FAA Mixture Design Procedure for Asphalt-Rubber Concrete

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A mixture design procedure was developed to allow the use of asphalt-rubber binders in concrete for flexible airport pavements. The rubber material considered in this project included only rubbers produced by grinding scrap tires. Such materials are widely available across the United States and have been used in seal coat and interlayer construction for almost 25 years. However, only limited experimentation has been done using this type of asphalt-rubber in concrete for flexible pavements. The asphalt-rubbers chosen for use in this project were produced in the field. The materials used in this study were shown to be similar to materials produced in the laboratory from the same combination of ingredients. The results of this study include a suggested laboratory procedure for producing asphalt-rubber for use in the asphalt-rubber concrete mixture design procedure. A suggested setup of equipment is also included along with vendors who have these items on the shelf. The mixture design procedure includes modifications to the standard FAA procedure included in the Asphalt Institute MS-2 manual. These modifications mainly involve mixing and compaction temperatures and gradation changes to accommodate the solid rubber particles added to the asphalt.

Charles H. McDonald, Consulting Engineer, Phoenix, Arizona, is considered to be the father of the asphalt-rubber systems developed in the United States. McDonald's laboratory work, which was initiated in 1963, resulted, in the mid-1960s, in the development of a patented patching material that consisted of 25 percent ground scrap vehicle tire rubber and asphalt cement blended at approximately 375°F for 20 min.

McDonald continued his experimental work with the city of Phoenix and initiated research efforts with Atlos Rubber, Inc. Several experimental test sections were placed at Phoenix Sky Harbor International Airport (1966) and on US-80 near downtown Phoenix. Sahuaro Petroleum Asphalt Company (Sahuaro) became interested in the product and cooperated in testing seal coat applications. In 1975 Arizona Refining Company (ARCO) began experimental work with asphalt-rubber binder systems. The result of the experimental work conducted by McDonald, ADOT, Sahuaro, and ARCO has led to the use of asphalt-rubber in about 35 states.

National conferences have shown the need for additional information on performance, relationships between laboratory developed properties and performance, design techniques for specific applications, specifications and tests for compliance, and construction practices. Although recent work has helped to more clearly define some of those areas of concern, there is a continued need to more clearly define the circumstances in which these various treatments can best be used to solve the maintenance problems encountered.

LABORATORY TESTING AND PRODUCTION OF ASPHALT-RUBBER BINDERS

Laboratory Testing of Asphalt-Rubber Binders

Concerted attempts have been made to evaluate asphalt-rubber binders by applying laboratory tests developed for specification testing and characterization of asphalt cements. Few attempts show much success. Repeatability depends on uniform consistency of the asphalt. Because asphalt-rubber is a blend of asphalt and fine rubber particles, the discrete nature of the rubber produces considerable variation in test results.

A variety of laboratory tests for characterizing asphalt-rubber materials has been evaluated by researchers such as Pavlovich et al. *(1)*, Shuler and Hamberg *(2)*, Jimenez *(3)*, Oliver *(4)*, and Chehovits et al. *(5)* (see Table 1). Although several of these test procedures offer promise for characterizing the behavior of asphalt-rubber or for detecting differences among various combinations of components, none appears to be suitable for use in specification testing of these materials. Indeed, little of the research to date has been directed toward defining the characteristics that an asphalt-rubber binder should have in order to meet prescribed performance requirements.

One of the most significant problems faced by asphalt technologists is that there are inadequate behavioral models to describe the function of the binder in an asphalt aggregate system. Therefore, technologists continue to use correlations between laboratory tests, such as the ring and ball softening point, and engineering properties, such as stiffness, developed by Shell researchers during the 1950s and 1960s.

These methods appear to work for asphalt cements and have been organized into well-developed, comprehensive design procedures. However, design methods such as the Shell Pavement Design Guide *(6)* cannot be applied to asphalt-rubber binders without extensive testing programs to develop the relationships among binder characteristics and mixture properties. In the current study, procedural or recipe methods were selected for preparation of the asphalt-rubber mixtures for both

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TABLE 1 LABORATORY TESTS USED TO CHARACTERIZE ASPHALT-RUBBER

Laboratory Procedure	Pavlovich et al. *(1)*	Shuler and Hamberg *(2)*	Jimenez *(3)*	Oliver *(4)*	Chehovits et al. *(5)*
Ring and ball softening point	x				
Absolute viscosity at 140°F	x				
Ductility at 39.2°F and 77°F	x		x		
Double ball softening point (phase change temperature)			x		
Force ductility	x	x			
Constant stress (Schweyer) rheometer	x	x			
Sliding plate microviscometer/ rheometer				x	x
Falling coaxial cylinder viscometer			x		

laboratory studies and full-scale field projects until more fundamental relationships can be developed.

Factors That Affect Properties of Asphalt-Rubber Materials

Background

Rubber has been incorporated in asphalt roadways since the beginning of this century *(7)*. Early asphalt-rubber combinations used natural rubber, which is susceptible to oxidation and, when overheated, converts to an oil and loses its beneficial properties *(8)*. These deficiencies were overcome with synthetic rubber, which was compounded and vulcanized to resist heat and weathering. Although synthetic rubber lacked the solubility of natural rubber, it could be reacted with asphalt to produce similar characteristics, but much larger quantities were required.

In some cases the synthetic rubber appeared to absorb the oils out of the asphalt leaving blends that exhibited poor adhesive properties *(8)*. Researchers found that asphalts with low aromatic oil contents produced these dry blends. This problem was overcome when whole truck tire rubber, with about 18 percent natural rubber *(9)*, was used. With this high-natural-rubber scrap the blend exhibited the desired sticky elastic character of the early natural rubber blends but had greater heat stability.

On the basis of the knowledge gained from these trial investigations, formulations of asphalt, extender oil, and scrap rubber have been developed that produce a material with the desired characteristics. A discussion of the factors that affect asphalt-rubber properties follows.

Rubber Factors

The factors that most influence the formulation of asphalt-rubber are discussed in this subsection. Most of these factors have been investigated thoroughly. Although most are known to be important in asphalt-rubber production, their effect on specific performance-related factors is not well understood.

Rubber Type A wide assortment of scrap rubber is available for use in asphalt-rubber systems. The chemical composition of the rubber varies depending on the sources of the scrap such as automobile tires, and truck or bus tires, and whether the rubber is tread peel or whole carcass rubber. LaGrone *(10)* defined the terms related to processing of scrap rubber and provided typical composition of scrap rubbers available for production of asphalt-rubber binders. The type of rubber selected affects the elasticity of the resulting asphalt-rubber *(1, 2, 4, 5, 9)* and the stability of the reacted product *(8)*.

Rubber Processing Method The method of processing the scrap rubber significantly affects the digestion of the rubber and the properties of the asphalt-rubber. Oliver *(4)* found rubber morphology (structure) to be the most important factor affecting elastic properties. Shuler *(11)* reported differences in viscosity among rubbers of different morphology, but morphology was confounded with differences in particle size and natural rubber content.

Oliver *(4)* included electron micrographs of rubber particles to show the differences between the surface morphology of particles ground at ambient temperature and those cryogenically ground. These differences affect the surface area of the rubber and the rate at which the reaction occurs.

In addition to rubber morphology, the size of the rubber particles and whether the rubber has been processed after grinding (i.e., devulcanized) both affect the rate of reaction of the asphalt-rubber *(8, 9)*. These last two factors affect the type of asphalt selected for the digestion process *(12)* more than the engineering properties of the asphalt-rubber produced *(4, 11)*.

Rubber Concentration Asphalt-rubber, as currently used, includes between about 15 and 28 percent by total weight of dry rubber in an asphalt cement matrix. The rubber concentration is acknowledged by all researchers to significantly affect the properties of the reacted asphalt-rubber binder. Specifying agencies often use the general specifications of a supplier including the proportions of the asphalt-rubber components, the component specifications, and the blending conditions. Indeed, specifications from Texas *(13)*, New York *(14)*, and Arizona *(12)* are similar in style and content, which indicates

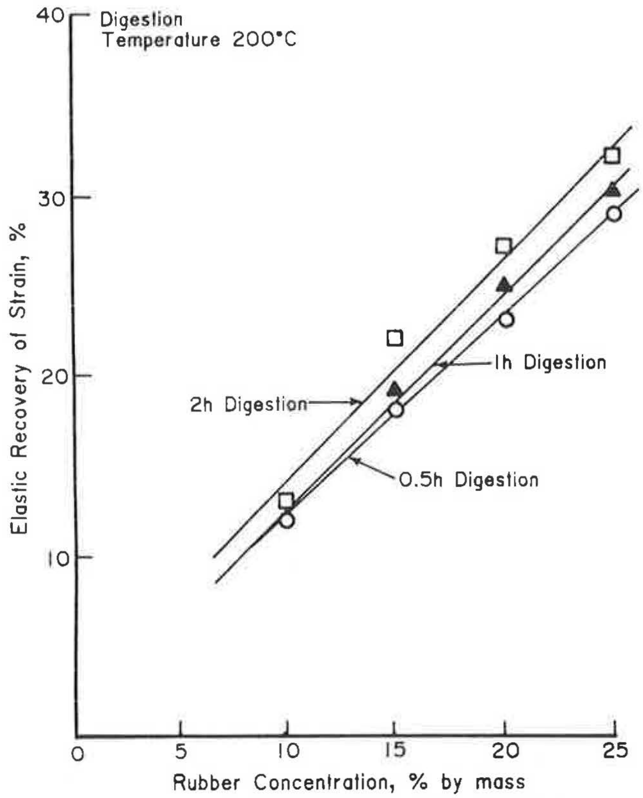

FIGURE 1 Effect of rubber concentration on elastic recovery *(4)*.

that the product is fairly well defined in terms of materials and processes.

Researchers all indicate that rubber concentration significantly affects the properties being measured. The effect of rubber concentration on elastic recovery found by Oliver is shown in Figure 1. Similar levels of strain recovery have been reported by Chehovits et al. *(5)*.

Reaction Temperature and Mixing Time Reaction temperature and mixing time combinations significantly affect asphalt-rubber properties *(1, 2, 4, 11)*. Figure 1 shows the effect of mixing time at a constant temperature on elastic recovery. Figure 1 data indicate that a prescribed elastic recovery could be achieved by reducing rubber concentration while increasing mixing time. However, Shuler *(11)* has shown that as the mixing time increases the amount of solid rubber in the mixture begins to be reduced. Shuler extracted the solid rubber from the asphalt-rubber mixture and performed gel permeation chromatography (GPC) tests on both the virgin asphalt and the asphalt-rubber. The GPC molecular weight distribution was shifted at both the high and the low ends indicating that, as digestion continues, some rubber may be lost to the asphalt. Huff and Vallerga *(8)* also discuss the reaction of natural rubber in asphalt cement and point out that when high-natural-rubber scrap is used the material exhibits the same characteristics as those with only natural rubber and asphalt. The major difference between these two types of mixtures is that synthetic rubber digestion is slower, but it is more heat stable than natural blends and more forgiving of field delays.

Shuler *(11)* has also shown that, even though various combinations of mixing temperature and time may be selected, the viscosity during digestion can be used to terminate the mixing process at a consistent viscosity level (Figure 2). Monitoring the viscosity in the field can also allow materials to be prepared in the laboratory at the same digestion level. That materials can be produced in the laboratory with properties similar to those produced in the field from the same ingredients has been verified by Shuler *(11)* and Shuler et al. *(15)*. However, Shuler et al. *(15)* indicated that low-level field digestion did not produce mixture properties corresponding to those produced by low-level digestion in the laboratory. Low-level field digestion was somewhere between low and moderate laboratory levels. The important thing is that laboratory-produced asphalt-rubbers are similar to those produced in the field. A suggested laboratory production procedure is described in the next section.

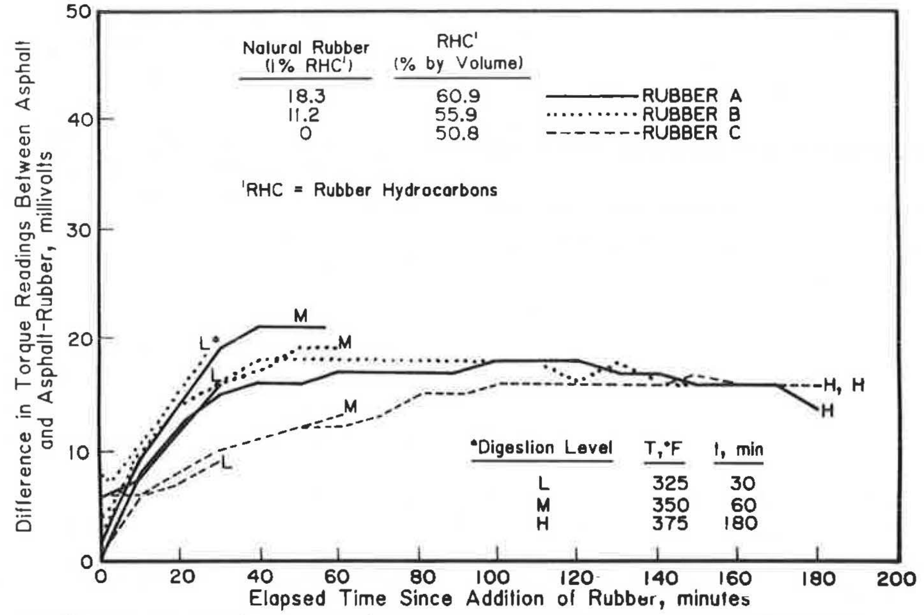

FIGURE 2 Torque-fork output for three rubbers used in El Paso at 22 percent rubber and three digestion levels *(11)*.

Laboratory Production of Asphalt-Rubber

Asphalt-rubber has been produced in the laboratory by using a variety of techniques that vary from open containers *(12)* to closed systems *(15)*. Apparently both systems produce suitable asphalt-rubber materials.

Reaction times in laboratory studies have varied from 0.5 to 2 hr at temperatures that typically range from 325°F to 450°F. The effect of reaction time has been evaluated using both viscosity and the properties of the reacted asphalt-rubber. Oliver *(4)* investigated the effect of both reaction time and temperature on elastic recovery strain of natural and synthetic rubbers. The plots in Figure 3 quite clearly show the interaction and that the properties can be significantly reduced by too long a reaction time. Notice in Figure 3 that the peak of elastic recovery shifts toward lower temperature as digestion time increases and that the elastic recovery drops off sharply for the 2-hr digestion time when temperature exceeds 425°F. Oliver showed that synthetic rubber is much more stable under higher digestion conditions than are natural rubbers.

Shuler et al. *(15)* conducted a study to evaluate the effect of rubber type, concentration, and digestion conditions on viscosity and properties of the resultant asphalt-rubber binders. A series of plots was included to show the influence of these factors. Figure 2 shows several of these effects. All three of these rubbers were vulcanized with Rubbers A and B ground under ambient conditions; Rubber C was cryogenically ground. A review of the plots shows that at least the medium level of digestion is required to achieve a stable viscosity within a reasonable time and that the high temperature (375°F) has the advantage that most mixtures reached a stable viscosity within 1 hr. Notice too that Rubber C is the slowest reacting mixture; it has no natural rubber and was cryogenically ground. However, Rubbers A and B both reach stable viscosities at 375°F after 1 hr of digestion.

On the basis of a survey of laboratory reaction conditions from selected literature and Shuler's *(11)* comparison of viscosities of rubber asphalts produced in both the field and the laboratory, it is recommended that laboratory mixing be performed at 375°F for 1 hr or until the viscosity-versus-time plot is relatively constant. A suggested procedure is described next.

Suggested Laboratory Procedure

Equipment

The following list of equipment is recommended for digestion of asphalt with rubber to produce binders for mixture design:

1. Induction motor stirrer—variable torque, constant speed motor capable of operating at 500 rpm to monitor viscosity and automatically adjust motor power to maintain selected speed.
2. Proportional temperature controller to maintain temperature in reaction kettle to within ±0.10°C for temperatures up to 250°C. Power available to heaters shall be approximately 750 watts.
3. Electric heating mantle for round bottom 2000-mL flash with thermocouple and power output of from 500 to 750 watts.
4. Three-neck reaction flask with 24/40 ground glass joints.
5. Teflon bearing for stirring rod used with Item 1 can be custom made or scavenged from a closed system stirrer for vacuum work such as Fischer 14-513-100 stirrer for vacuum work or Cole-Parmer K-4740-00 closed system stirrer with 24/40 glass joint.
6. Ring stand and supporting equipment.

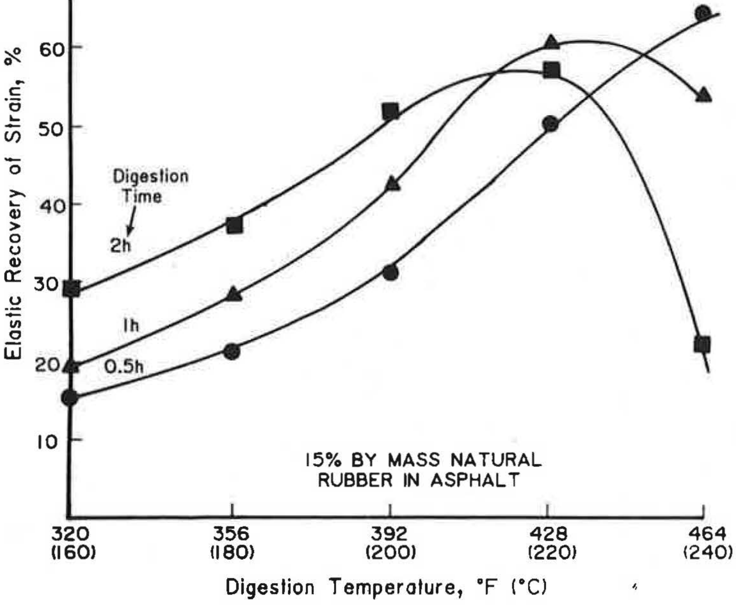

FIGURE 3 Effect of digestion time and temperature on elastic recovery for asphalt-rubber from national rubber tire buffings *(4)*.

7. Strip chart recorder for monitoring output of stirrer (optional).

Procedure

The suggested procedure is based largely on the experience of researchers from Arizona, New Mexico, and Texas *(1, 2, 11, 15, 16)*. The procedure is based on the assumption that reaction should continue until a stable viscosity (torque from the stirrer) is achieved. Even though a stable viscosity can be achieved using a variety of mixing times and temperatures, a particular combination is suggested in order to provide guidance in preparing suitable materials for mixture design. Figure 4 shows a typical equipment setup.

The proposed reaction system consists of a constant-speed motor with a propeller stirrer for constant agitation of the asphalt-rubber. Heat is supplied through an electric heating mantle and is monitored and adjusted by an electronic temperature controller. The stirrer acts as a rotational viscometer that can measure relative changes in fluid viscosity during digestion. Viscosity can be estimated by calibrating the stirrer output with viscosity measurements from a Haake portable rotational viscometer model VT-02 or a Brookfield viscometer. Shuler et al. *(15)* developed such a correlation with a Brookfield viscometer; the coefficient of determination was 99 percent. Such procedures appear to be quite satisfactory for controlling the mixing process and for correlating laboratory viscosity with viscosity during digestion in the field.

Samples of the materials to be used in the field should be secured using appropriate statistical sampling procedures to ensure that representative materials are obtained. Materials to be sampled include the asphalt cement, the rubbers, and the diluents.

- Step 1: Heat approximately 1000 mL of the asphalt slowly and stir to avoid local overheating. When the asphalt is fluid add the appropriate amount to the 2000-mL reaction flask; also add diluent if included in the mixture. Insert the mixer propeller, continue heating the asphalt, and increase the mixer speed to 500 rpm.
- Step 2: When the asphalt cement reaches 375°F, add the proper blend of rubber to the flask through the neck. Add the rubber as quickly as possible (approximately 10 sec). Begin digestion time as soon as the rubber has been added and the environment of the flask secured.
- Step 3: Continue reacting the asphalt-rubber for not less than 1 hr or until the output from the stirrer reaches a uniform level. Reaction time is a function of the type, morphology, concentration, and gradation of the rubber materials and can vary considerably (see Figure 2 and the attendant discussion).
- Step 4: On completion of blending, the asphalt-rubber is ready for mixing or storing.

ASPHALT-RUBBER CONCRETE MIXTURE DESIGN

Background

Although asphalt-rubber materials have been used extensively in seal coat and interlayer construction, only a limited amount of experimental work has been done using asphalt-rubber as a binder in asphalt concrete construction. Some of the earliest work reported in the literature was by Jimenez *(17)* in 1979 and later *(12)* in 1982. Jimenez prepared asphalt-rubber using the same techniques and formulations as those used for seal coats, membranes, and interlayers in Arizona. The aggregate was for a standard dense-graded surface with a top size of 3/8 in.

Jimenez used two different compaction methods:

1. The Triaxial Institute compactor, also known as the California kneading compactor, using test method ARIZ 803, and

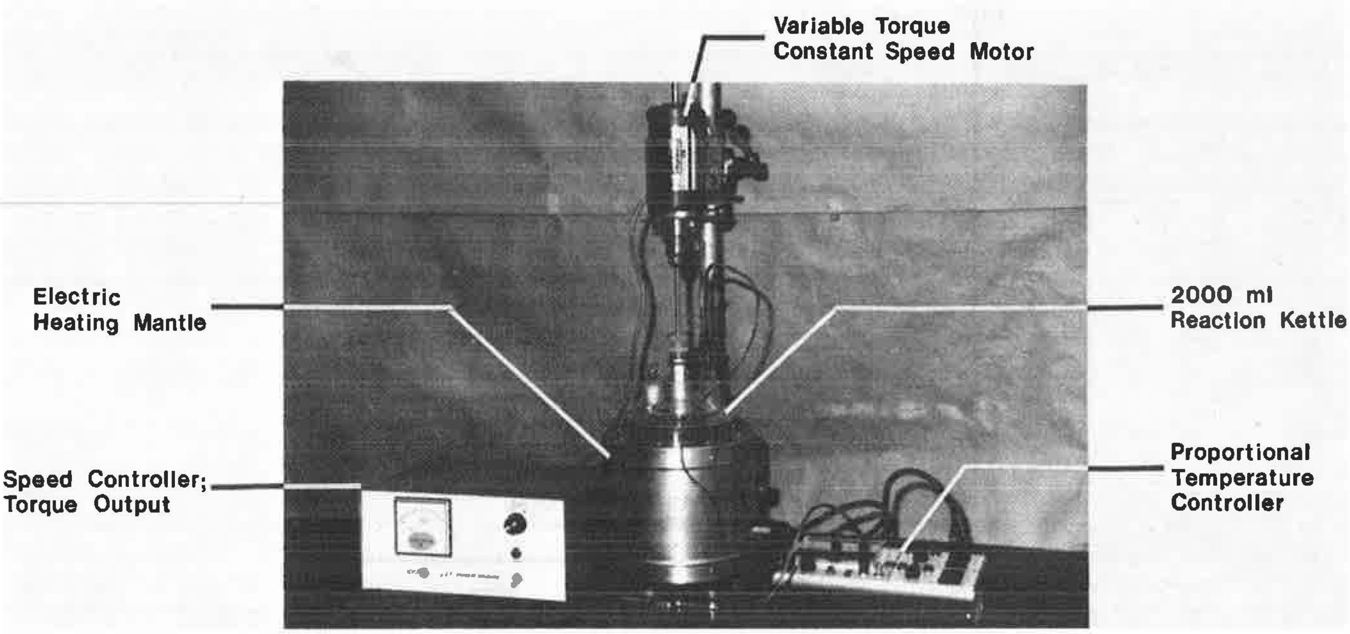

FIGURE 4 Suggested equipment setup for laboratory production of asphalt-rubber material *(15)*.

2. The vibratory kneading compactor described elsewhere *(18)*.

Both of these methods employ techniques for applying compactive energy that are considerably different from that of the standard Marshall test method used by the FAA *(19)*.

Jimenez observed a number of differences between the behavior of the asphalt-rubber concrete specimens and a standard asphalt concrete. He noted that, after compaction with the California kneading compactor, it was necessary to leave the asphalt-rubber concrete specimens in the mold for 3 days because, if extracted before then, the specimens would swell up to the point of cracking and the radial dimension would increase so much that the specimens would not fit into the Hveem stabilometer shell. During testing he found that the asphalt-rubber specimens would not hold the confining pressure without a preload applied before Hveem testing began.

Hveem specimens were also prepared using a modification of the vibratory kneading compaction procedure. The modification involved the application of a static load of 3,770 lb after vibratory compaction was completed. Apparently the swelling problems noted with the California kneading compactor did not occur with the vibratory kneading compactor *(12)*. None of the other researchers who have prepared asphalt-rubber concrete specimens have reported significant problems with swelling of specimens *(20, 21)*. Lalwani et al. *(20)* and Schuler et al. *(21)* used the Marshall hammer for specimen compaction. However, in this study, when specimens were extruded immediately after compaction, some swelling did occur. Therefore all specimens were allowed to cool to room temperature before extrusion from the mold.

Only a limited number of studies have been reported that used asphalt-rubber binders as defined in this paper. Other studies have included the use of scrap rubber in an asphalt concrete, but the rubber is treated as an aggregate and not reacted with the asphalt before mixing with the aggregates. One of the latest studies of this type was conducted by Takallou et al. *(22)*.

The combinations of mixing and compaction conditions for asphalt-rubber concrete included in the literature cited previously are given in Table 2. Notice that both the mixing and the compaction temperatures are considerably higher than those used for asphalt concrete. The primary reasons for the higher than normal temperatures are (a) the very high viscosity of the asphalt-rubber binder at typical mixing and compaction temperatures defined for the Marshall method *(19)* and (b) the difficulty of wetting the aggregate surface with the asphalt-rubber, which is more elastic than the untreated asphalt cement *(23)*. It should be noted, however, that in the laboratory no problems have been reported with coating aggregate particles using standard mixing equipment *(12, 17, 21)*.

Development of the Modified Mixture Design Method

Asphalt-rubber concrete was fabricated and tested in the laboratory. Two gradings of aggregate were evaluated using asphalt-rubber and conventional asphalt binders. Results of laboratory tests are compared with control asphalt concretes fabricated with identical types and gradations of aggregate. The control mixtures were fabricated using conventional techniques for asphalt cement binder. The experimental mixes were fabricated using slightly modified techniques and two asphalt-rubber binders.

Materials

Asphalt-rubber from two sources was used for the experiments reported in this section of the paper. Samples of the asphalt-rubber were obtained in the field from actual construction sites. Type A contained 25 percent rubber by weight and Type B contained 18 percent. The gradations of the rubber particles are shown in Figure 5.

Two standard laboratory aggregates used by the Texas Transportation Institute on numerous other research projects were used for the mix design. These aggregates are a subrounded river gravel obtained from a local Brazos River source and a limestone from near Brownwood, Texas. Gradations used for control asphalt concrete mixes are shown in Figure 5. Although these gradations follow the lower edge of the FAA specification band, it was reasoned that mixtures in this region would be most critical and that fabrication procedures suitable for them would function properly for coarser gradations. A slight modification was made in the gradations of these materials to allow room for rubber particles in the mix. A blending of the rubber grading and modified mineral aggregate grading resulted in a combined gradation that matched the control aggregate gradation without rubber.

Control asphalt concretes were prepared using AC-10 asphalt cement and subrounded river gravel and limestone at the gradations shown in Figure 5. Control asphalt concrete test

TABLE 2 ASPHALT-RUBBER CONCRETE SPECIMEN PREPARATION CONDITIONS REPORTED IN THE LITERATURE

	Compaction Type				Temperature Conditions (°F)		
					Mixing		
Investigator	California Kneading Compactor	Vibratory Kneading Compactor	75-Blow Marshall Hammer	Mixing Time (min)	Asphalt-Rubber	Aggregate	Compaction
Jimenez *(12, 17)*	x	x		2	375	300	250
Lalwani *(20)*			x	—[a]	—[b]	—[b]	—[b]
Dickson *(23)*			x	Until coated	375	375	375
Vallerga *(24)*			—[b]	—[b]	350	350	325

[a] Not included but no problem in mixing reported.
[b] Not included.

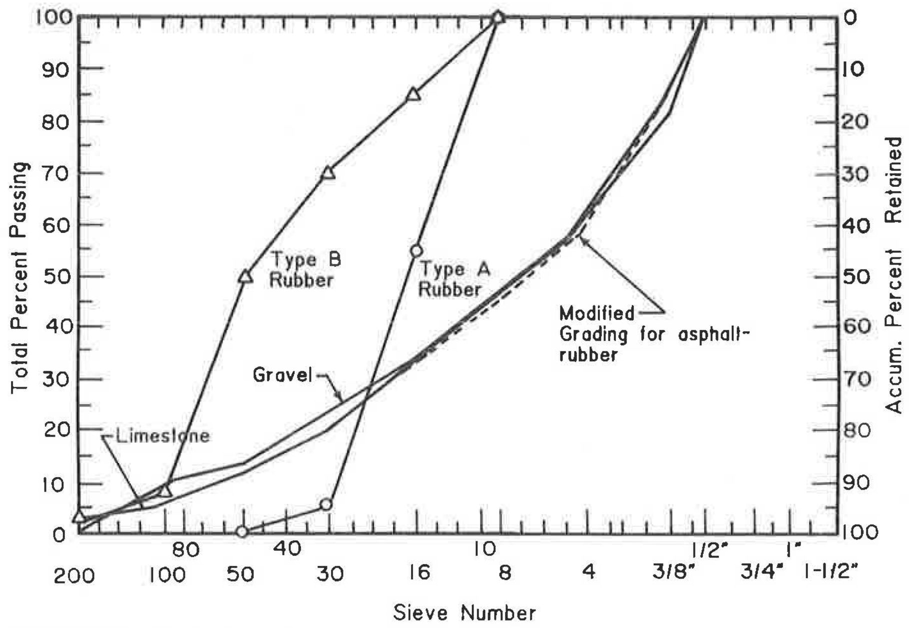

FIGURE 5 Gradations of aggregates and rubbers for asphalt-rubber concrete.

results for the gravel mix were obtained from a recent study by Button et al. *(25)*, and control asphalt concrete test results for the limestone mix were obtained during the course of this study.

Specimen Fabrication Experiment

To determine if the fabrication techniques for preparing laboratory specimens needed to be different from those of the standard Marshall mixture design method, an experiment was performed that included variations in compactive effort and mixing and compaction temperatures. These experiments were conducted using the subrounded river gravel because (a) the principal investigators thought that this material would be most sensitive to variations in the viscosity of the asphalt-rubber with temperature and (b) subrounded gravel is relatively easy to compact, so variations in response of the mixtures to compactive effort would primarily reflect the effect of the asphalt-rubber binder.

The fabrication experiment was conducted at a binder content of 5.5 percent by weight of the aggregate in order to yield an air void content between 6 and 8 percent. This range of air void content was selected to allow comparisons of the properties of the asphalt-rubber concrete and the control mixtures, which were prepared with air void content between 6 and 8 percent to allow running moisture susceptibility tests using the modified Lottman conditioning procedures.

Design of Experiment Asphalt-rubber concrete samples were fabricated at 5.5 percent binder by weight of aggregate using the Marshall method of compaction. Three different blow counts (25, 50, and 75 blows per face) and three different temperatures (275°F, 325°F, and 375°F) were used to determine an optimum fabrication technique. Because this portion of the study was a cooperative venture of the FHWA and the Texas State Department of Highways and Public Transportation (SDHPT), the following tests were performed on all specimens: Marshall stability (lb), Hveem stability (%), resilient modulus at 77°F (psi), and air voids (%).

Evaluation of Results Tests were performed on specimens fabricated at the various temperatures and compactive efforts and the test results are shown in Figure 6. Test results for Marshall stability show that both compactive effort and compaction temperature have a significant effect on Marshall stability. Even at the low compactive effort, a compaction temperature of 375°F reduces the viscosity of the asphalt-rubber at compaction sufficiently for the compacted specimen to show a stability much higher than that of the control asphalt concrete with an AC-10. The additional compactive effort of from 25 to 75 blows produces a mixture with an increase in stability at 375°F of about 50 percent. Hveem stability is fairly insensitive to temperature and number of blows of compaction. This is because Hveem stability is largely a measure of aggregate interlock and friction and is not particularly sensitive to binder viscosity. When the aggregates have achieved a fairly dense state, Hveem stability does not change much with changes in binder viscosity.

Air void content is fairly sensitive to both compaction effort and temperature. Air void content generally decreases either as mixture temperature increases or as compactive effort increases. Notice that only at 75 blows per face does the air void content approach the selected value of 7 percent. This perhaps reflects the difficulty of compacting fine dense-graded mixtures.

Resilient modulus is less sensitive to compactive effort than to compaction temperature. There is generally an increase in resilient modulus with an increase in both temperature and compactive effort. However, because the Marshall mixture

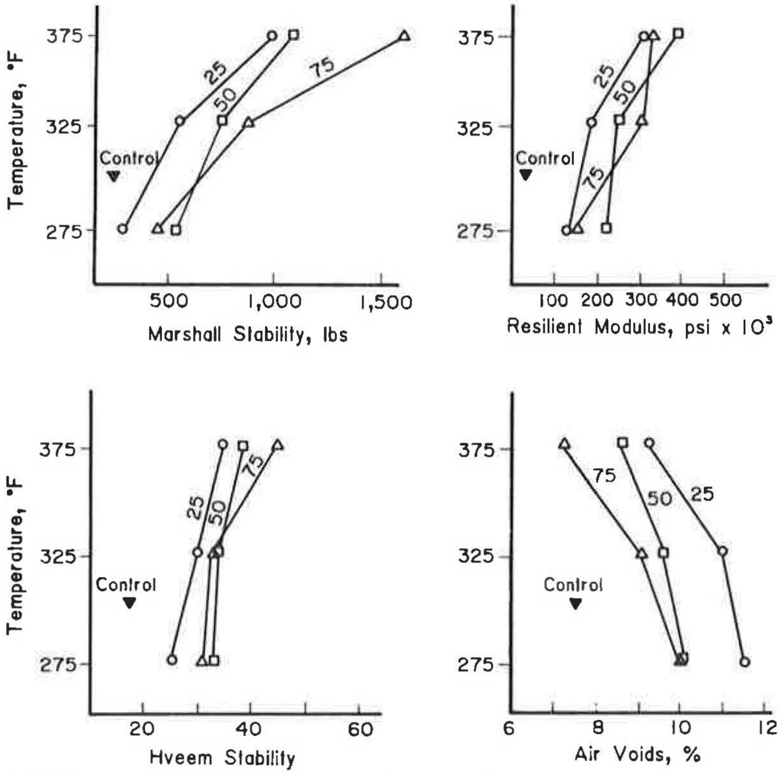

FIGURE 6 Asphalt-rubber concrete properties for fabrication experiment using gravel aggregate and Rubber B.

design method does not include resilient modulus, more emphasis was placed on the sensitivity of Marshall stability and air void content to fabrication conditions.

Because there is a clear effect of temperature and compactive effort on both Marshall stability and void content, it is not difficult to determine that both the highest temperature and compactive effort should be used in fabricating the asphalt-rubber concrete specimens for mixture design, and, indeed, the major modifications to the current MS-2 manual procedures include modifications of the mixing and compaction temperatures.

Sample Mixture Design

An example mixture design was performed in the laboratory to evaluate the modification to the design procedure and to verify that a satisfactory design could be developed using crushed materials and a different asphalt-rubber. A mixture design was developed using the crushed limestone with the gradation shown in Figure 5 and Type-A asphalt-rubber. The modifications to the standard MS-2 procedure included

1. Adjusting the aggregate grading to permit space for the rubber particles—in essence the rubber was treated as an additional aggregate;
2. Mixing and compaction temperatures were 375°F; therefore the aggregates and the asphalt-rubber were heated to 375°F before mixing;
3. Compaction effort was 75 blows per face without regard to gear load;
4. Mixing was performed using a high-energy mechanical mixer; and
5. Compacted specimens were allowed to cool to room temperature before being extruded from the mold.

Using these modifications, three specimens were prepared at each of the following asphalt-rubber contents: 4.5, 5.5, 6.0, 7.5, and 8.5 percent asphalt-rubber by weight of aggregate. The results of testing are shown in Figure 7 for the standard plots used in the Marshall mixture design procedure. These plots show behavior similar to that expected from any dense-graded aggregate, and the design laboratory asphalt content is 6.7 percent on the basis of the data in the following table.

Property	*Percentage Asphalt-Rubber*
Optimum for maximum stability	6.2
Optimum for bulk specific gravity	7.2
Median for air void content	6.7
Average	6.7

Summary

A set of modifications to the standard FAA mixture design procedure has been suggested. These modifications will permit the use of asphalt-rubber instead of asphalt in asphalt concrete.

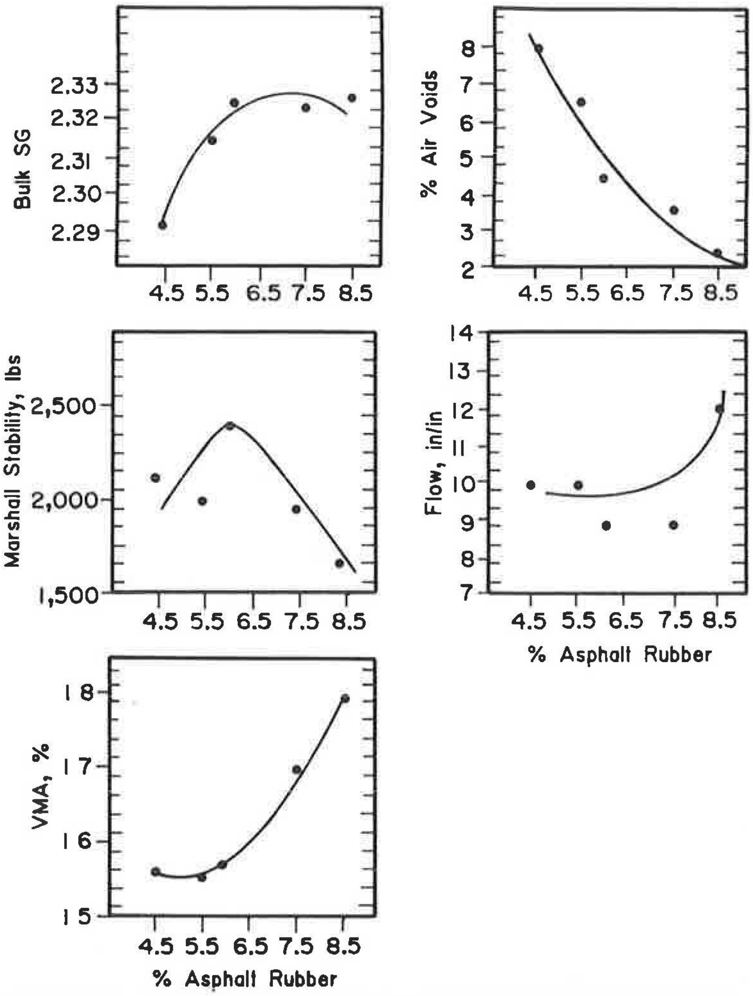

FIGURE 7 Asphalt-rubber concrete mixture design results for Type-A asphalt-rubber.

The only rubber included in this investigation was that produced by grinding scrap tires. The suggested modifications were developed on the basis of results of an experiment involving a range of mixing and compaction temperatures and compactive efforts.

A mixture design was performed on an asphalt-rubber and an aggregate that were different from those used to develop the modifications. No problems were encountered in the conduct of the mixture design nor in analysis of the test results.

CONCLUSIONS AND RECOMMENDATIONS

The primary objectives of this research were to define the laboratory conditions necessary for producing a mixture design of asphalt-rubber concrete. Because laboratory tests used to evaluate the properties of asphalt-rubber are not defined sufficiently for specification purposes, a procedural method has been included for laboratory production of asphalt-rubber.

Within the bounds of the experiments included in this overall research effort *(11, 15, 21, 26)*, the following conclusions and recommendations are deemed appropriate:

1. Laboratory-produced blends of asphalt-rubber binder using the same combination of asphalt and ground scrap tire rubber as is used in field installations have been shown to exhibit similar properties. Therefore, laboratory-prepared materials should exhibit characteristics similar to those of materials prepared in the field.
2. Reacted asphalt-rubber binders can be produced in the laboratory in quantities sufficient for use in asphalt-rubber concrete mixture design using a modification of the Marshall method of mixture design. These reacted materials can be prepared beforehand, cold-stored, and reheated for use in mixture design with no apparent effect on binder characteristics.
3. A laboratory procedure for producing asphalt-rubber binders has been presented.
4. Coating aggregates with hot asphalt-rubber is easily accomplished using a Hobart A200 mechanical laboratory mixer at temperatures well below those needed for compaction (375°F).
5. The aggregate gradation should be modified to allow space for the ground rubber. This is most easily accomplished by considering the rubber as an extra aggregate.
6. For Marshall hammer compaction, 75 blows per face at

375°F appear adequate. The specimens should be cooled to room temperature in the mold before extrusion.

7. Successful mixture designs can be accomplished in the laboratory using the procedures suggested in this paper. Mixtures prepared with asphalt-rubber binders exhibit higher stabilities than do similar mixtures made with asphalt cement.

8. Field trials should be conducted using dense-graded materials to ensure that these recommendations are applicable to a wider range of materials.

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