Effect of Mix Ingredients on the Behavior of Rubber-Modified Asphalt Mixtures

H. B. TAKALLOU, R. G. HICKS, AND D. C. ESCH

Presented are the results of a laboratory study to evaluate the effect of rubber gradation and content, air voids, aggregate gradation, mix, temperature, and curing conditions on the properties of rubber-modified asphalt mixtures. Twenty different mix combinations were evaluated for diametral modulus and fatigue at two different temperatures [−6°C (21.2°F) and +10°C (50°F)]. Only the results of the tests at +10°C (50°F) are presented. The findings of this study indicate that rubber gradation and content, aggregate gradation, and use of surcharge during sample preparation have considerable effect on the design asphalt content and on the modulus and fatigue life of the mix. The laboratory data were used to develop guidelines for use of rubber asphalt mixes in Alaska.

Rubber-modified asphalt mixtures are 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. The concept was originated in the late 1960s by the Swedish companies Skega AB and AB Vaegfoerbaettringar (ABV), and was patented under the trade name Rubit (*1*). The product has been patented in the United States under the trade name Plusride; Plusride is a trademark for a rubber-modified asphalt mix that is marketed by All Seasons Surfacing Corporation of Bellevue, Washington (*2*).

Currently, many state highway agencies are evaluating the use of rubber-modified asphalt pavements in field trials (*3–6*). The potential advantages of using these mixtures include improved ice control and increased pavement life. The study discussed in this paper involved an evaluation of mix ingredients (rubber, asphalt, and aggregate) with the intent of optimizing mix properties and increasing pavement life for the least cost.

OBJECTIVES

The purpose of this paper is to evaluate the effect of mix ingredients on the performance of rubber-modified asphalt mixtures. To accomplish this, a laboratory study was initiated to evaluate the effect on mix properties and pavement life of

- Amount and gradation of rubber;
- Aggregate gradation;
- Void content; and
- Mix temperature, cure time, and surcharge.

LABORATORY PROGRAM

Variables Considered

To evaluate the effect of mix variations on the behavior of rubber-asphalt mixture, it was necessary to first establish a list of variables to be considered. The test variables considered for this study are given in Table 1.

Variations in void content were selected to determine if acceptable mixes could be produced at higher void contents. Two percent (usually recommended) and 4 percent (usually obtained in the field) were selected for study. Rubber contents of 2 and 3 percent by weight of aggregate were also selected to determine their effects on optimum asphalt content, resilient modulus, and fatigue life. The existing rubber gradation employed is a mixture of 20 percent fine (− #40) and 80 percent coarse rubber (#40 × ¼ in.). Increasing the amount of fine rubber to 40 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. Increasing the mix temperature increases the potential for dissolving some of the finer rubber into the asphalt. This interaction may improve resilient modulus or fatigue life. One compaction temperature, 129°C (265°F), was selected. However, to obtain 4 percent void content in the mix, the compaction temperature and compaction effort (usually 50 blows) were lowered to 99°C (210°F) and 10 blows, respectively. The high mixing temperature and lower compaction temperature simulate the effects of cooling during a long haul and placement.

Two mix curing periods (0 and 2 hr) were also selected for study to determine whether increased curing or reaction time can impart any beneficial effects. Two aggregate gradations were used to perform the tests: (a) the recommended aggregate gradation by Plusride (gap graded), and (b) the mid-band gradation used for conventional asphalt mixes (see Table 2). Finally, two levels of surcharge were evaluated, 0 and 5 lb.

Materials Used

Aggregate

The aggregates were obtained from the actual source used for the rubber-modified pavement at the Lemon Road project in Juneau, Alaska. Tables 2 and 3 give the gradations and properties of aggregates that were used in making the laboratory samples of rubber-asphalt mixtures.

H. B. Takallou and R. G. Hicks, Transportation Research Institute, Oregon State University, Corvallis, Oreg. 97331-2302. D. C. Esch, Alaska Department of Transportation and Public Facilities, Research Section, 2301 Peger Road, Fairbanks, Alaska 99708.

TABLE 1 VARIABLES AND LEVELS OF TREATMENT CONSIDERED FOR LABORATORY EXPERIMENT

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

TABLE 2 AGGREGATE GRADATION USED AND CORRESPONDING SPECIFICATION FOR PLUSRIDE™ 12

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

Asphalt

The paving grade asphalt generally used in the project area was selected. For this study, an AC-5 was used. Its physical properties are given in Table 4.

Rostler–Sternberg composition data for this asphalt were determined by using the former ASTM procedure D2006 described by Anderson and Dukatz (*7*) and Rostler et al. (*8*). 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 5.

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 increase sievability on the following sizes: ¼ in. × 4, 4 × 10, 10 × 20, 20 × 40, 40 × 50, and –50. The talcum powder was removed by sieving the fine rubber (–50) through a No. 200 sieve. The different size fractions of the rubbers were stored in separate containers. The rubber properties and gradations are given in Tables 6 and 7.

TABLE 3 AGGREGATE PROPERTIES FOR LEMON CREEK PROJECT

Property	Test Value
Specific gravity (apparent) (T-85)	2.76
Liquid limit (T-83)	Not apparent (25 max)
Plastic limit (T-89)	Nonplastic (6 max)
Los Angeles abrasion, % (T-35)	33
Sodium sulfate soundness, % (T-104)	1
AASHTO classification	A-1-a

Note: The Lemon Creek project was performed by the Alaska Department of Transportation and Public Facilities.

TABLE 4 ASPHALT CEMENT (AC-5) CHARACTERISTICS—ANCHORAGE, ALASKA

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

[a] AASHTO M 266, Table 1.
CS = Centistake; COC = Cleveland Open Cup.

Tests and Test Methods

The two general types of tests used in this study were mix design tests and mix properties tests. The mix properties of these different types of tests are summarized in the following table.

Type of Test	*Mix Properties*
Mix design	Stability
	Flow
	Voids[a]
Mix property	Diametral modulus
	Diametral fatigue

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

In the following sections, the procedures and equipment used in performing each of the tests are described.

TABLE 5 CHEMICAL ANALYSIS BY ROSTLER-STERNBERG METHOD[a]

Composition	Percentages
Asphaltenes	14.8
Nitrogen bases (N)	31.6
First acidaffins (A1)	10.1
Second acidaffins (A2)	29.4
Paraffins (P)	14.1
Refractive index of paraffins (N_D^{25})	1.4825
Rostler parameter[b]	0.96

[a] Tested by Matrecon, Inc., Oakland, California.

[b] Rostler parameter = (N + A1)/(A2 + P).

Mix Design Tests

The Marshall mix design procedure was used as part of this study. The samples were prepared by using the standard Alaska Department of Transportation and Public Facilities procedure (T-17). This method is the 50-blow Marshall procedure.

A total of 66 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 by using an MTS testing machine with a rate of loading of 2 in./min. The tests for diametral modulus were conducted by using a load duration of 0.1 sec and a load frequenty of 1 Hz, at a temperature of 22°C ±2°C (71.6°F).

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

- Rubber content—2 and 3 percent;
- Rubber gradation—coarse, medium, and fine; and
- Aggregate gradation—gap and dense graded.

The 2 percent void content was used as the selecting criterion for the optimum asphalt content for each combination.

Mix Property Tests

After the optimum asphalt contents were determined for the different mix combinations, other tests were used to evaluate their mix properties. For all dynamic tests, samples were subjected to a constant load, applied at 60 cycles per minute with a load duration of 0.1 sec, and tested at temperatures of +10°C (50°F) and −6°C (21.2°F) in the as-compacted condition as follows:

TABLE 6 RUBBER PROPERTIES—GRADATION

	a) Gradation					
Sieve Size	Coarse	Fine	80/20	60/40	0/100	All Seasons 80/20 Rubber Specifications (2)
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	-

Resilient Modulus Test Method The diametral modulus test (ASTM D-4123) was used to evaluate the effects of mix variables at the different temperatures and strain levels. Horizontal deformation was measured with two horizontal transducers attached to the specimen. Repeated loads were measured with a load cell under the specimen. Load and deformation were recorded with a two-channel oscillographic recorder. The duration of pulse loading was 0.1 sec, which corresponds to a 30-mph actual tire speed (*9*). The load was applied at a frequency of 60 cycles per minute. A seating load of about 10 percent of the required dynamic load at the specified strain level was used to hold the specimen in place. The modulus was calculated by using the following equation (*10*):

$$M_R = f(\mu + 0.2734)/t(\Delta h) \qquad (1)$$

where

M_R = resilient modulus (psi),
f = dynamic load (lb),
μ = Poisson's ratio (μ is assumed equal to 0.40),
t = thickness of specimen (in.), and
Δh = total elastic horizontal deformation (in.).

All tests were performed in a controlled temperature environment.

TABLE 7 OTHER PHYSICAL PROPERTIES OF RUBBER

Property	Percent
Natural or synthetic rubber	
Natural rubber	20
Synthetic rubber	80
Mixture	
Carbon black	30
Acetone	15
Hydrocarbon	45
Fiber	10

Note: Specific gravity is 1.28.
Rubber data source: Conversation with M. Cryst, General Manager, Rubber Granulators, Everett, Washington, November 1984.

The test system shown in Figure 1 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. To sense the temperature at the geometrical center of the specimen, three thermistors were used.

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

Fatigue Life Method and Procedure The diametral test was also used to predict fatigue life for different material combinations. Tests were conducted at 10°C (50°F) for 20 different material combinations by using at least three different tensile strain levels. Between 4 and 10 specimens were tested for each material combination at each temperature and strain level.

After the resilient modulus was determined for each combination at the desired strain level (after 150 repetitions), the

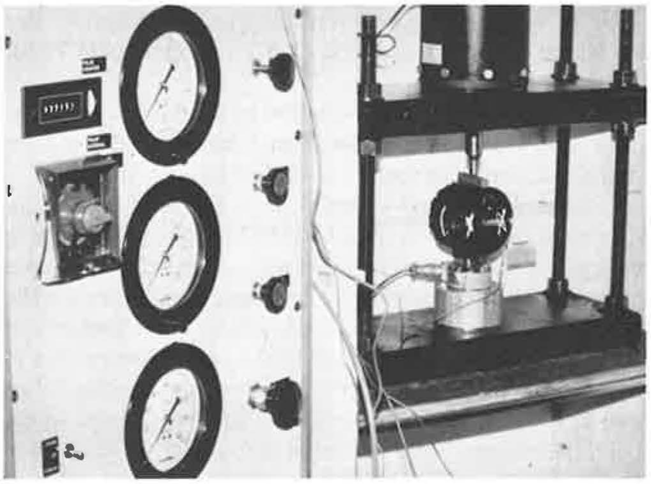


FIGURE 1 Testing apparatus and Shel-Low temperature incubator.

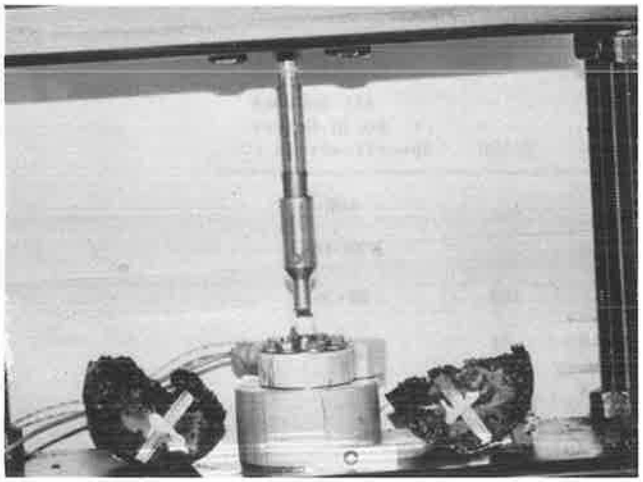


FIGURE 2 Failed specimen with broken foil tape.

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 ½-in.-wide loading strips. A seating load was applied (usually less than 10 percent of dynamic 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 2) and the counter on the control panel to stop.

Fabrication of Samples

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 to produce 1100 g. To ensure hot and dry mix, the aggregates were placed in an oven at the selected temperature [190°C (375°F) or 218°C (425°F)] for at least 12 hr. The asphalt was heated to 135°C (275°F) before mixing. Overheated asphalts were avoided.
2. The rubber fractions were combined to desired gradation and weight (i.e., 33 g for a 1100-g specimen).
3. The heated aggregate was mixed with the rubber granules and placed in an oven at 190°C (375°F) or 218°C (425°F) for approximately 3 min.
4. The asphalt required was added to the mixture of aggregate and rubber and mixed for about 3 min to yield a mixture having a uniform distribution of asphalt throughout.
5. Standard Marshall molds, 4 in. in diameter and 2½ in. high, were heated in an oven to 135°C (275°F). The forming mold part of the compaction mold was lubricated with silicone grease for ease of removing the specimen from the mold. The standard filter papers were not used because of the tendency of rubber-modified asphalt to stick to the paper. Alternatives to filter paper were release paper or a greased composition paper, both of which were used. The entire batch was placed in the mold. Before compaction, some of the samples were cured in the open molds at 190°C (375°F) or 218°C (425°F) for 2 hr 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., 129°C (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 were lowered to 99°C (210°F) and 10 blows, respectively.
7. The specimens were removed from the mold at room temperature by means of an extrusion jack and then placed on a smooth, level surface until ready for testing. In some cases, a 5-lb surcharge was applied immediately after compaction to evaluate the effect of surcharge on the mix property. The surcharge was removed after a 24-hr period, and the specimen was then extruded from the mold. The purpose of the surcharge was to restrain the compacted samples from rebounding before cooling.
8. The bulk specific gravity and height of each compacted test specimen were measured immediately after extrusion from the mold (AASHTO T-166).

TEST RESULTS

Mix Design

The standard Marshall samples were tested for flow, stability, void content, and diametral modulus. However, the stability, unit weight, and flow factors were not used as criteria for mix design. Air voids (2 percent) were used as the sole criterion for mix design. Recommended asphalt contents and mix properties for each mix design combination are given in Table 8.

Mix Properties at +10°C

Twenty different mix combinations were tested at 100 microstrain in a +10°C (50°F) environmental chamber for resilient modulus and fatigue (Table 9). For all dynamic tests, samples were subjected to a constant load, applied at 60 cycles per minute, with a load duration of 0.1 sec. A 28-lb seating load was applied to all samples. At least three samples for each combination were tested. The results of resilient modulus and fatigue for 20 different mixes are summarized in Table 10.

Discussion of Results

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

Effect of Aggregate Gradation

The effects of aggregate gradation on resilient modulus and fatigue life for three different mixing conditions are shown in Figures 3 and 4. These figures show that the mixtures with gap-graded aggregate in all three mixing conditions have lower

TABLE 8 RECOMMENDED ASPHALT CONTENT AND MIX PROPERTIES AT 2 PERCENT AIR VOIDS

Aggregate Gradation	Rubber Content	Rubber Gradation (% Coarse/%Fine)	Design Asphalt Content %	Marshall Stability lbs	Flow (.01 in)
Gap-Graded	2	0/100	7.0	920	15
		60/40	7.2	690	21
		80/20	8.0	665	23
	3	0/100	7.5	600	19
		60/40	7.5	650	22
		80/20	9.3	436	33
Dense-Graded	0	No Rubber	5.5	1500	8
	3	80/20	7.5	550	22

resilient modulus and higher fatigue life than the mixtures with dense-graded aggregate.

Effect of Rubber Gradations (fine, medium, and coarse)

The resilient modulus and fatigue life for three different rubber gradations (fine, medium, and coarse) are compared in Figures 5 and 6. The mixture with fine rubber has the highest modulus and lowest fatigue life, and the mixture with coarse rubber has the lowest modulus and highest fatigue life.

Effect of Rubber Content (2 versus 3 percent)

The effect of rubber content on resilient modulus and fatigue is shown in Figures 7 and 8. The samples with 3 percent rubber

TABLE 9 SPECIMEN IDENTIFICATION

Specimen Identification	Rubber Content (%)	Rubber Blend (% Fine/% Coarse)	Mixing/Compaction Temperature (°F)	Asphalt Content (%)	Aggregate Gradation	Cure Time (hrs)	Surcharge (lbs)
A[a]	3	80/20	375/265	9.3	Gap	0	0
B	3	80/20	375/265	9.3	Gap	2	0
C[a]	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[a]	2	80/20	375/265	8.0	Gap	0	0
L	2	60/40	375/265	7.2	Gap	0	0
M[a]	2	0/100	375/265	7.0	Gap	0	0
N[a]	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[a]	0	0	375/265	5.5	Dense	0	0

[a] Mix combinations used to establish fatigue curves.

TABLE 10 SUMMARY OF RESILIENT MODULUS AND FATIGUE LIFE

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

Note: Test temperature = +10°C and strain level = 100 microstrain. N_f = number of repetitious to failure.

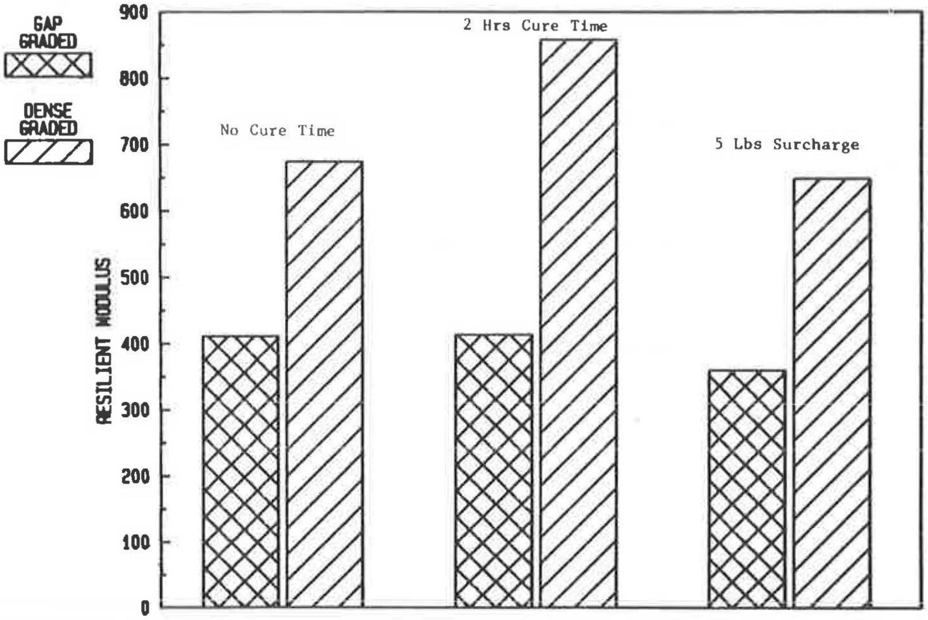


FIGURE 3 Effect of aggregate gradation, cure time, and surcharge on resilient modulus at +10°C (3 percent rubber, 80/20 blend).

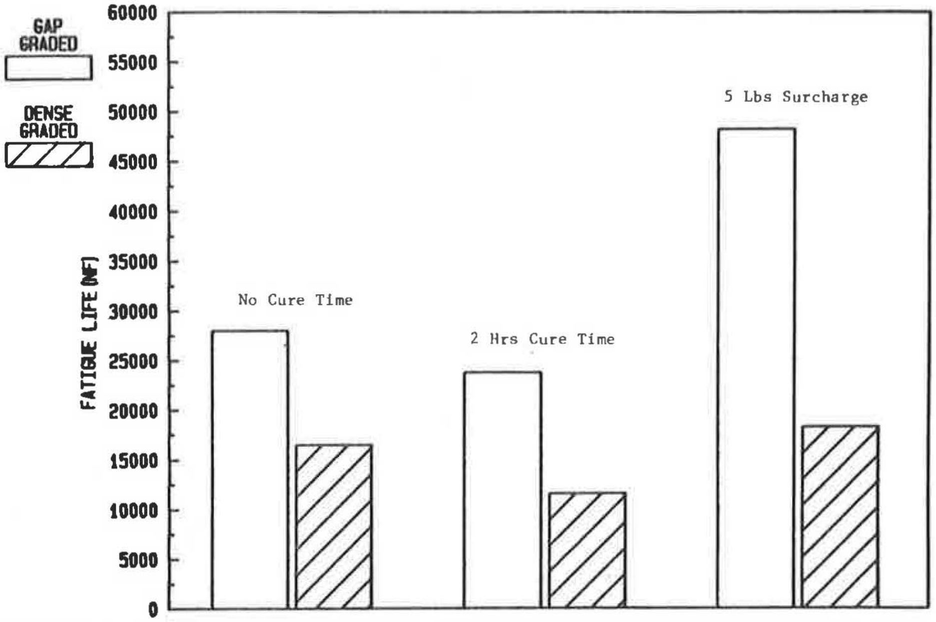


FIGURE 4 Effect of aggregate gradation, cure time, and surcharge on fatigue life at +10°C (3 percent rubber, 80/20 blend).

content generally have lower resilient modulus than the samples with 2 percent rubber content (Figure 7). The rubber content variations did not show any significant impact on fatigue life (Figure 8), with the exception of the fine rubber (0/100) samples.

Effect of Mixing Temperature [190°C (375°F) versus 218°C (425°F)]

The effect of mixing temperature on resilient modulus and fatigue life is shown in Figures 9 and 10. There were no significant differences in resilient modulus for the two temperatures, but in some cases, the fatigue lives for samples with 218°C (425°F) mixing temperature were higher than for the samples with 190°C (375°F) mixing temperature. This may be due to the type of fatigue failure. The gap- and dense-graded materials, which had no cure or surcharge application, failed by fracturing the sample. The gap-graded materials, which had a surcharge application or were cured, failed by plastic deformation.

Effect of Cure Time (0 versus 2 hr)

To evaluate the effect of cure time, samples were cured in the mold open to air at 190°C (375°F) and 218°C (425°F) for 2 hr before compaction. The cure time did not have an effect on the

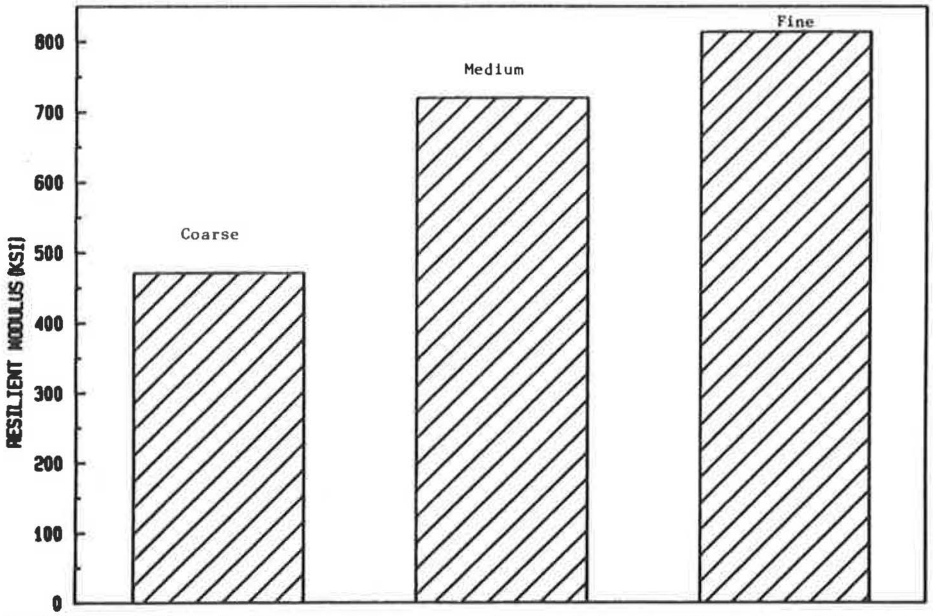


FIGURE 5 Effect of rubber gradations on resilient modulus at +10°C (gap-graded aggregate).

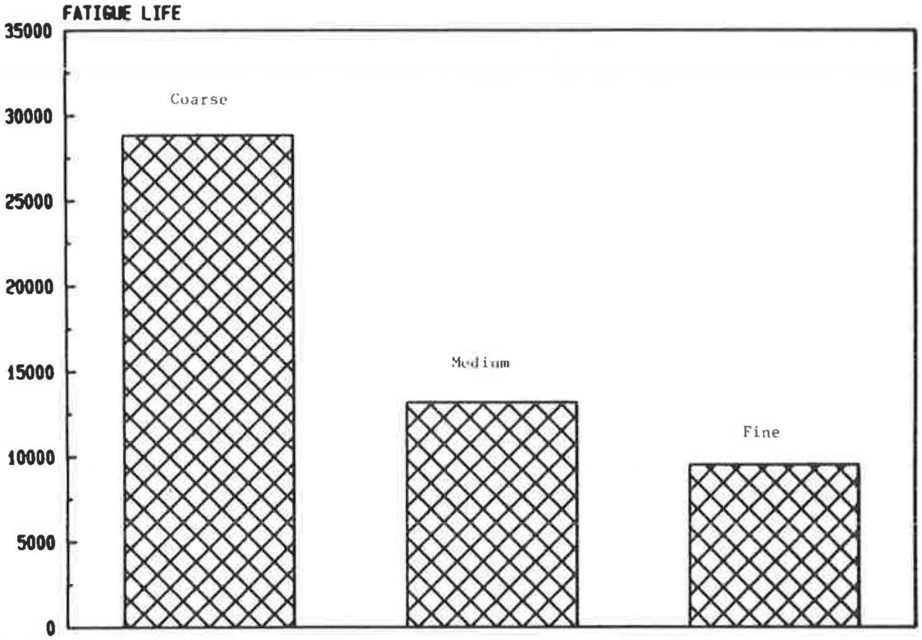


FIGURE 6 **Effect of rubber gradations on fatigue life at +10°C (gap-graded aggregate).**

modulus, but did have an effect on fatigue life. For example, the fatigue life for samples cured at 218°C (425°F) decreased by 35 percent, whereas the fatigue life for samples cured at 190°C (375°F) decreased by 15 percent; this could be due to oxidation of the binder. Curing in absence of air would probably have produced a different result.

Effect of Surcharge (0 versus 5 lb)

The 5-lb surcharge had little effect on modulus, but a significant effect on fatigue life with gap-graded aggregate, and a slight effect on the fatigue life for dense-graded aggregate. For the gap-graded mixtures, the voids were about the same; however, for the dense-graded mixtures, the voids with the surcharge were less (3 versus 2 percent).

Effect of Air Voids (2 versus 4 percent)

The resilient modulus slightly decreased when the air void content increased from 2 to 4 percent for the gap-graded mix. However, the modulus of the dense-graded mix was reduced by 50 percent when the air void content was increased. The dif-

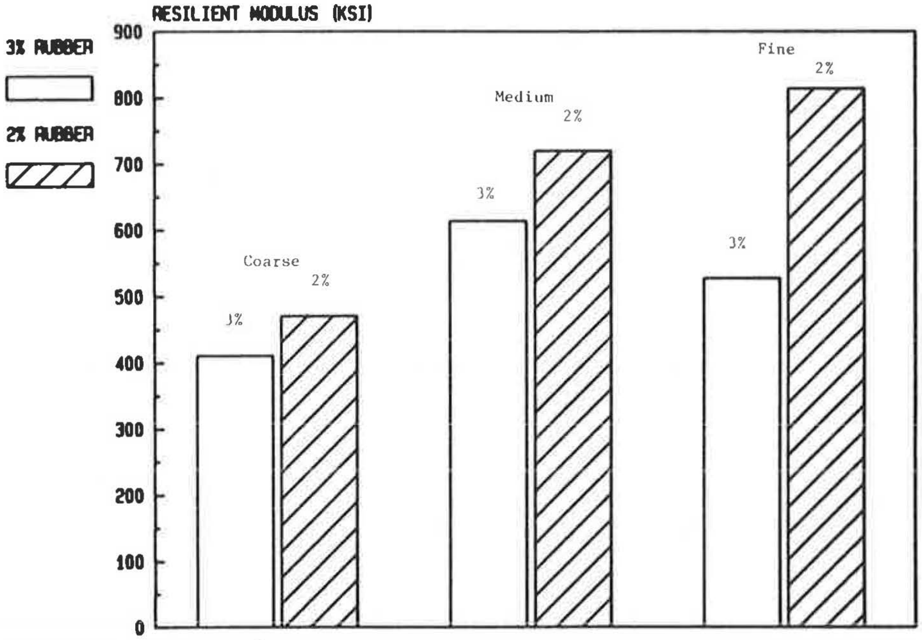


FIGURE 7 **Effect of rubber content on resilient modulus at +10°C (gap-graded aggregate).**

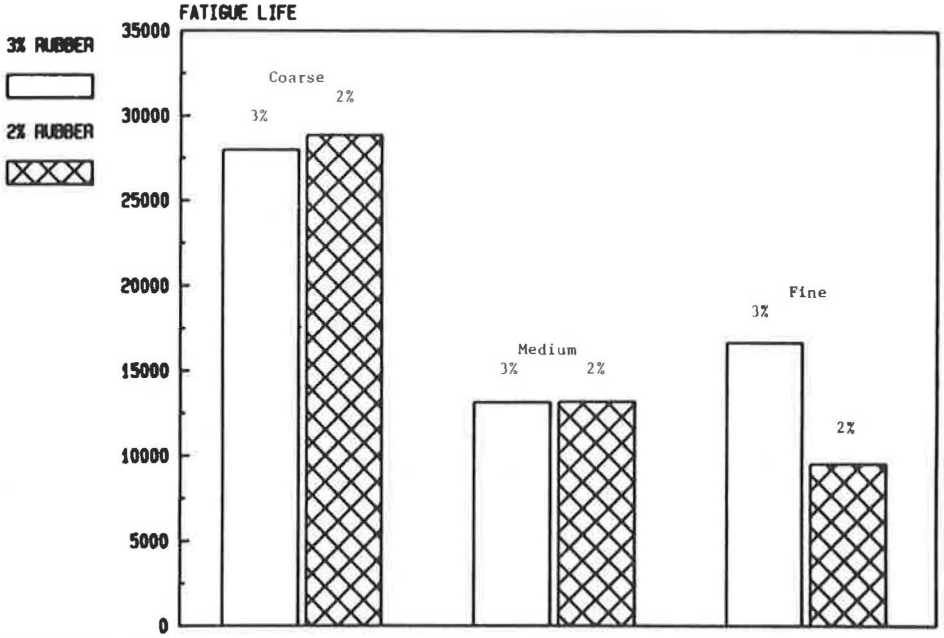


FIGURE 8 Effect of rubber content on fatigue life at +10°C (gap-graded aggregate).

ference in sensitivity to air voids between gap-graded and dense-graded mixes can be attributed to asphalt content (9.3 versus 7.5 percent). 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 the dense-graded rubber mix reduced with an increase in air voids. This behavior is similar to that of conventional dense-graded mixes. However, the fatigue life for the gap-graded rubber mix increased with an increase in air voids. This is contrary to the conventional relationship between air voids and fatigue life. Therefore, selection of the optimum asphalt content by using air voids as the sole criterion may not produce optimum mix properties in rubber mixes. The mode of failure may be another reason for these contrary results. The mode of failure for all of the gap-graded specimens at 2 percent air void was brittle fracture. The specimens at 4 percent air void failed by plastic deformation.

Comparison of Rubber-Modified versus Conventional Mix at +10°C

The resilient modulus of conventional asphalt mix was approximately twice the value obtained for dense-graded rubber mix

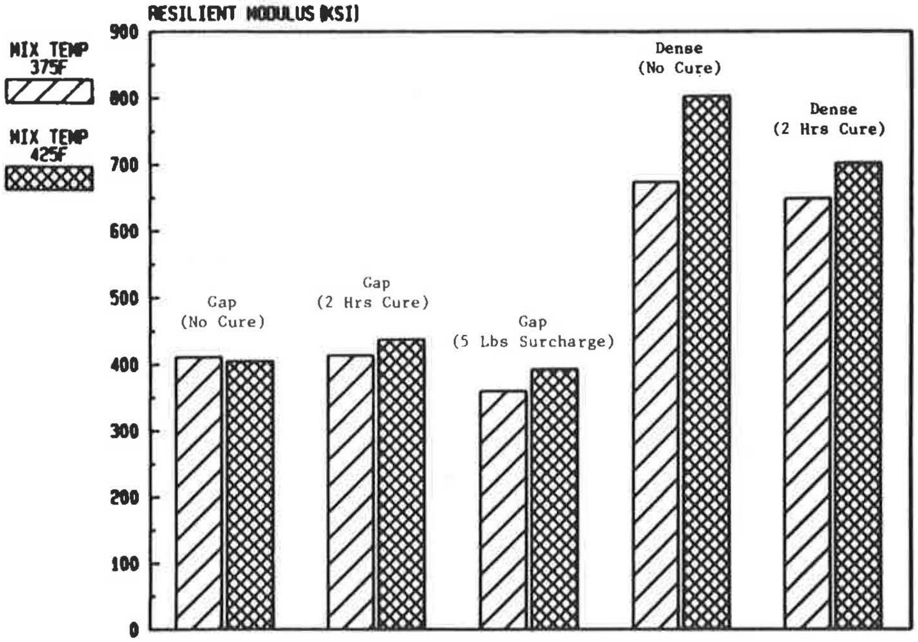


FIGURE 9 Effect of mixing temperature on resilient modulus at +10°C (3 percent rubber, 80/20 blend).

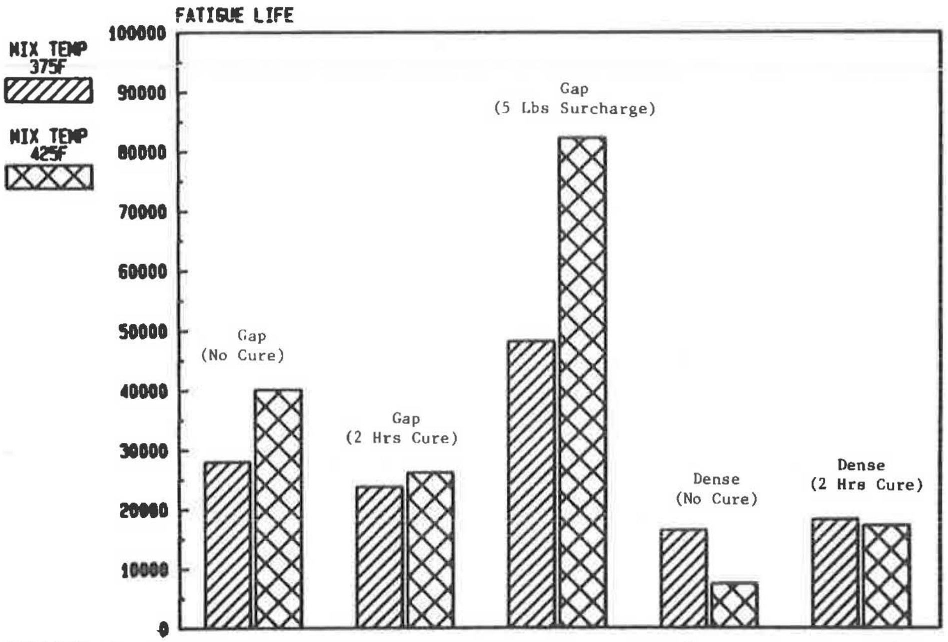


FIGURE 10 Effect of mixing temperature on fatigue life at +10°C (3 percent rubber, 80/20 blend).

and almost three times the value for gap-graded rubber mix (Figure 11). 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 with the modulus values (Figure 12). The higher the modulus, the lower the fatigue life.

Fatigue Curves 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.

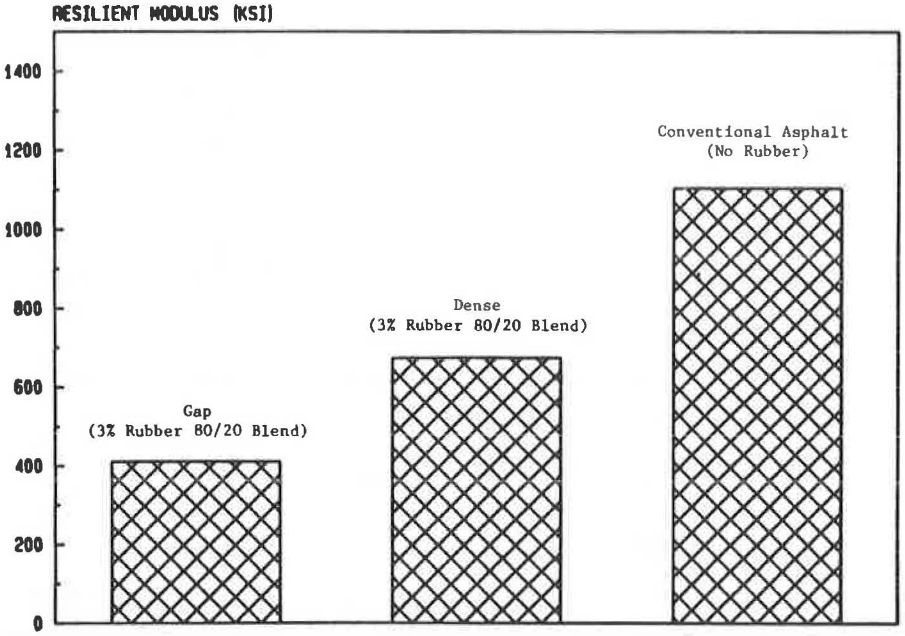


FIGURE 11 Effect of rubber content and aggregate gradation on resilient modulus at +10°C.

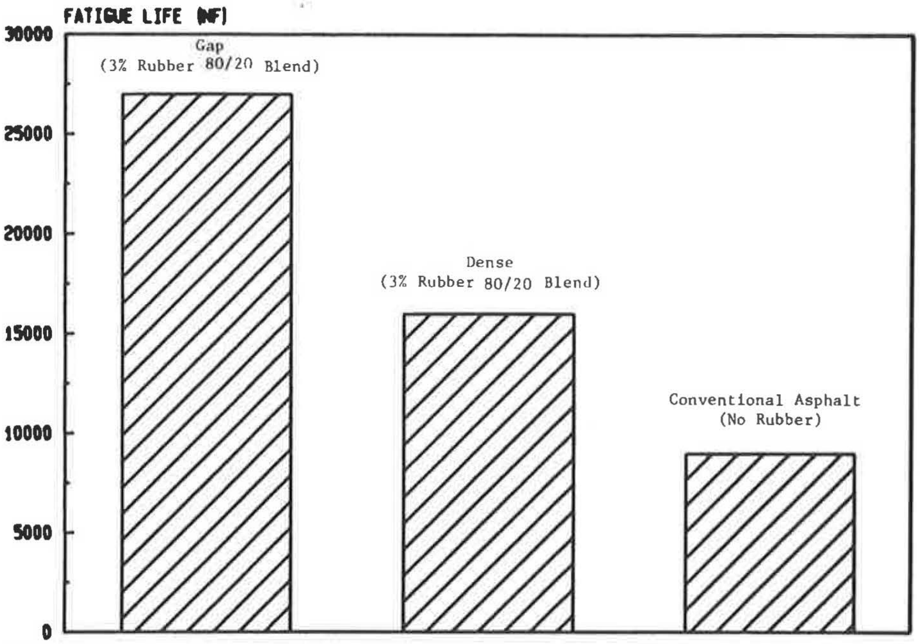


FIGURE 12 Effect of rubber content and aggregate gradation on fatigue life at +10°C.

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 *(10)*:

$$N_f = a(\varepsilon_t)^{-b} \qquad (2)$$

where

N_f = number of repetitions to failure,
a = antilog of the intercept of the logarithmic relationship,
ε_t = initial tensile strain (in./in.), and
b = slope of the logarithmic relationship between fatigue life and initial strain.

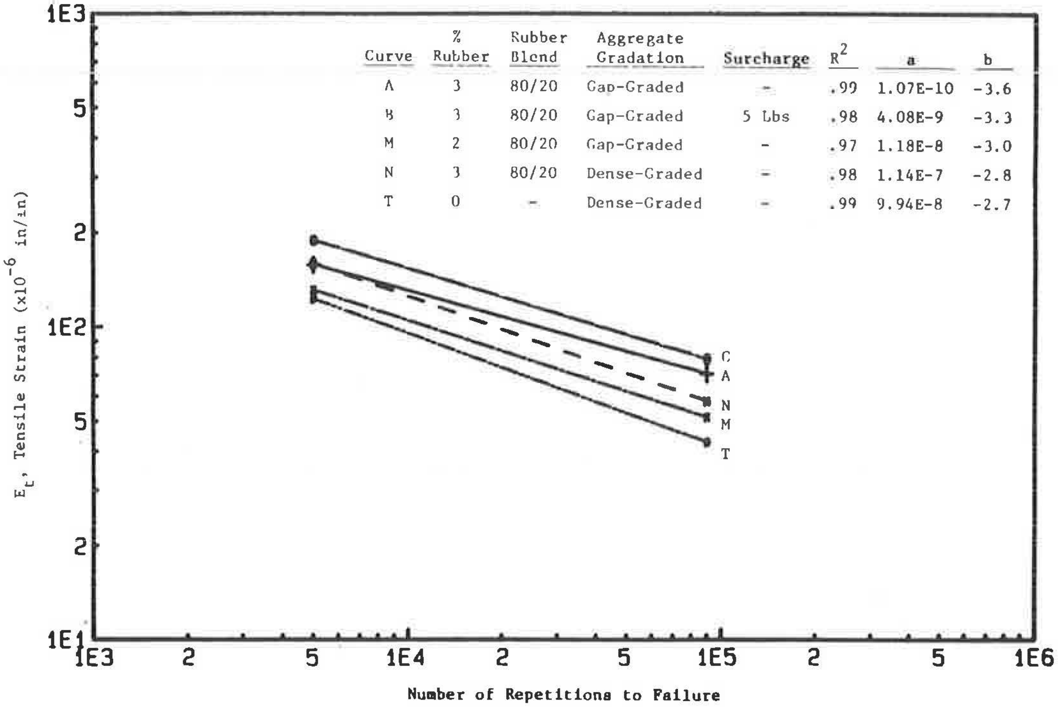
Values of a and b are affected by mix type, asphalt content, rubber gradation, rubber content, and aggregate gradation. A low value of a usually indicates a low fatigue life, assuming the fatigue curves are parallel to one another.

The results of the fatigue tests are shown in Figure 13. As indicated, the conventional mix has the lowest a-value, whereas the rubberized asphalt with surcharge has the highest a-value. The fatigue life equations are shown in Figure 13 together with R^2, or coefficient of determination. R^2-values tend to be greater than 0.95. If the performance of the pavement is based on fatigue, Figure 13 shows the rubber-modified mixes to be superior to conventional asphalt mixes.

CONCLUSIONS

The aim of the study was to test laboratory-prepared specimens to evaluate the effect of mix ingredients on the performance of rubber-modified asphalt mixtures. Based on the results of this study, the following conclusions appear warranted:

1. The laboratory mix design results indicate 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. For example, the mixture with gap-graded aggregate and 3 percent coarse rubber (based on dry aggregate weights) required the highest design asphalt content (9.3 percent). Reducing the rubber content to 2 percent resulted in a reduction in asphalt content to 8.0 percent. 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 percent). The asphalt contents reported were for 2 percent air voids.
2. Resilient modulus values for rubber mixes were generally higher for dense-graded aggregates than for gap-graded aggregates.
3. The gap-graded mix had a higher (by 40 percent) fatigue life at +10°C (50°F) than the dense-graded mix.
4. The resilient modulus values for gap-graded and dense-graded aggregates increased at +10°C (50°F) as the rubber gradation became finer. The fatigue lives were reduced by about 20 percent as the rubber gradation became finer.
5. As the percent rubber by dry weight of aggregate increased from 2 to 3 percent, the modulus values generally decreased at +10°C (50°F) for gap-graded mixes. The fatigue life of gap-graded mixes was not significantly affected at +10°C (50°F) by increasing the rubber content from 2 to 3 percent.
6. 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.
7. A high mixing temperature [218°C (425°F)] slightly increased the modulus and the fatigue life for gap-graded mixes tested at +10°C (50°F). Dense-graded mixes tested at +10°C (50°F) showed an increase in modulus, but a decrease in fatigue life with higher mixing temperatures.



Curve	% Rubber	Rubber Blend	Aggregate Gradation	Surcharge	R^2	a	b
A	3	80/20	Gap-Graded	-	.99	1.07E-10	-3.6
B	3	80/20	Gap-Graded	5 Lbs	.98	4.08E-9	-3.3
M	2	80/20	Gap-Graded	-	.97	1.18E-8	-3.0
N	3	80/20	Dense-Graded	-	.98	1.14E-7	-2.8
T	0	-	Dense-Graded	-	.99	9.94E-8	-2.7

FIGURE 13 Laboratory fatigue curves at +10°C.

8. The effect of cure time after mixing, on both resilient modulus and fatigue life at both curing temperatures [190°C (375°F) and 218°C (425°F)], was not significant.

9. The 5-lb surcharge weight, which was applied after compaction, increased the fatigue life and decreased the resilient modulus at +10°C (50°F).

10. The fatigue life increased with increasing voids (2 to 4 percent). Although this is contrary to the conventional relationship between air voids and fatigue life, it is based on a considerable number of tests, indicating additional work is needed to document the effects of voids for rubber-asphalt mixes. The resilient modulus values at both temperatures decreased as air voids increased, as would be expected.

ACKNOWLEDGMENTS

The authors wish to acknowledge the support of the Alaska Department of Transportation and Public Facilities and the FHWA, U.S. Department of Transportation, who sponsored this study. Special thanks go to numerous laboratory personnel from Oregon State University and ADOTPF personnel. Also, special mention should be made of university students Jay McQuillen, James Lundy, and Ginnie Grilley, who assisted in the conduct of the research.

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Publication of this paper sponsored by Committee on Characteristics of Nonbituminous Components of Bituminous Paving Mixtures.