEW
06 "ANNUAL COST"
07 AVIEW
08 "COST CONV AC=?"
09 PROMPT
10 STO 01
11 "COST MOD,=?"
12 PROMPT
13 STO 02
14 "DISCOUNT RATE=?"
15 PROMPT
16 STO 03
17♦LBL 15
18 "CONV AC LIFE=?"
19 PROMPT
20 STO 04
21 RCL 03
22 1
23 +
24 STO 05
25 RCL 04
26 Y↑X
27 1
28 -
29 STO 06
30 RCL 05
31 ENTER↑
32 RCL 04
33 Y↑X
34 RCL 03
35 *
36 ENTER↑
37 RCL 06
38 /
39 RCL 01
40 *
41 RCL 02
42 /
43 STO 07
44 ENTER↑
45 RCL 07
46 ENTER↑
47 RCL 03
48 -
49 /
50 LN
51 RCL 05
52 LN
53 /
54 "LIFE MOD="
55 ARCL X
56 AVIEW
57 BEEP
58 "PLACE X=0 IF"
59 AVIEW
60 "IF MORE MOD"
61 AVIEW
62 "LIFES ARE"
63 AVIEW
64 "REQUIRE: IF"
65 AVIEW
66 "CALCS ARE"
67 AVIEW
68 "COMPLETE, PLACE"
69 AVIEW
70 "ANY INTEGER"
71 AVIEW
72 "EQUAL TO X"
73 AVIEW
74 "X=?"
75 PROMPT
76 ENTER↑
77 X=0?
78 GTO 15
79 BEEP
80 "RUN COMPLETE"
81 AVIEW
82 "END"
83 END
```

System: HP41C

Required Registers = 43