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Asphalt-rubber surfaced street, Washington, D. C.



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IN THIS ISSUE

Two Articles on Rubber-Asphalt:

The Effect of Various Rubbers on the Properties of Petroleum Asphalts..... 64

A Laboratory Study of Rubber-Asphalt Paving Mixtures 91

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U. S. DEPARTMENT OF COMMERCE

SINCLAIR WEEKS, Secretary

BUREAU OF PUBLIC ROADS

FRANCIS V. du PONT, Commissioner

Contents of this publication may be reprinted. Mention of source is requested.

Two Articles on Rubber-Asphalt:

The Effect of Various Rubbers on the Properties of Petroleum Asphalts A Laboratory Study of Rubber-Asphalt Paving Mixtures

Public attention has been caught, in recent years, by reports of the experimental use of rubber in bituminous pavements. Claims have been made that the use of rubber in various forms extends the life of bituminous surfaces, increases their elasticity, decreases their brittleness at low temperatures, increases their resistance to the action of water and to abrasion by traffic, reduces skidding, and minimizes maintenance requirements.

Many experimental rubber-asphalt pavement sections have been built to determine under actual service conditions the comparative degree of progressive alteration in properties of the rubber-asphalt mixtures that occurs with age. Skid resistance measurements have also been made. The Bureau of Public Roads has observed the construction of some of these test sections, and is following the study of their performance with close interest.

The bibliography in this issue of PUBLIC ROADS indicates the wide variety of experimental work that has been done in the use of rubber in bituminous pavements. No technical analyses of general coverage of the subject have appeared, however, and for this reason the Bureau of Public Roads undertook the laboratory research reported in the two articles presented here.

The amount of rubber used in a "rubber road" is quite small. The asphalt in a bituminous pavement serves as the cementing agent for the gravel or crushed stone, sand, and mineral filler which make up the bulk of the mixture. When rubber is added, it amounts to only about 5 percent of the asphalt, which itself is only from 5 to 10 percent of the total weight of the pavement material. Thus the rubber represents about one-fourth to one-half of one percent of the weight of the paving mixture.

Nature of Studies

The first article in this issue of PUBLIC ROADS describes a study of rubber-asphalt blends, either prepared in the laboratory or extracted from pavement mixtures sampled in the field. Three asphalts and fourteen different rubbers—natural, synthetic, and reclaimed—were used in the laboratory-prepared blends. Mineral aggregate was

not involved in the laboratory tests described in this study.

The second article reports a laboratory study of rubber-asphalt paving mixtures, mineral aggregate being included in this case. The asphalt used was one of the three included in the first study, and is identified as AC-2 in both reports. In the preparation of the mixtures, the rubber was either preblended with the asphalt and the blend then mixed with the aggregate, or the rubber in powder or crumb form was added to the hot aggregate before addition of the asphalt. The plasticized rubber and the three powdered rubber materials identified as R-1, R-2, and R-6 were used in both studies.

Rubber-Asphalt Blends

Disregarding some inconsistencies, the character of the rubber-asphalt blends was affected by the type and amount of rubber used, the nature and source of the asphalt, and the temperature, time of heating, and amount of stirring in the preparation of the blends.

In general, the addition of rubber increased the softening point and viscosity of asphalts and decreased their penetration, flow, susceptibility to temperature change, and ductility at 77° F. With two exceptions, the low-temperature ductility of the asphalts was not very much influenced by the addition of rubber. There was a wide difference in the resistance of different rubber-asphalt blends to the changes produced by high temperatures such as are required in the processing of paving mixtures. Tests with one asphalt showed that its elasticity was increased in varying degree by the addition of various rubbers.

Tests of rubber-asphalt in pavement mixtures taken from experimental road sections were fruitless, since the properties of the rubber-asphalt material cannot be determined by available methods of extraction and recovery.

Rubber-Asphalt Paving Mixtures

In the study of rubber-asphalt paving mixtures, involving mineral aggregate, both favorable and unfavorable results were indicated. When powdered rubber was used, the compactibility of the paving mixture

was lowered and there was higher susceptibility to temperature change than in the comparable mixes without rubber. Mixtures with preblended rubber were much more compactible and stable than mixtures in which the rubber was added as a powder. Mixtures containing three of the four preblended rubbers showed higher stabilities than mixtures without rubber.

Tests of the paving mixtures failed to indicate that bituminous surfaces containing rubber would be both substantially more plastic at low temperatures and substantially less plastic at high temperatures than surfaces without rubber. Mixtures containing plasticized rubber or preblended natural rubber were less plastic at both 77° and 140° F. than mixtures with the rubber omitted. In general, mixtures containing synthetic or reclaimed rubber, in either powder or preblend form, were more plastic at both 77° and 140° F. than the control mix without rubber. The single exception was the mixture containing preblended synthetic rubber which, after oven exposure for 21 days, was slightly less plastic at 140° F. and slightly more plastic at 77° F. than the mix without rubber.

The tests showed that the addition of rubber in either powder or preblend form did not increase the resistance of the mixtures to the action of water.

Mixtures of Ottawa sand and preblended asphalt and natural rubber were found to be more resistant to abrasion than mixtures without rubber or any of the other rubber-asphalt mixtures.

Significance of Tests

What do these laboratory tests signify? The effects of the addition of different rubbers to different asphalts may vary widely: the use of rubber shows promise of benefits in some respects; in others it does not. Conclusions as to benefits of real economic value in the addition of rubber to asphalt must wait on further observation of the behavior of experimental pavements under the influence of age, weather, and traffic. None of these experimental pavements have as yet shown significant behavior differences between comparable rubber-asphalt and plain asphalt sections.

The Effect of Various Rubbers on the Properties of Petroleum Asphalts

BY THE PHYSICAL RESEARCH BRANCH

BUREAU OF PUBLIC ROADS

Reported by **RICHARD H. LEWIS, Senior Chemist, and J. YORK WELBORN, Highway Physical Research Engineer**

THE investigations of the effect of rubber on bituminous materials (1)¹ used in paving mixtures were initially confined to laboratory studies. These investigations were concerned with the changes that occurred when rubber latex was blended with blown, native, and petroleum asphalts and with asphaltic emulsions.

In 1933, an unvulcanized rubber powder, first known as Stam rubber powder and later (after modifications in processing) as Pulvatex, was developed by the Department of Rubber Research of the Experimental Station, West Java, at Buitenzorg, Java. In 1938, Meolorub, formerly called P.W.J. rubber powder or Van Dalfsen rubber powder, was developed by the same research institution. These two materials are protected by patents of the Rubber Foundation at Delft, Netherlands.

Pulvatex is prepared by spraying field latex or creamed latex in a current of hot air, while simultaneously a certain quantity of dried diatomaceous earth is blown in the dispersed particles so that a dehydrated mass is produced in which the dessicated rubber particles do not adhere. Meolorub is prepared by heating fresh latex with certain chemicals by means of which sulfur is fixed. The product is then flocculated by means of acid, dehydrated, disintegrated, and dried. Meolorub has undergone a certain amount of vulcanization, in contrast to the unvulcanized Pulvatex. The two materials are unlike in appearance: Pulvatex has a grayish brown color and the texture of flour; Meolorub is a yellow crumbly material having the appearance of coarsely ground corn meal.

Other rubbers in powdered or crumb form have been developed from natural rubber latex (2) but the natural rubber powder generally used in asphaltic construction in the earlier work was of the Meolorub or Pulvatex types.

The results of the investigations covering the effects of both the rubber latex and the powdered or crumb rubbers showed that the consistency, softening point, temperature susceptibility and ductility of the asphalt were so altered that the performance of pavements and surfacing mixtures might be materially benefited by the admixture of rubber compounds.

¹ Italic numbers in parentheses refer to the bibliography on pages 88 and 89.

Test pavements

Experimental sections of surface dressings, composed of sand, filler, cutback asphalt, and a small amount of rubber powder, laid on old asphaltic concrete roads in the Netherlands from 1935 to 1938, were still in excellent condition after being subjected to the heavy traffic imposed by the German and Allied armies during World War II (3). The sections sealed with the rubberized surfacing mixture were in much better condition than the untreated asphaltic concrete. However, according to available reports, a similar surfacing mixture without added rubber was not used over the old asphaltic concrete to provide a direct comparison of the surface dressings with and without the rubber admixture.

Nevertheless, the excellent condition of the rubberized asphaltic seal treatments impressed representatives of the rubber industry in the United States who had inspected these roads. As a result, the Goodyear Tire and Rubber Company developed synthetic rubber powder of the GR-S Type V. It was vulcanized in latex form to prevent coalescence on drying. Several experimental sections of asphaltic pavement containing this material were constructed in 1947. On the basis of performance of these sections, the first large-scale construction of an asphaltic pavement containing rubberized asphalt in any form in the United States was laid on Exchange Street in Akron, Ohio, in September 1948 (4).

From 1948 to date, asphaltic surfaces containing rubber in some form have been built elsewhere in the United States, and in Canada, Europe, the Far East, Australia, New Zealand, and South Africa (5).

In most of the areas outside the United States, natural rubber, similar to Meolorub, has been used with liquid or semisolid asphaltic materials in asphaltic paving mixtures and in surface treatment work. Some construction in the Far East has been done with a rubberized binder prepared by combining rubber latex and emulsified asphalts. In the United States natural, synthetic, reclaimed, processed, and scrap rubber in powdered form have been used in asphaltic paving mixtures, and powdered natural rubber added to cutback asphalts has been used for seal coating and surface treatment work. Blends of synthetic rubber latex and emulsified asphalt have been used as binders for hot asphaltic concrete in one

State. Blends of plasticized rubber asphalt, normally used for joint sealing purposes, and meeting the test requirements of Federal specification SS-S-164, and petroleum asphalts have also been used as binders for asphaltic concrete and sheet asphalt mixtures.

Preblended binders used

In May 1950, experimental rubberized asphaltic pavements were constructed in Singapore (6), using natural rubber in the amount of 5 percent of the asphalt, incorporated into the mixtures in various ways. In one mixture, the powdered rubber was added to the aggregate at the mixer box. In a second mixture, the powdered rubber was added to the hot asphalt in the asphalt bucket and, after a short period of stirring to distribute the powdered rubber, the contents of the asphalt bucket were dumped over the heated aggregate in the mixer box. In a third mixture, the rubber powder was preblended by heating the asphalt to 330° F., adding the required amount of rubber, and stirring the rubber-asphalt blend for 4 hours at the 330° F. temperature. The blend was then poured onto the hot aggregate in the mixer box, the mineral filler added, and the ingredients mixed for 3 minutes. The temperature of the mixture was about 300° F. when dumped from the mixing box and about 275° F. at the time of laying. No data were presented to show the test characteristics of the two rubberized blends used in the mixtures.

An inspection report on the condition of these experimental sections (7) indicated that the sections containing the rubber which was preblended with the asphalt for 4 hours before adding to the hot aggregate were in a satisfactory condition, while the sections in which the rubber was added to hot asphalt for a short mixing period before pouring into the mixer, and those in which the rubber powder was added directly to the hot aggregate, were still deficient in stability 12 months after construction.

In a more recent article (8), descriptions are given of several experimental road surfacings, laid during 1950 and 1951 in various parts of the British Empire, in which Meolorub rubber powder was used with asphalt. On the basis of these road trials several methods of adding the rubber to the finished mixture were recommended, with special regard to the temperatures employed. In preblending the rubber with the asphalt before incorporation in

paving mixtures, it was recommended that the powder be added slowly and the blend agitated for not less than 1 hour at 325° F. or 2 hours at 300° F. It was stated that the preblended rubber-asphalt prepared under the above conditions could be cooled and again reheated for use. It was also stated that if the rubber-asphalt blend is stored hot before use, it may be maintained at a temperature of 325° F. for 24 hours, 300° F. for 2 days, 280° F. for 4 days, or 260° F. for 8 days without serious alterations to the properties of the blend; but temperatures above 320° F. should be avoided.

It also was recommended that, due to the additional tenacity imparted by the rubber to the mixture, the temperature of the mixture should be approximately 20° F. higher than that usually used. Again, no test results were given in this report on the preblended rubber-asphalt mixtures to evaluate the changes that occurred in the test characteristics of the asphalts during their blending and storage.

In 1952, the Massachusetts Department of Public Works resurfaced a 1.7-mile section of U. S. 6 with standard bituminous concrete (9). The specifications required that the asphalt in one-half of the section contain 7.5 percent by weight of GR-S synthetic rubber powder, the type of which was not given, added and dispersed in the asphalt by the following procedure:

The specified amount of powder is added at a minimum of 200° F. with suitable agitation. It is sifted through a ¼-inch mesh sieve into the mixture to prevent lumping. The temperature of the mixture is then raised to 250 to 275° F. and the mixing is continued for a minimum of 2 hours. The asphalt containing the dispersed rubber powder is then mixed with the aggregate in the usual manner.

In the description of this project the physical characteristics of the rubberized asphalt blend were not reported.

Synthetic preblend in Akron

In September 1948, the Goodyear Tire and Rubber Company, in cooperation with the City of Akron, laid an experimental pavement in which synthetic rubber GR-S Type V was used (10). The asphaltic concrete mixture, conforming to requirements of Ohio specification T-35, was typical of those in general use in that area except for the addition of rubber to the binder. The asphalt cement of 70-85 penetration was heated to 300° F. and synthetic rubber was added and mixed for 2 hours to produce blends containing 5 and 7.5 percent by weight of rubber. The rubber-asphalt blends were then allowed to stand overnight before mixing with the aggregate. The characteristics of these rubber-asphalt blends, as reported by the City of Akron (10), are given in table 1. These data show that the addition of rubber to the asphalt cement caused a reduction in penetration and ductility and increased the softening point. Solubility tests of the rubber-asphalt blends in carbon disulfide indicated that the rubber was not soluble. The test results also indicate that

the insoluble rubber did not affect the Oliensis spot test.

The asphaltic-concrete mixtures containing the rubber powder were handled in the normal manner during mixing, transportation, laying, and compacting. An inspection of the pavement sections made in February 1949 showed no visual difference between those containing rubber and those containing asphalt without rubber.

Objective of Study

The above review of the literature indicates that rubber in many forms has been added to asphaltic materials for road-building purposes. These include rubber latex combined with asphalt cements and asphalt emulsions, plasticized rubber with fluid and semisolid asphaltic materials, and various kinds of powdered rubber combined with cutback asphalts and road tars for surface treatments and cold-laid mixtures and with asphalt cement for hot-laid mixtures. However, the chief objective of the investigation reported here was to determine the effect of various kinds of rubber powders on the properties of the petroleum asphalts normally used in the construction of high-type paving surfaces.

In the preparation of asphaltic-concrete mixtures, the rubber powder usually has been added to the hot aggregate in the mixing box at the paving plant prior to the addition of the asphalt. This is the most convenient method and is recommended by the Natural Rubber Bureau. However, the rubber powder may not be completely blended with the asphalt during the mixing and laying of the paving mixture and the degree of alteration which has taken place cannot be determined. As will be shown later, on account of the high degree of insolubility of the rubber powders in the solvents normally used in the extraction of bitumens from paving mixtures, the material extracted and recovered from rubberized asphalt mixtures may differ greatly from the binder as it exists in the pavement.

Therefore, this report deals primarily with the effect of the various kinds of powdered rubber on the physical properties of selected asphalt in order to obtain data that may prove of value in establishing the relative efficiency of the different rubbers as admixtures to the asphalt binders.

Summary of Observations

The report shows that a number of variables affect the characteristics of blends of rubber with petroleum paving asphalts. In some cases the effect of these variables is not consistent. Disregarding the inconsistencies, the following statements may be made:

The type of rubber used in the blend affects the characteristics of the asphalt in varying degree: Natural and GR-S Type II synthetic rubbers produce large changes; polybutadiene rubber produces medium changes; and reclaimed, processed, tire-scrap, and GR-S Type V synthetic rubbers produce only small changes.

The changes in the properties of a given asphalt become more pronounced with increases in the rubber content of the blend.

With a given type and amount of rubber in the blend, the changes in the properties of the asphalt vary with its character and source.

The temperature, time of heating, and amount of stirring in the preparation of the blend all have their effects on the character of the blend.

Insofar as individual test characteristics are concerned, the addition of rubber to asphalt has the following effects:

For all asphalts studied, the softening point and viscosity were increased and the susceptibility to temperature change was decreased. The flow was also decreased except for the blend of Venezuelan asphalt with 5 percent of reclaimed rubber.

In general, the penetration of the asphalts was decreased by the addition of rubber. Exceptions to this were the blends of California asphalt with natural rubber and with 5 percent of synthetic rubber.

Tests with one asphalt showed that the elasticity was increased in varying degree by the addition of various rubbers.

The ductilities of the asphalts at 77° F. were greatly decreased by the addition of the various rubbers. Exceptions to this were the blends of California asphalt with natural rubber and GR-S Type II synthetic rubber.

Previous studies have shown that all paving asphalts have a much lower ductility at 39.2° F. than at 77° F. when tested at a rate of 5 centimeters per minute. Blends of the three asphalts with 7.5 percent of various rubbers also had much lower ductilities at 39.2° F. than at 77° F. except the blends containing GR-S Type II rubber. With the exception of these and the blend of California asphalt and natural rubber, the low-temperature ductility of the asphalts was not influenced greatly by the addition of rubber.

The results of thin-film oven tests show that there is a wide difference in the resistance of different rubber-asphalt blends to the high temperatures encountered in the processing of bituminous paving mixtures.

All of these indications provide useful information. However, the properties of rubber asphalt blends as they exist in rubber-asphalt pavements cannot be determined by available methods of extraction and recovery. There-

Table 1.—Analysis of asphalt and rubber-asphalt blends used as binders in asphaltic concrete on Exchange Street, Akron, Ohio, 1948

	Un-blended asphalt	Asphalt with 5% rubber	Asphalt with 7.5% rubber
Foaming when heated to 350.6° F.....	None	None	None
Flash point.....°F.....	617	599-608	599-608
Penetration at 100 g., 5 sec., 77° F.....	75	63	57
Softening point, R and B.....°F.....	120-127	124-129	120-134
Ductility at 77° F. cm.....	100+	12-28	14.5-20
Loss at 325° F., 5 hrs. percent.....	0.1	0.1	0.1
Residue, percent of original penetration. Material soluble in CS ₂percent.....	68.0-85.6	66.8-82.5	81.0-87.7
Insoluble matter in CCl ₄do.....	99.5	94.9	92.4
Oliensis spot test.....	0.3	5.2	7.6
	Neg.	Neg.	Neg.

Table 2.—Types of rubber powders used in investigation

Sample No.	Producer	Type, source, and method of preparation of rubber powder
R-1	A	Natural; East Indies.
R-2	B	Reclaimed, 16 mesh.
R-3	B	Reclaimed, 12 mesh.
R-4	B	Reclaimed, 8 mesh.
R-5	C	Processed.
R-6	D	GR-S Type V, 70/30 butadiene-styrene; prepared by vulcanization, coagulation, and pulverization in presence of detackifier.
R-7	D	GR-S Type II, 75/25 butadiene-styrene; prepared by coagulation in presence of resin polymer detackifier.
R-8	D	GR-S Type II, 75/25 butadiene-styrene; prepared by coagulation in presence of soap detackifier.
R-9 ¹	D	GR-S Type V, 70/30 butadiene-styrene; prepared by vulcanization, coagulation, and pulverization in presence of a detackifier.
R-10	D	Polybutadiene; made from polybutadiene latex by coagulation in presence of a resin polymer as detackifier.
R-13	D	GR-S Type II, 75/25 butadiene styrene; prepared from GR-S Type II latex, spray dried with polyvinyl chloride as detackifier, and ground with perlite to pulverize.
R-14	D	Polybutadiene; prepared from polybutadiene latex, spray dried with polyvinyl chloride as detackifier, and ground with perlite to pulverize.
R-15	E	Reclaimed; powdered.
R-16	E	Ground vulcanized tire treads.

¹ Designated by producers as Powderpol and considered by producer to be quite similar to R-6.

fore, since experimental asphalt pavements containing various rubber powders have not as yet shown significant differences in behavior between the sections containing asphalt alone and those containing rubber-asphalt blends, it is not possible at this time to evaluate the influence of the rubber by means of tests of the blends made in the laboratory.

Rubber Powders Investigated

Representative rubber powders obtained either from construction projects or from interested producers were included in the investigation. The sample identification and a brief description of all the rubbers used are given in table 2. Material R-1 from producer A was the natural, partially vulcanized, rubber powder known as Mealorub, which has been previously described. Materials R-2, R-3, and R-4, differing only in particle size, were reclaimed rubbers from producer B. Material R-15 from producer E was also a reclaimed rubber. Reclaimed rubber is described (11) as follows:

During the reclaiming operations the vulcanized rubber compound in the original scrap becomes devulcanized, i. e., it again becomes processable, so that it can again be compounded and vulcanized. Reclaim is valued largely for its rubber hydrogen content, other ingredients consisting essentially of fillers and softeners, some of which were in the original rubber scrap and some of which were added during reclaim manufacturing process. Reclaim may, therefore, be considered as a partially compounded rubber.

Material R-5, furnished by producer C, was designated as processed rubber. This

producer stated that processed rubber is a compounded rubber with a specific gravity of 1.17 ± 0.03 , ground to pass a 20-mesh sieve.

The seven synthetic rubbers from producer D consisted of two GR-S Type V powders, R-6 and R-9, similar to the material used in the Exchange Street pavement, Akron, Ohio. Rubbers R-7, R-8, and R-13 were of GR-S Type II, and R-10 and R-14 were polybutadiene powders prepared from the polymerization of polybutadiene latex.

The results of a laboratory study of the effect on petroleum asphalts of butadiene-based synthetic rubber powders, including the GR-S Type V rubber used in the Exchange Street experimental sections in Akron, were given in a report published in 1951 (12). This report showed that synthetic rubbers added to hot asphalts raised the softening point and reduced the cold flow, the susceptibility to temperature, and the penetration of the asphalt.

Rubber R-16 from producer E was ground, vulcanized tire-tread scrap. The ground tire-tread scrap is similar to that used by A. E. H. Dussek in his composite surfacing material, patented in Great Britain in 1935 and in the United States in 1938 (13, 14). Dussek, in 1951, discussed the performance of a paving mixture containing ground vulcanized tire-tread scrap laid in 1937 at Clifton Rise, New Cross, England (15). The quantity of rubber used in this paving mixture was, however, much greater than the amounts of other rubber powders that have been used in rubberized asphaltic paving mixtures. At the time of his report, the pavement was said to be in excellent condition.

With the exception of rubbers R-7, R-8, R-10, R-13, and R-14, all the rubbers listed in table 2 have been used in experimental sections of rubberized asphalt paving mixtures. Although not used in this study, another rubber product has been developed recently and has been used in asphaltic paving mixtures (16, 17). This is a material in

which a GR-S Type II rubber latex, similar to that used in rubber R-13 of this report, is co-precipitated with a mineral filler. The material is said to mix more readily with asphaltic materials either alone or in asphaltic aggregate mixtures.

In this study, no attempt was made to examine these various rubbers chemically. Determinations of specific gravity, bulk density, ash content, grading, and solubility in organic solvents were made. The results of these and other tests are given in table 3.

The wide range in specific gravity of the various rubbers accounts, no doubt, for the tendency of some of them to settle out or to float to the surface when mixed with asphaltic materials and allowed to stand for long periods of time in a fluid condition. This tendency was noticed particularly for those rubbers that were not dispersed readily in the asphaltic materials. Also, because of this wide difference in specific gravities, proportioning the rubber powders on a weight basis, as used in this study, may affect the comparative results slightly.

Physical Properties Differ

The solubility of the rubbers in the organic solvents not only aids in distinguishing the different types of rubber but also gives an indication of the probable solubility of the rubber portion of a rubber-asphalt blend when it is extracted from an asphalt mixture for the determination of bitumen content. The results of the solubility tests showed that the two GR-S Type V synthetic rubbers R-6 and R-9, and the partially vulcanized natural rubber R-1, had similar solubilities in the three solvents. Of the reclaimed rubbers, R-15 had a much greater solubility in all solvents than R-2, R-3, and R-4. It is of interest to note that the processed rubber R-5 and the ground, vulcanized tire-tread scrap R-16 had similar solubility in all solvents. There was considerable variation in the solubility of the GR-S Type II rubbers R-7, R-8, and

Table 3.—Results of tests on rubber powders

	Type and identification of rubber powders													
	Natural (R-1)	Reclaimed (R-2)	Reclaimed, 16 mesh (R-3)	Reclaimed, 8 mesh (R-4)	Processed (R-5)	GR-S Type V (R-6)	GR-S Type II (R-7)	GR-S Type II (R-8)	GR-S Type V (R-9)	Polybutadiene (R-10)	GR-S Type II (R-13)	Polybutadiene (R-14)	Reclaimed powder (R-15)	Ground scrap (R-16)
Specific gravity, 77°/77° F.	0.980	1.122	1.118	1.121	1.170	1.002	0.972	0.924	0.975	0.935	1.070	1.017	1.189	1.128
Bulk density in air, g./cm. ³	0.37	0.37	0.31	0.33	0.37	0.33	0.28	0.21	0.31	0.19	0.30	0.39	0.25	0.34
Organic matter insoluble in 86° B naphtha														
percent.....	93.8	71.1	78.1	72.1	85.8	93.9	79.3	71.8	92.4	64.0	66.0	47.2	61.6	86.1
In cold CS ₂do	93.8	68.3	71.5	70.7	84.0	93.8	44.1	54.1	93.5	72.3	43.7	46.7	60.4	85.1
In hot CS ₂do	91.4	64.3	67.5	67.2	82.0	91.9	39.7	41.3	90.6	65.6	41.0	38.4	58.3	82.4
In hot CaH ₂do	91.0	64.5	67.6	66.7	82.0	91.1	60.0	77.3	92.3	84.8	61.0	64.5	57.4	79.6
Ash by ignition.....do	6.2	9.4	8.1	8.7	6.6	2.6	1.5	1.9	2.6	1.4	14.3	7.5	14.0	7.6
Loss on heating—														
At 212° F., 24 hr.														
percent.....	+0.65	0.35	0.48	0.38	0.65	0.30	0.31	0.32	0.17	0.41	0.30	0.27	2.69	+1.72
At 325° F., 2 hr.....do	+0.86	0.51	0.51	0.19	+0.16	0.63	0.61	0.35	0.34	1.06	+1.61	+0.11	1.52	+1.05
At 325° F., 24 hr.....do	+0.94	1.60	1.25	1.30	+1.12	+1.64	0.20	+5.37	0.39	+4.83	+1.40	+0.70	1.99	+1.33
Grading, percentage passing—														
No. 10 sieve.....	100	99	99	96	100	100	78	96	100	100	100	100	86	100
No. 20 sieve.....	97	69	18	21	100	100	46	47	100	83	100	86	22	92
No. 30 sieve.....	83	33	7	9	88	98	30	27	96	73	89	75	11	64
No. 40 sieve.....	57	14	2	3	50	90	18	15	68	59	57	49	4	22
No. 50 sieve.....	31	4	1	1	26	83	10	3	38	36	31	27	2	4
No. 80 sieve.....	8	1	—	—	10	71	4	—	13	15	14	7	1	2
No. 100 sieve.....	3	—	—	—	5	61	2	—	9	7	10	4	—	—

Table 4.—Analysis of original asphalts used in rubber-asphalt blends

	Asphalt AC-1	Asphalt AC-2	Asphalt AC-3
Specific gravity, 77°/77° F.....	1.020	1.012	1.013
Penetration, 100 g., 5 sec.—			
At 50° F.....	20	24	16
At 77° F.....	89	94	90
At 95° F.....	232	238	270
Softening point.....°F.....	118.0	120.0	113.2
Ductility, 77° F.....cm.....	+250	195	200
Standard oven test, 5 hr., 325° F.:			
Loss.....percent.....	0.14	0.02	0.09
Tests on residue:			
Penetration, 77° F.....	77	76	78
Softening point °F.....	122.0	123.8	114.4
Ductility, 77° F.....cm.....	+250	160	+250
Thin-film oven test, 5 hr., 325° F.:			
Loss.....percent.....	0.28	+0.01	0.33
Tests on residue:			
Penetration, 77° F.....	51	56	51
Softening point °F.....	131	134	121
Ductility, 77° F.....cm.....	237	52	215
Bitumen soluble in CS ₂percent.....	99.89	99.94	99.95
Organic insoluble do.....	0.09	0.02	0.00
Inorganic insoluble do.....	0.02	0.04	0.05
Oliensis spot test, standard naphtha.....	Neg.	Neg.	Neg.

R-13, R-14, and R-16 increased in weight from 0.70 to 5.37 percent, rubber R-8 showed an increase of 5.37 percent, and rubber R-10 an increase of 4.83 percent.

The increase in weight of some of the rubbers indicates that oxidation might occur when they are exposed to high temperatures such as those encountered during the dry mixing with heated mineral aggregates in a mixing plant. The fineness of the rubber powder and the large surface area exposed may be inductive to alterations of the rubber if the temperature is too high or the mixing period too long.

The results of the sieve analyses of the various rubbers showed that there was a wide range in their fineness. Rubbers R-1, R-5, R-9, R-10, R-13, and R-14 had approximately the same fineness, while rubbers R-2, R-3, R-4, R-7, R-8, R-15, and R-16 were coarser, and rubber R-6 was much finer than those in the first named group.

Preliminary Study of Blends

Although other penetration grades of petroleum asphalts were used in the investigation of the rubber-asphalt blends, the test results of the asphalts most extensively used are given in table 4. These were of the 85-100 penetration grade. AC-1 is a vacuum-refined Venezuelan asphalt that is refined along the eastern seaboard and is used extensively in that area. AC-2 came from a midwest producer and, although the source is not known, it was furnished by the producer who supplied the asphalt used in the rubberized asphaltic concrete constructed on Exchange Street, Akron, Ohio, in 1948. AC-3 is a California asphalt of the low-gravity, low-sulfur, and low-asphaltene type that is extensively used on the west coast.

All of the rubbers described in tables 2 and 3 were first blended with the Venezuelan asphalt AC-1. Five percent of rubber by weight of the blended material was used except for rubbers R-13 and R-14, for which 6 percent was used. (Since this percentage is

considered equivalent to 5 percent of the other rubbers, it is reported as 5 percent in table 5.) These blends were prepared in an oil-jacketed heating kettle equipped with an electric stirrer for circulating the oil, a thermostatic temperature regulator, and a motor-driven stirrer for mixing the rubber and asphalt (fig. 1).

With this equipment the temperature could be controlled within a range of ±5° F. of the desired mixing temperature. For the blends prepared at 300° F. it was necessary to maintain the temperature of the oil bath at approximately 315° F. For blends prepared at higher temperatures, this differential in temperature was a few degrees more.

In preparing the rubber-asphalt blends, 300 grams of asphalt were heated on a hotplate to the desired mixing temperature and weighed into the preheated mixing kettle. The desired amount of rubber powder was then added to the asphalt with the stirrer operating at a speed of approximately 200 r.p.m. By means of a rheostat connected to the motor, this approximate speed was maintained throughout the heating and mixing period. A thermometer placed in the mixture indicated the temperature of the material throughout the mixing process.

In the preliminary study, the original asphalt and all of the rubber-asphalt blends were heated for 2 hours at 300° F. The literature indicated that a wide variety of temperatures had been used in previous investigations, but a temperature of 300° F. was selected as being reasonably close to the temperatures normally used in hot paving plants for the 85-100 penetration grade of asphalt. Preliminary work also indicated that usually the maximum effect of the rubbers can be obtained at this temperature within a 2-hour heating period. Endres, et al. (12), used a temperature of 302° F. and a heating period of 5 hours with only occasional stirring, while in this study the stirring was continuous.

After completion of the 2-hour blending period, the rubber-asphalt blends and the unblended asphalts were tested by the AASHO

R-13, except in hot carbon disulfide. The two polybutadiene rubbers R-10 and R-14 differed in solubility in all the solvents.

There was a wide range in the percentage of ash by ignition, ranging from 1.4 percent for rubber R-10 to 14.3 percent for rubber R-13. However, only in the case of rubbers R-13 and R-14, in which perlite was used to prevent coagulation of the rubber particles, was the percentage of ash considered in the proportioning of the rubber-asphalt blends. The producer suggested that 6 percent of these materials be used for comparison with 5 percent of the other synthetic rubber powders.

The reclaimed rubbers R-2, R-3, R-4, and R-15 and synthetic rubbers R-7 and R-9 all lost weight when heated under all the conditions described in the table. Rubbers R-1 and R-16 increased in weight for all conditions of heating. When heated for 24 hours at 325° F., rubbers R-1, R-5, R-6, R-8, R-10,

Table 5.—Results of tests on unblended asphalt AC-1 and blends containing 5 percent of various rubbers after mixing for 2 hours at 300° F.

	Un-blended asphalt AC-1	Rubbers blended (5 percent) with asphalt AC-1													
		R-1	R-2	R-3	R-4	R-5	R-6	R-7	R-8	R-9	R-10	R-13	R-14	R-15	R-16
Specific gravity, 77°/77° F.....	1.019	1.015	1.022	1.022	1.027	1.028	1.015	1.016	1.014	1.015	1.007	1.020	1.020	1.028	1.025
Penetration, 100 g., 5 sec.—															
At 50° F.....	22	22	21	18	19	20	20	19	23	18	23	22	27	18	19
At 77° F.....	87	66	76	80	78	73	71	68	73	67	71	73	73	73	67
At 95° F.....	213	139	189	188	186	172	156	157	157	156	147	157	149	179	156
Softening point.....°F.....	118	143	123	122	119	124	125	128	135	126	136	134	136	124	129
Ductility 77° F.....cm.....	195	28	31	38	31	13.5	23	32	40	19.5	22.5	66	38	28	20
Rebound.....percent.....		63	48	61	58	26	13	36	55	6	43	66	60	46	49
Ductility, 60° F.....cm.....	+250	17.5	12	11	10	11.5	12.5	62	74	8	18.5	41	15	12	13
Rebound.....percent.....		40	38	39	38	50	22	45	57	38	45	54	52	47	58
Flow at 140° F., 1 hr.....cm.....	12.3	3.7	11.5	10.8	11.3	10.5	10.0	7.9	6.6	9.7	6.0	3.9	3.7	12.6	11.2
Thin-film oven test:															
Loss 325° F., 5 hr.....percent.....	0.25	0.19	0.35	0.35	0.40	0.27	0.24	0.24	0.28	0.21	0.26	0.30	0.30	0.31	0.23
Tests on residue:															
Penetration, 100 g., 5 sec.—															
At 50° F.....	13	17	13	13	13	13	16	17	18	15	19	-----	-----	15	15
At 77° F.....	51	65	47	46	46	46	52	52	56	48	57	57	62	47	47
At 95° F.....	114	242	96	100	97	98	109	111	116	99	113	-----	-----	98	100
Softening point.....°F.....	131	129	138	136	136	138	137	137	142	142	142	151	160	142	140
Ductility, 77° F.....cm.....	+220	+250	8	10	7.5	12.5	12	50	40	10	25	48	14	14	12
Rebound.....percent.....			34	35	47	52	19	60	58	45	48	59	55	64	58
Soluble in CS ₂do.....	99.89	97.59	95.90	94.60	95.42	95.30	95.22	97.94	98.37	94.90	97.15	97.69	96.13	95.57	95.09
Organic insoluble.....do.....	0.09	2.12	3.63	4.97	4.12	4.24	4.70	1.96	1.49	4.93	2.80	1.62	2.53	3.22	4.32
Inorganic insoluble.....do.....	0.02	0.29	0.47	0.43	0.46	0.46	0.08	0.10	0.14	0.17	0.05	0.69	1.34	1.21	0.59
Organic insoluble in 80° naphtha.....do.....	19.59	21.79	21.77	24.21	21.37	24.30	24.19	21.67	21.56	24.39	23.36	20.09	21.45	21.99	22.83
Oliensis spot test, standard naphtha.....	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(2)	(2)	(1)	(2)	(2)	(2)	(1)	(2)

1 Negative. 2 Positive. 3 Slightly positive.

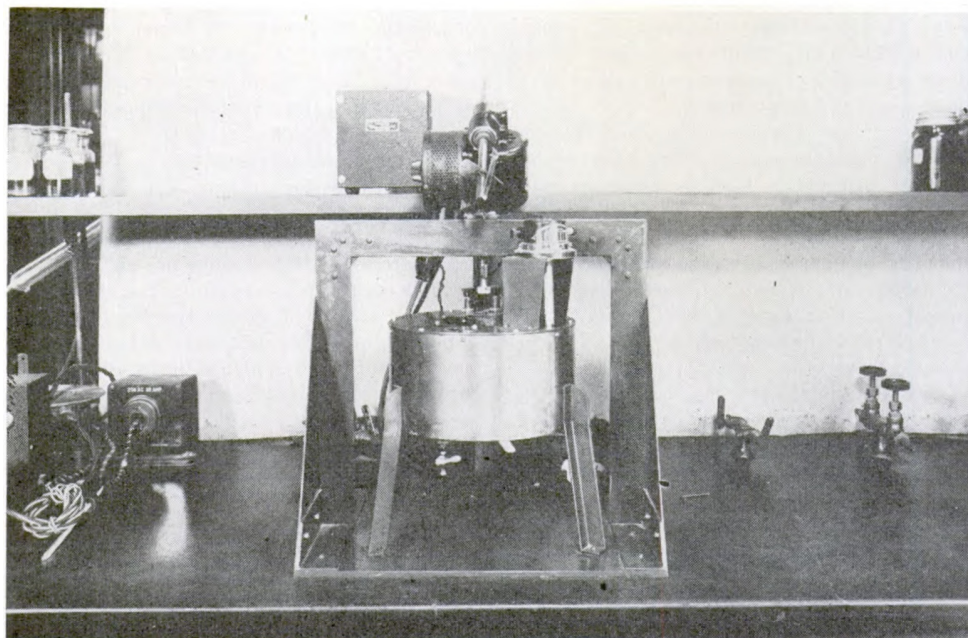


Figure 1.—Mixing kettle used for preparing rubber-asphalt blends.

test methods usually employed for the control of asphalt cements and also by methods that, although not standard for these materials, might furnish some information on the effect of the rubber on the properties of the asphalts.

The results of tests on the 5-percent rubber blends with asphalt AC-1 are given in table 5. An examination of the test data in this table shows that, as compared with the unblended asphalt, the addition of 5 percent of the rubber powders reduced the penetration at 77° F. from 7 points for the reclaimed rubber R-3 to 21 points for the natural rubber R-1. The softening point was raised 25° F. for rubber R-1 and only 1° F. for rubber R-4. As compared with the unblended asphalt, the reduction in ductility at 77° F. for all blends was exceedingly high—the most ductile blend, that containing rubber R-13, having only 34 percent of the ductility of the unblended asphalt.

In the thin-film oven tests, the rubber-asphalt blends behaved like the unblended asphalt except that the ductility at 77° F. of the blend containing rubber R-1 increased enormously as compared with the original

ductility of the blend. Blends with rubbers R-7 and R-10 also showed some increase. In the thin-film oven test all the blends and the unblended AC-1 asphalt showed a material reduction in penetration at 77° F., except the blend containing rubber R-1, which had approximately the same consistency, before and after the test. The softening points of residues from thin-film oven tests increased from 7° to 24° F., except for the softening point of the blend containing rubber R-1, which decreased 14° F.

The organic matter of the blends insoluble in carbon disulfide varied from 4.97 for the blend with rubber R-3 to 1.49 for that with R-8. The blends containing the GR-S Type V rubbers R-6, and R-9, the reclaimed rubbers R-2, R-3, and R-4, the processed rubber R-5, and the ground tire scrap R-16, all were highly insoluble in carbon disulfide.

In making the Oliensis spot test, results of which are given in table 5, standard naphtha was used as solvent by the procedure given in AASHTO method T 102-42. It is apparent that the character of the spot is influenced by the type of rubber. Except for the blend

with ground scrap rubber R-16, the only blends that showed positive spots were those containing synthetic rubbers. This condition may be due either to the solubility of the rubber in the asphalt and solvent, or to the presence of large amounts of the organic or inorganic material added to the rubber as a detackifier. Blends containing rubbers R-13 and R-14 contained the largest amount of ash and gave the darkest spot.

Rubbers Selected for Detailed Study

On the basis of the preliminary study, five rubbers were selected for a more detailed study so that the various kinds of rubber would be represented and also so that rubbers would be included that had the minimum and maximum effect on the asphalt. Those selected were the natural rubber R-1, the reclaimed rubber R-2, the GR-S Type V rubber R-6, the polybutadiene rubber R-10, and the GR-S Type II rubber R-13. In a few of the tests other rubbers were also included.

Blends of the five rubbers with the three asphalts were prepared to determine the effect of rubber content and of the time and temperature of mixing on the test characteristics. In order to determine the effect of different amounts of rubber on the properties of the blends, 5.0, 7.5, and 10.0 percent of each rubber were added to the asphalts. As mentioned previously, due to the large amount of inorganic matter used as a detackifier in the manufacture of rubber R-13, the producer held that 6 percent of this material would be equivalent to 5 percent of the other synthetic rubbers. Therefore, for this rubber the blends contained 6.0, 9.0, and 12.0 percent of the powder as received but in the tables and charts these percentages are reported as 5.0, 7.5, and 10.0. As in the preliminary study, the blends were prepared by mixing the asphalt and rubber at 300° F. for 2 hours.

In the preliminary study considerable change, as evidenced by a noticeable increase in consistency, occurred in some of the blends during the 2-hour mixing period. In order to determine the rate and extent of these alterations, sufficient material was removed intermittently during the 2-hour period of mixing for softening-point determinations. This was

Table 6.—Effect of time of mixing at 300° F. on softening point of asphalts and rubber-asphalt blends

	Softening point (in °F.) of blend containing rubber in percentages indicated															
	Un-blended asphalt	R-1			R-2			R-6			R-10			R-13		
		5%	7.5%	10%	5%	7.5%	10%	5%	7.5%	10%	5%	7.5%	10%	5%	7.5%	10%
Asphalt AC-1 and blends after mixing—																
5 min.....	118.0	125.0	131.0	117.0	122.4	123.3	125.2	127.8	131.8	134.5	144.8	153.8	127.2	134.5	144.5	
30 min.....	118.0	133.5	143.3	122.7	125.8	127.5	124.9	129.0	134.5	136.5	145.8	158.0	132.0	167.0	188.0	
60 min.....	118.0	140.0	153.0	124.5	126.0	129.8	127.0	130.3	132.3	135.5	146.3	159.3	134.0	172.5	188.0	
90 min.....	118.0	143.0	158.6	121.3	126.5	130.8	125.6	130.5	133.5	136.0	147.3	161.1	134.3	175.5	184.5	
120 min.....	118.0	142.5	157.3	122.9	128.8	130.8	125.0	130.3	135.3	136.0	146.5	160.6	134.0	174.0	181.0	
Asphalt AC-2 and blends after mixing—																
5 min.....	120.0	125.5	129.7	133.3	121.0	123.0	124.0	125.3	128.8	134.0	138.6	150.5	160.3	127.3	133.3	141.5
30 min.....	121.0	134.6	143.0	151.5	123.5	125.8	129.3	126.0	130.0	135.0	140.3	153.5	166.3	130.5	156.0	178.0
60 min.....	121.2	142.0	156.5	168.8	123.3	128.0	130.5	127.8	131.2	135.0	140.3	153.0	167.0	137.4	163.5	189.3
90 min.....	121.5	147.5	164.5	181.5	123.5	128.0	131.3	127.8	131.4	135.0	140.5	153.5	166.8	143.0	167.5	186.5
120 min.....	121.5	147.3	162.3	180.0	125.5	127.5	131.8	127.0	131.6	135.0	141.0	153.5	168.5	142.8	158.0	178.0
Asphalt AC-3 and blends after mixing—																
5 min.....	113.2	121.0	126.0	126.5	113.8	116.0	115.4	119.0	121.5	125.5	124.5	130.5	136.3	119.5	123.3	131.0
30 min.....	113.1	127.0	137.0	147.0	115.0	117.2	118.5	120.8	122.0	126.5	124.0	129.8	135.0	125.8	138.0	156.0
60 min.....	113.5	123.5	130.0	136.3	116.0	117.0	118.6	120.0	122.5	126.0	124.0	129.9	136.0	128.0	140.0	156.2
90 min.....	114.5	120.0	123.0	131.0	116.3	117.8	119.8	120.0	123.0	126.5	124.0	130.0	136.3	128.8	141.5	156.4
120 min.....	114.8	118.0	121.8	129.3	116.3	118.3	120.3	120.0	123.4	126.8	124.0	129.8	137.3	129.3	141.3	155.5

Table 7.—Results of tests on asphalts and rubber-asphalt blends after mixing for 2 hours at 300° F.

Blend identification	Penetration, 100 gm., 5 sec.			Softening point	Ductility, 77° F.		Flow, 140° F., 1 hour	Thin-film oven test, 1/8-in. film, 5 hr., 325° F.						Solubility in CS ₂
	At 50° F.	At 77° F.	At 95° F.		Elongation	Rebound		Loss on heating	Tests on residue					
									Penetration, 77° F.	Softening point	Ductility, 77° F.			
			Elongation		Rebound									
Unblended AC-1.....	22	87		213		° F. 118.0	Cm. 195	Percent	Cm. 12.3	Percent 0.25	51	° F. 131	Cm. +220	Percent
Blend of AC-1 and—														
R-1, 5 percent.....	22	66	139	142.5	28	63	3.7	.19	65	129	+250		97.59	
R-1, 7.5 percent.....	18	57	115	157.3	20	60	1.6	.24	62	134	135		96.30	
R-1, 10 percent.....	19	51	99	172.0	8	63	1.1		67	142	65	35	96.53	
R-2, 5 percent.....	21	76	189	122.9	31	48	11.5	.35	47	138	8	34	95.90	
R-2, 7.5 percent.....	17	68	156	128.8	16	37	7.0	.41	46	142	9	49	94.08	
R-2, 10 percent.....	19	64	143	130.8	10	37	4.5	.56	40	149	8	58	92.26	
R-6, 5 percent.....	20	71	156	120.0	23	13	10.0	.24	52	137	12	19	95.22	
R-6, 7.5 percent.....	19	64	150	130.3	19	19	7.3	.26	46	140	10.5	43	92.79	
R-6, 10 percent.....	17	58	128	135.3	16	23	6.5	.26	46	145	9		91.53	
R-10, 5 percent.....	23	71	147	136.0	22.5	43	6.0	.26	57	142	25	48	97.15	
R-10, 7.5 percent.....	23	65	118	146.5	18	47	1.9	.32	56	159	16.5	50	95.64	
R-10, 10 percent.....	29	65	107	160.6	11.5	52	1.0	.33	56	174	9	55	94.20	
R-13, 5 percent.....	22	73	157	134.0	66	66	3.9	.30	57	151	48	59	97.69	
R-13, 7.5 percent.....	24	66	120	174.0	34	72	1.2	.33	53	171	27	66	96.13	
R-13, 10 percent.....	24	65	110	181.0	25	73	1.0	.33	54	184	22	67	95.11	
Unblended AC-2.....	23	87	224	121.5	159		14.5	+ .05	55	134	45		99.94	
Blend of AC-2 and—														
R-1, 5 percent.....	20	67	125	147.3	15	60	3.5	.00	72	131	53		97.69	
R-1, 7.5 percent.....	23	60	115	162.3	8	56	1.2	.00	71	137	22	31	97.16	
R-1, 10 percent.....	19	52	97	180.0	4.5	67	0.8	.04	81	144	18.5	34	95.24	
R-2, 5 percent.....	24	80	188	125.5	15.5	32	9.8	.11	52	141	15.5	36	96.12	
R-2, 7.5 percent.....	24	75	168	127.5	8.5	29	8.4	.08	49	145	8.5	50	93.93	
R-2, 10 percent.....	23	69	148	131.8	9	35	5.2	.22	49	149	9.0	54	92.50	
R-6, 5 percent.....	23	74	171	127.0	17.5	17	8.7	.04	59	136	7.5	37	95.01	
R-6, 7.5 percent.....	22	67	152	131.6	14.5	19	7.8	.04	58	140	6	44	92.64	
R-6, 10 percent.....	21	62	132	135.0	12	20	5.5	.07	54	146	6.5	46	90.05	
R-10, 5 percent.....	30	75	140	141.0	13	46	3.6	.05	63	147	15.5	48	96.85	
R-10, 7.5 percent.....	32	70	120	153.5	7.8	39	1.9	.10	61	162	10	50	95.61	
R-10, 10 percent.....	34	69	108	168.5	4	56	.8	.11	63	179	5	50	94.31	
R-13, 5 percent.....	27	80	158	142.8	43	70	3.2	.06	65	150	31	63	98.02	
R-13, 7.5 percent.....	28	73	130	158.0	32	67	1.9	.16	62	178	24	63	96.85	
R-13, 10 percent.....	28	67	109	178.0	18	63	1.0	.16	60	184	28.5	58	95.64	
Unblended AC-3.....	15	86	264	114.8	+250		15.0	.33	48	122	235		99.95	
Blend of AC-3 and—														
R-1, 5 percent.....	13	95	272	118.0	+250		12.5	.41	65	120	+250		98.98	
R-1, 7.5 percent.....	20	101	267	121.8	+250		10.8	.36	73	120	+250		98.85	
R-1, 10 percent.....	33	123	298	129.3	+250		7.5	.14	82	120	+250		98.40	
R-2, 5 percent.....	15	82	237	116.3	32	57	13.4	.43	48	126	14.5	43	96.06	
R-2, 7.5 percent.....	16	81	223	118.3	19	49	10.2	.50	47	130	17.0	48	93.59	
R-2, 10 percent.....	16	79	198	120.3	16	49	8.5	.57	49	134	15.0	50	91.36	
R-6, 5 percent.....	12	72	200	120.0	25	16	12.7	.37	49	129	27	37	94.95	
R-6, 7.5 percent.....	13	66	186	123.4	21	17	11.6	.34	48	132	24	21	92.69	
R-6, 10 percent.....	11	63	165	126.8	18.5	15	9.3	.32	45	135	24	38	90.40	
R-10, 5 percent.....	16	77	202	124.0	49	43	10.4	.32	62	130	113	65	97.14	
R-10, 7.5 percent.....	17	76	174	129.8	36	50	8.1	.36	62	138	80	73	94.56	
R-10, 10 percent.....	20	76	161	137.3	34	57	3.8	.38	59	161	75	71	92.88	
R-13, 5 percent.....	15	86	217	129.3	+250		6.1	.41	54	130	+250		96.96	
R-13, 7.5 percent.....	16	82	203	141.3	+250		2.9	.41	59	149	190	77	97.02	
R-13, 10 percent.....	19	83	183	155.5	205	75	1.4	.46	58	170	130	73	96.08	

done after 5, 30, 60, and 90 minutes of mixing. At the end of 2 hours the blend was removed from the heating kettle and tested for penetration at 50°, 77°, and 95° F., softening point, ductility, oven heat, flow, and solubility tests. The results of the softening-point tests on samples taken at intervals during the 2-hour heating period are given in table 6 and the results of tests on the blends at the end of 2 hours are given in table 7.

Changes occurring in the rubber-asphalt blends during the 2-hour heating and mixing period, as indicated by the softening-point test, are shown in figures 2, 3, and 4 for the blends prepared with asphalts AC-1, AC-2, and AC-3, respectively. The effect of heating on the softening points of the asphalts without rubber also is shown.

It is of interest to note the wide difference in the change of softening point caused by the various kinds of rubber during the mixing period. When the rubber content of the blend was increased there was a much greater rise in softening point for some of the rubbers than for others. This was particularly true for the mixtures containing rubbers R-1 and R-13, with all the asphalts.

The effect of rubber content on the softening point of the blends is more clearly shown in figure 5 where the rubber content is plotted against the actual increase in softening point during the 2-hour mixing period. For some of the rubber-asphalt blends, the maximum increase occurred within the 2-hour period. This was particularly true for the blends of asphalts AC-1 and AC-2 with the synthetic rubber R-13, and of AC-3 with the natural rubber R-1. Therefore, two sets of curves are shown for these particular blends: The solid-line curves show the increase in softening point at the end of the 2-hour mixing and the broken-line curves show the maximum increase that developed during the mixing period.

Considering these maximum increases, the order in which the rubbers increased the softening point was the same for each asphalt used, but the amount of increase varied with the source of asphalt. Thus, not only the type and amount of rubber affects the softening point but the source of the asphalt is also of considerable importance. The influence of the source of the asphalt on the changes in softening point during the time of heating for

blends containing 7.5 percent of natural rubber R-1 is shown in figure 6. In general, the effect of source of asphalt is more pronounced for those rubbers that cause the greater changes in softening point. It can be seen in figures 2, 3, and 4 or figure 5 that rubber R-13 as well as Rubber R-1, shown in figure 6, increased the softening point of asphalts AC-1 and AC-2 much more than they did the softening point of AC-3. It also can be seen that rubbers R-2 and R-6 produced little change in softening point of any of the asphalts.

Effect on Penetration

Penetration tests were made at 50°, 77°, and 95° F. on the various rubber-asphalt blends. These results are used to show the change in consistency and to determine a susceptibility factor. The effect of the addition of rubber to the asphalts on penetration is illustrated in figure 7. In general, the addition of rubber to the asphalt resulted in a decrease in penetration at 77° F. For all rubbers the penetration decreased with increase in rubber content, except for the blend of asphalt AC-3 and the natural rubber R-1.

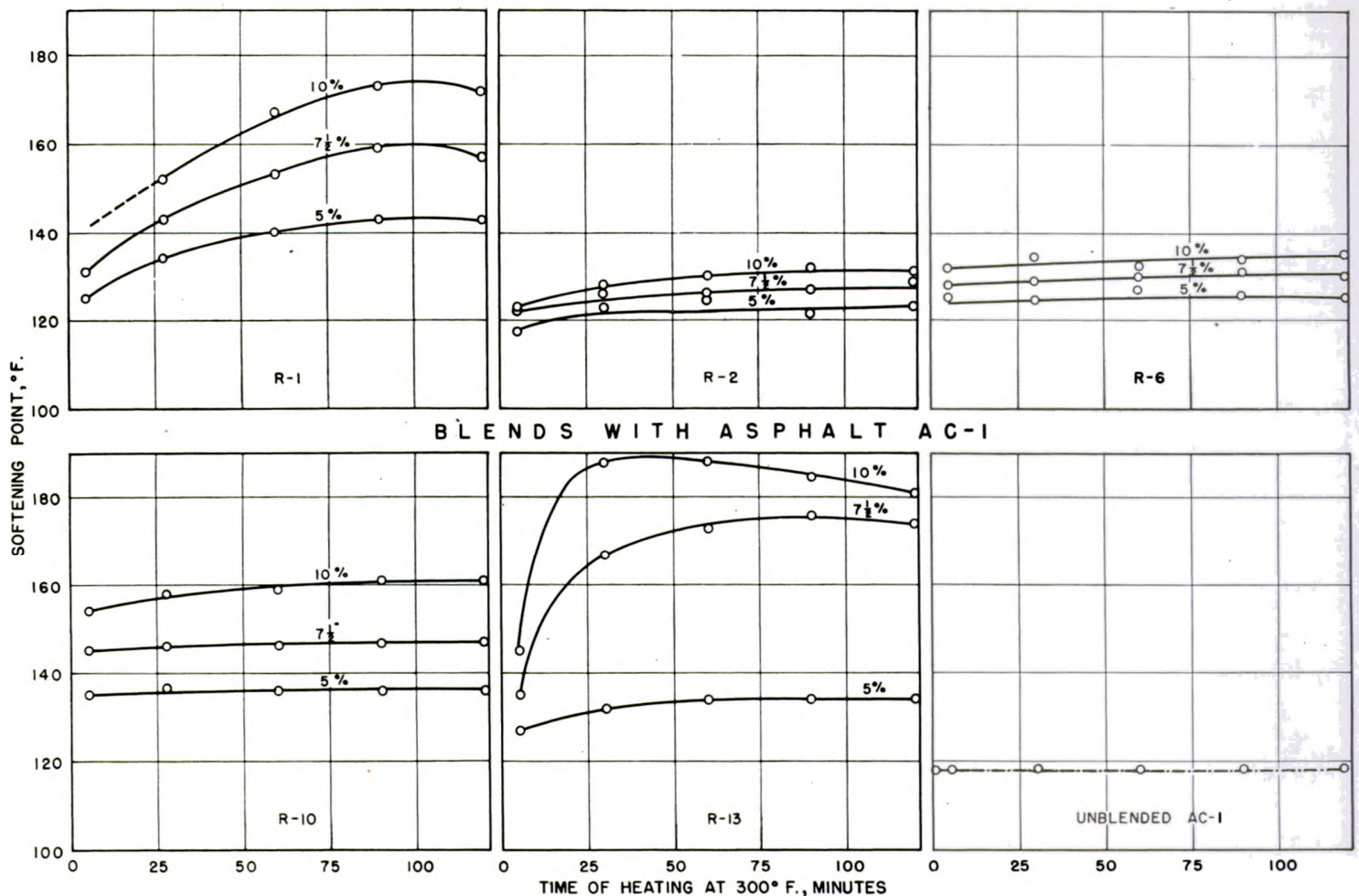


Figure 2.—Change in softening point during heating of blends of asphalt AC-1 with various amounts of powdered rubbers.

As mentioned previously, there was a pronounced decrease in softening point of this same blend during the 2-hour heating period, which indicated some decomposition of the rubber. This change is further reflected in the higher penetration values obtained.

Other investigators have shown that the addition of rubber reduces the susceptibility of asphalt to change in consistency with change in temperature. A previous study of asphalt cements has shown that the slope of log-penetration-temperature curves gives a true measure of the susceptibility of asphalts to temperature (18). Therefore, the penetration values obtained at 50°, 77°, and 95° F. as given in table 7 for the various rubber-asphalt blends were plotted, and the slopes of the resulting lines calculated from the following equation:

$$\text{Slope} = \frac{\log P_2 - \log P_1}{T_2 - T_1}$$

where P_2 and P_1 are penetrations at the two temperatures T_2 and T_1 in degrees Fahrenheit.

For most of the blends the plot of log-penetration versus temperature resulted in straight lines through the three points. Exceptions to this were the blends prepared from asphalt AC-3 and rubbers R-1 and R-13. Here the three points were not linear and for comparative purposes the slopes were calculated from straight lines through the penetra-

tions at 77° and 95° F. The results of the calculated slopes are given in table 8. In general, the susceptibility of the asphalt as measured by the slope of the log-penetration-temperature curves was decreased by the addition of rubber, the amount of decrease being greater with increase in rubber content. The effect of the rubber on lowering the susceptibility varied with the type of rubber and also with the asphalt used. For each of the three asphalts used here, the greatest reduction was produced with rubbers R-10 and R-13 and the least reduction with rubbers R-2 and R-6.

Susceptibility to Temperature Change

The report on paving asphalts of the 50-60 and 85-100 penetration grades (18) showed that the slope of the log-penetration-temperature curves for the 50-60 grades varied from 0.0172 to 0.0307, with an average of 0.0230, and for the 85-100 grade varied from 0.0188 to 0.0324, with an average of 0.0242. The slope of the log-penetration-temperature curves of highly blown asphalts (19), of approximately 50 penetration, used in sealing expansion joints in concrete pavements, varied from 0.0090 to 0.0125, with an average of 0.0105. Although other investigators have shown that rubber reduces the susceptibility

of paving asphalts to temperature change, it is of interest to note that the slope values of many of the rubber-asphalt blends given in table 8 are within the range of the values of the paving asphalts and that only two blends have slope values within the range of those of the highly blown asphalts.

The decrease in susceptibility to change in consistency with change in temperature by

Table 8.—Slope of log-penetration-temperature curves of the original asphalts and the rubber-asphalt blends

Rubber in blend	Slope of curve for blend with asphalt		
	AC-1	AC-2	AC-3
None.....	0.0218	0.0226	0.0265
R-1, 5 percent.....	.0179	.0165	1.0258
R-1, 7.5 percent.....	.0174	.0155	1.0238
R-1, 10 percent.....	.0162	.0150	1.0189
R-2, 5 percent.....	.0217	.0207	.0264
R-2, 7.5 percent.....	.0204	.0197	.0249
R-2, 10 percent.....	.0194	.0184	.0231
R-6, 5 percent.....	.0198	.0202	.0250
R-6, 7.5 percent.....	.0196	.0201	.0253
R-6, 10 percent.....	.0195	.0185	.0235
R-10, 5 percent.....	.0176	.0150	.0234
R-10, 7.5 percent.....	.0146	.0130	.0204
R-10, 10 percent.....	.0128	.0111	.0185
R-13, 5 percent.....	.0187	.0165	1.0228
R-13, 7.5 percent.....	.0146	.0140	1.0220
R-13, 10 percent.....	.0128	.0115	1.0192

1 Values taken from curves from 77° to 95° F.

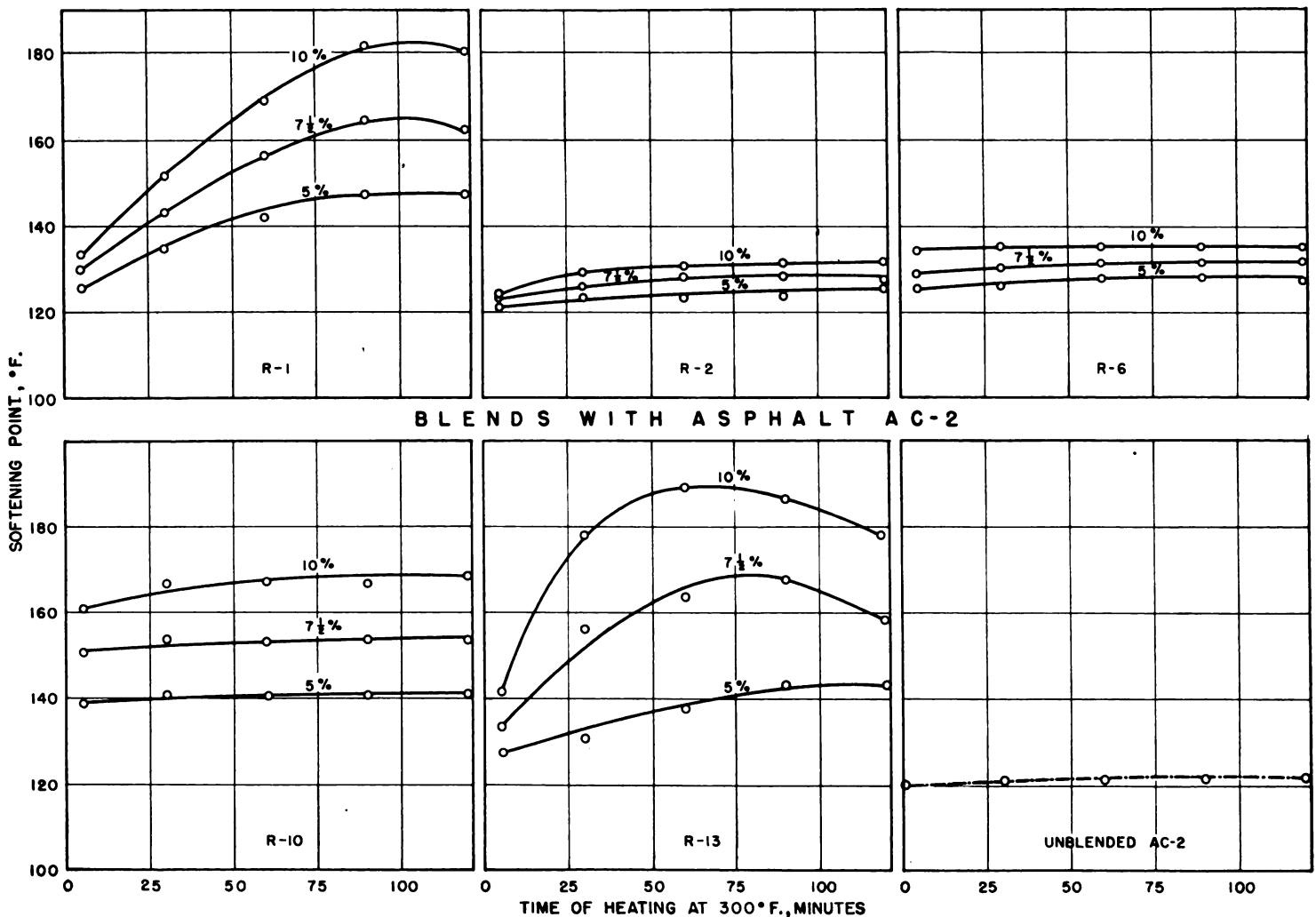


Figure 3.—Change in softening point during heating of blends of asphalt AC-2 with various amounts of powdered rubbers.

the addition of rubber should result in a rubber-asphalt blend that has a higher penetration at low temperature and a lower penetration at high temperature than the untreated asphalt. Such changes in penetration characteristics would make the pavement less brittle in cold weather and more stable in hot weather. In order to determine the effect of the various rubbers on the penetration at low and high temperatures, penetration values at 32° and 100° F. were extrapolated from the log-penetration-temperature curves. Although these are not the extreme temperatures that the asphalt might be subjected to in service they are suitable for comparative purposes. The results of the extrapolated penetration values are given in table 9.

Except for rubbers R-2 and R-6 with asphalt AC-1, the penetrations of the rubber-asphalt blends at 32° F. were higher than for the asphalts themselves. Rubbers R-10 and R-13 with all three asphalts and rubber R-1 with AC-3 showed a marked increase in penetration with increase in rubber content. The penetrations of all the rubber-asphalts were lower at 100° F. than the penetration of the corresponding unblended asphalt. For each rubber and asphalt the penetration was decreased by increase of the rubber content.

It is apparent that, in general, the rubbers do cause an increase in penetration at low

temperature and a decrease in penetration at high temperature. It also is apparent that the changes produced are not the same for each type of rubber and asphalt.

Effect on Ductility

Ductility tests were made on the original asphalts and the various rubber-asphalt blends after heating at 300° F. for 2 hours, as shown in tables 5 and 7. In the preliminary study ductility tests were made at both 60° and 77° F., while in the more detailed study ductility tests were made at 77° F. only.

In general, the addition of rubber to the asphalt caused a reduction in ductility at 77° F. The exceptions to this were the blends of asphalt AC-3 containing 5.0, 7.5, and 10.0 percent of rubber R-1 and the same asphalt with 5.0 and 7.5 percent of rubber R-13. It is probable that the ductility of many of the blends was affected by the presence of free particles of rubber. For those blends that had little or no decrease in ductility, the rubber was more completely dispersed. For the blends of rubber R-1 and R-13 with asphalt AC-3, the ductility was indeterminable except for the 10-percent blend of rubber R-13 due to the fact that their ductility was beyond the capacity of the ductility machine. Figure 8 shows the effect of rubber content on the ductility of some of the rubber-asphalt blends.

In the studies of paving asphalts previously referred to (18), when 50-60 and 85-100 penetration asphalts were subjected to lower temperatures, the values for ductility decreased, and at some definite temperature for the particular type of asphalt it became zero. For instance, the ductility of 50-60 penetration asphalts when tested at 77° F. at 5 cm. per minute, had ductilities of from 27 to 250+ cm. with an average of 175.5. The ductility of 85-100 penetration asphalts under the same conditions had ductilities of 101 to 250+ cm. with an average of 179.8. At 39.2° F., under a pull of 5 cm. per minute, the ductility of the same asphalts varied from 0 to 4.0 cm. with an average of 1.6 cm. for the 50-60 grade and from 0 to 9.7 cm. with an average of 4.3 cm. for the 85-100 grade. Compared with paving asphalts, blown asphalts have a low rate of change in ductility with change in temperature.

Low-Temperature Ductility

Ductilities of the asphalts and rubber-asphalt blends containing 7.5 percent of the various rubbers were determined at 39.2°, 60°, and 77° F. and the results are given in table 10. The effect of temperature on ductility for the original asphalts, the rubber-asphalt blends, and a typical blown asphalt included for comparison is shown in figure 9.

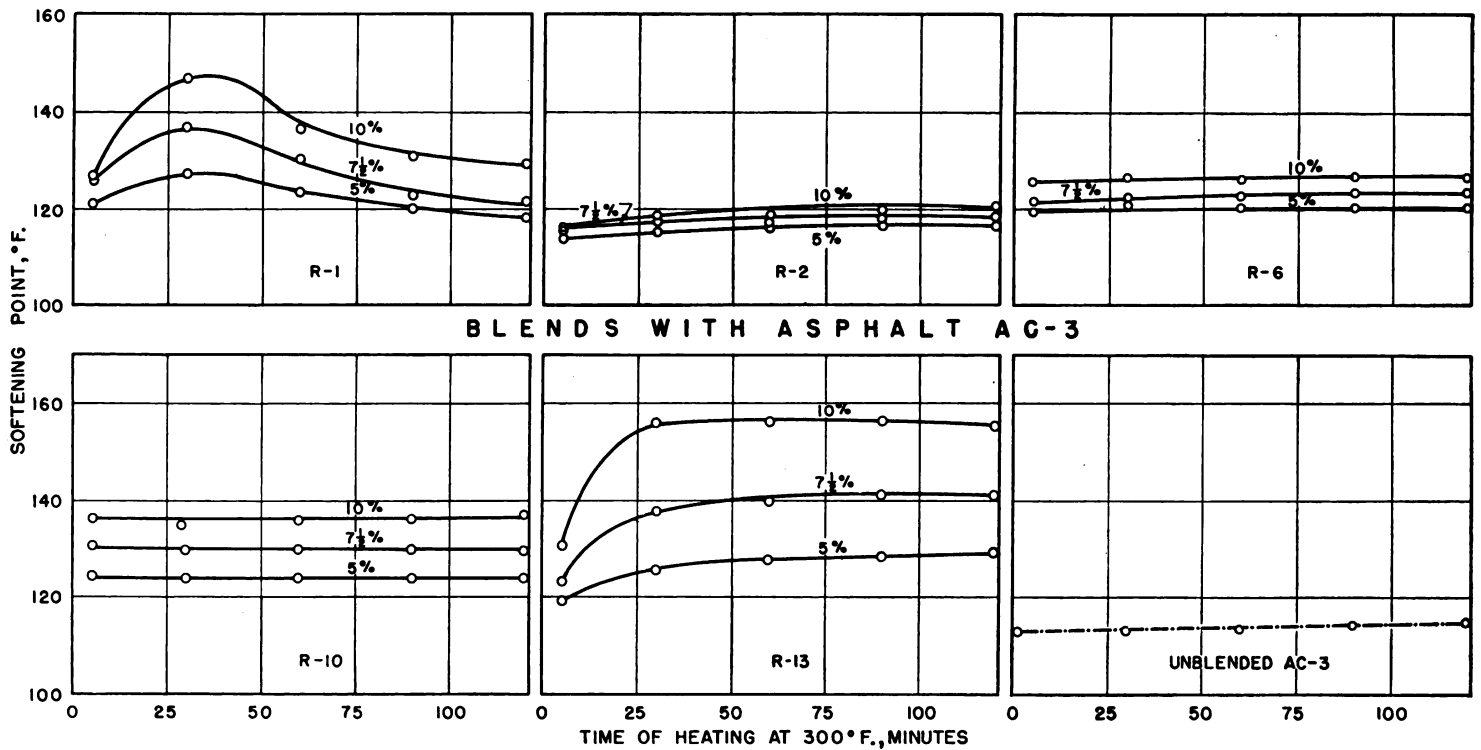


Figure 4.—Change in softening point during heating of blends of asphalt AC-3 with various amounts of powdered rubbers.

In the majority of cases, the rubber-asphalt blends did not change in ductility with change in temperature when tested at 5 cm. per minute as slowly as the typical blown asphalt also shown in figure 9, or as rapidly as the unblended petroleum asphalts. However, the ductility of the blends of rubbers R-7 and R-13 with asphalt AC-1 and of rubber R-13 with

asphalt AC-2 increased as the temperature of test was lowered, and at 39.2° F. these materials had ductilities much higher than many normal asphalts at temperatures producing maximum ductility. While the unblended asphalt AC-3 had no ductility at 39.2° F., the rubber-blend with 7.5 percent of R-1 rubber had a ductility of 70 cm. The addition of 7.5

percent R-13 rubber to AC-3 gave ductilities greater than the capacity of the testing machine at all test temperatures. This is a most unusual condition and it indicates that natural rubber with asphalt AC-3, and the GR-S type II rubber with all asphalts, definitely improve the low-temperature ductility characteristics of the asphalts covered in this study.

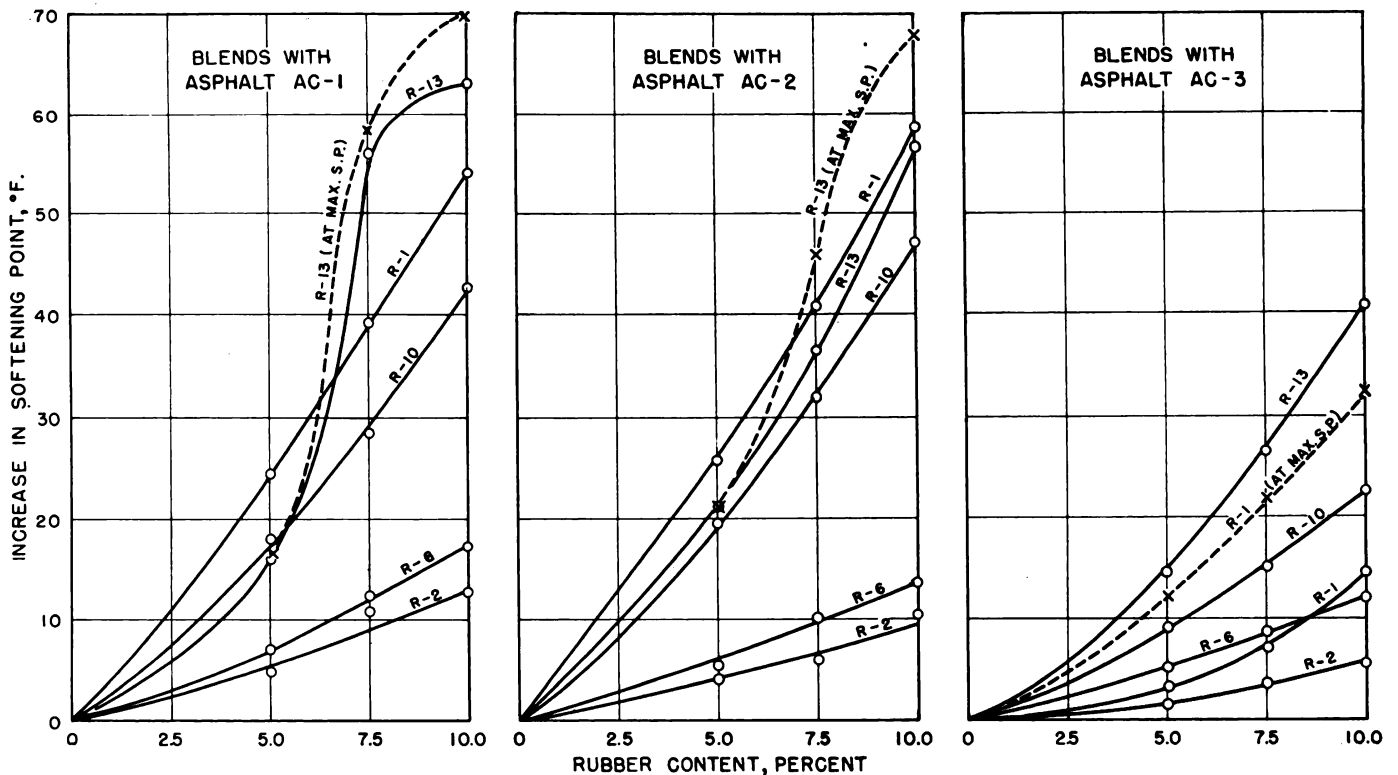


Figure 5.—Effect of rubber content on increase in softening point of rubber-asphalt blends (curves are for values after 2-hour mixing except as noted).

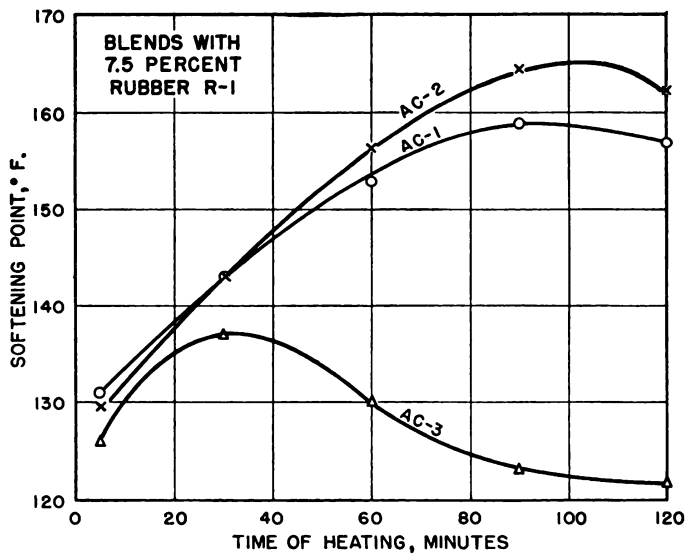


Figure 6.—Effect of time of heating on the softening point of rubber-asphalt blends prepared with different asphalts and 7.5 percent rubber R-1.

Rebound After Ductility

During the preparation and the handling of the various rubber-asphalt blends, it was noted that there was considerable difference in their elastic properties. The blends containing rubbers R-1 and R-13 particularly showed ability to recover to their original shape when deformed. In order to get some measure of this elastic behavior, the following data was obtained from the ductility test.

After the material was elongated to the point of rupture in the ductility test, the elongated specimen was allowed to remain

undisturbed for 15 minutes and the length of the broken threads was measured. The amount of original elongation less the length after 15 minutes was termed the rebound. This rebound in centimeters was calculated as a percentage of the original elongation. These values are given in tables 5 and 7 for the original blends and for the residues of the blends from the thin-film oven test.

Due to the high ductility values and to the fineness of the broken thread, the rebound of unblended asphalts AC-1, AC-2, and AC-3, all blends of AC-3 containing rubber R-1, and the 5- and 7.5-percent blends of rubber R-13

Table 9.—Penetration of asphalts and rubber-asphalt blends at 32° and 100° F. (extrapolated from log-penetration-temperature curves)

Rubber in blend	Penetration, 100 g., 5 sec.—					
	At 32° F.			At 100° F.		
	AC-1	AC-2	AC-3	AC-1	AC-2	AC-3
None.....	9.0	8.0	4.8	275	295	365
R-1, 5 percent.....	10.3	12.0	16.8	170	160	363
R-1, 7.5 percent.....	9.6	12.0	18.6	140	138	358
R-1, 10 percent.....	9.4	10.8	17.3	119	125	330
R-2, 5 percent.....	8.2	9.3	5.4	240	235	330
R-2, 7.5 percent.....	8.3	9.6	6.1	196	218	293
R-2, 10 percent.....	8.4	10.2	7.2	176	180	263
R-6, 5 percent.....	9.0	9.2	5.3	198	215	262
R-6, 7.5 percent.....	8.5	8.4	4.9	182	190	241
R-6, 10 percent.....	7.6	9.0	5.6	160	164	217
R-10, 5 percent.....	11.3	15.8	6.8	180	167	261
R-10, 7.5 percent.....	14.0	18.3	8.2	138	138	227
R-10, 10 percent.....	18.7	21.6	11.0	126	121	197
R-13, 5 percent.....	10.5	13.9	8.0	195	150	282
R-13, 7.5 percent.....	14.5	16.4	8.5	142	127	260
R-13, 10 percent.....	17.3	19.0	11.0	127	106	227

¹ Values extrapolated from curves through penetrations at 77° and 95° F.

and AC-3 could not be determined. The data in table 7 show, in general, that for the blends of asphalts AC-1 and AC-2 with various amounts of rubber, those containing rubbers

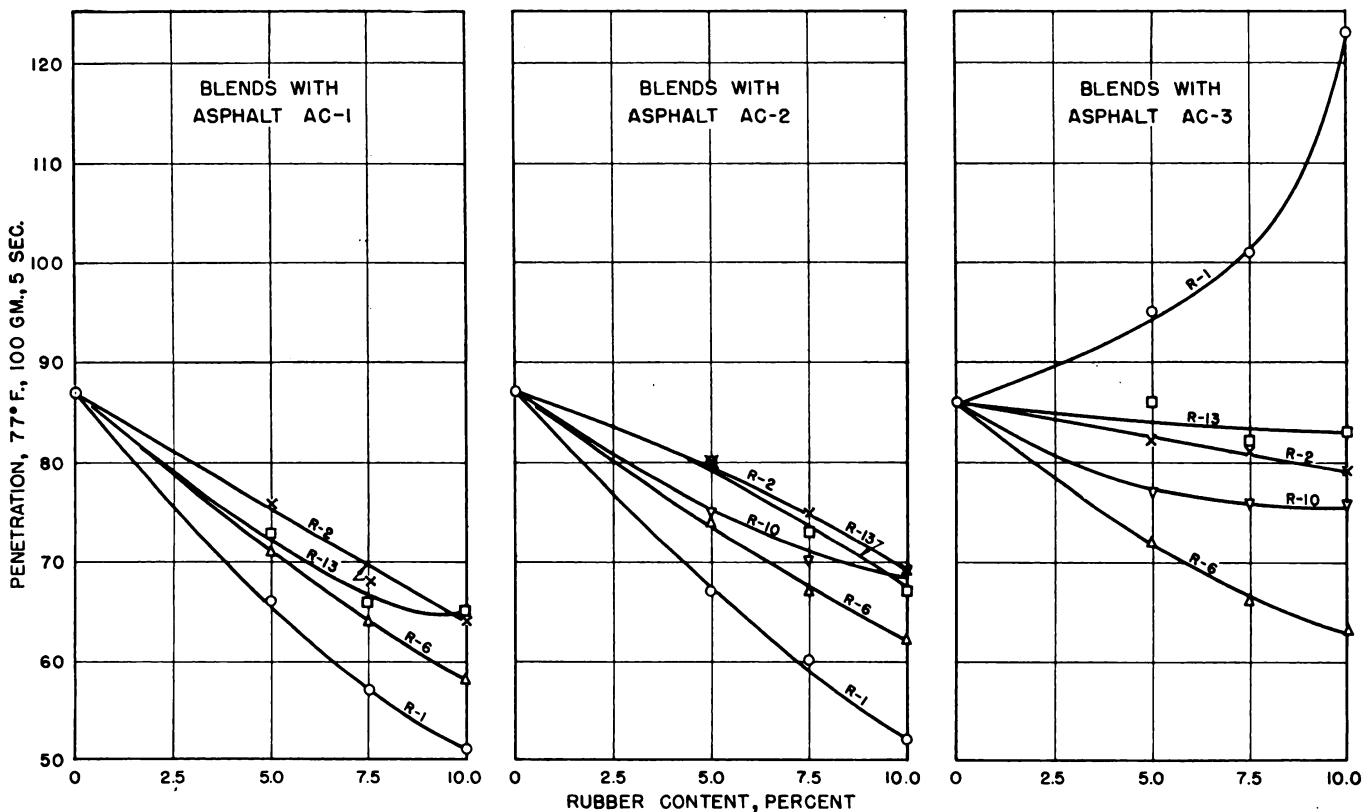


Figure 7.—Effect of rubber content on penetration of rubber-asphalt blends.

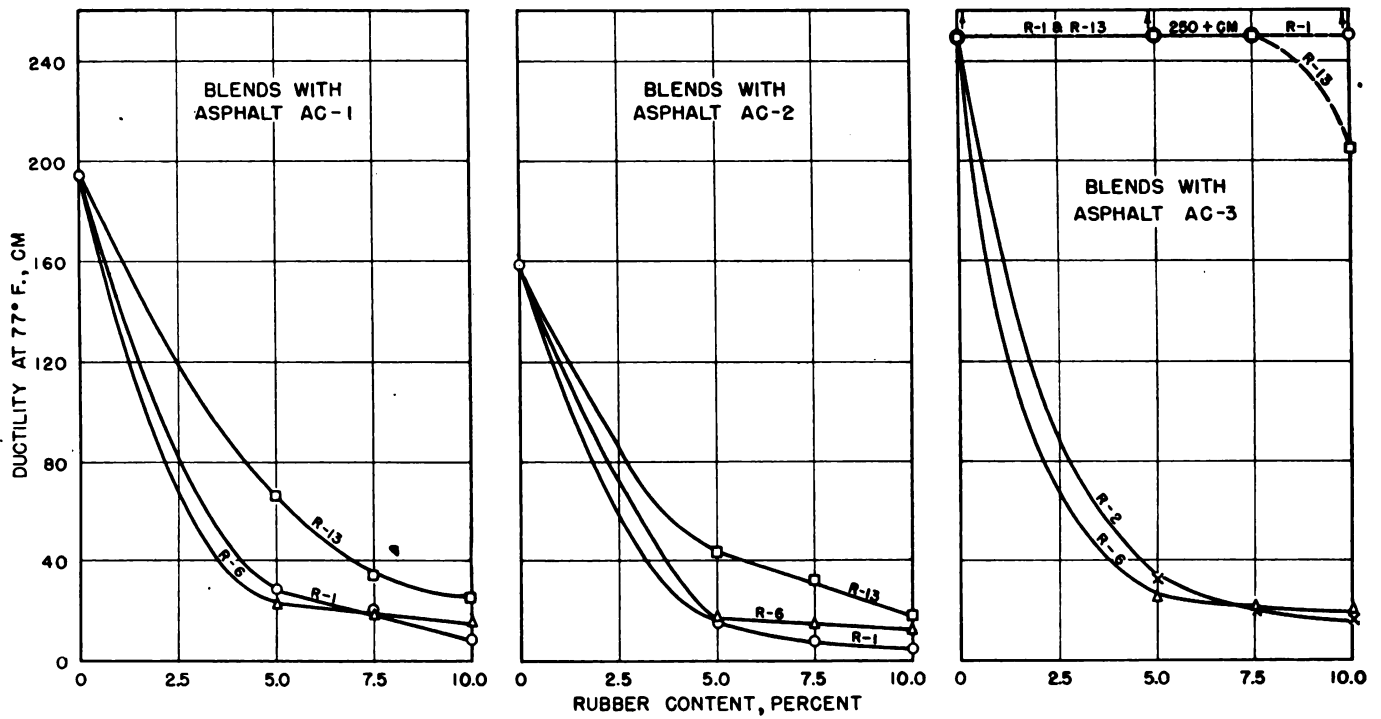


Figure 8.—Effect of rubber content on ductility of rubber-asphalt blends.

R-1 and R-13 had the highest amount of rebound and those containing R-2 and R-6 the lowest rebound.

Elasticity Measured

The development or increase in elasticity of asphaltic materials has been considered as one of the more important changes induced

by the addition of rubber. Such data as those obtained by measuring the rebound of the broken thread after the ductility test no doubt indicates this elastic property. However, this test is limited generally to relatively short elongations, that is, those less than 100 cm. Since some of the asphalts and rubber-asphalt blends had elongations well over 100, the

rebound could not be determined. Therefore, another test was developed in the laboratory by which the difference in elastic properties could be measured.

In this test a determination was made of the time required for a steel cylinder 1 inch in diameter and weighing 200 grams to penetrate into the asphalts or rubber-asphalt blends to a

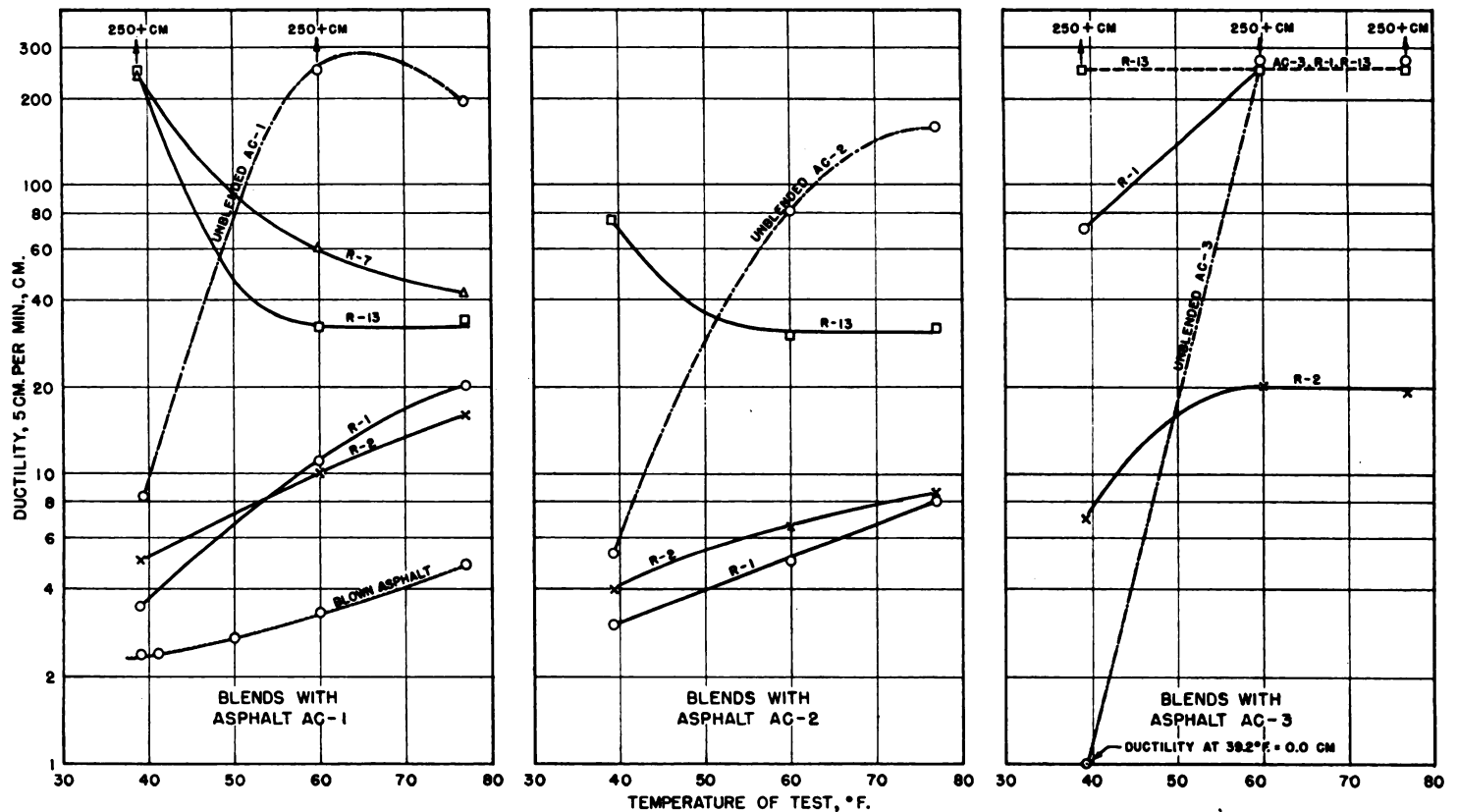


Figure 9.—Ductility-temperature curves for unblended asphalts and rubber-asphalt blends containing 7.5 percent of various powdered rubbers.

Table 10.—Results of ductility tests on asphalts and blends containing 7.5 percent rubber

Blend identification	Ductility at—			
	5 cm. per min. at—			1 cm. per min. at 39.2° F.
	77° F.	60° F.	39.2° F.	
Unblended AC-1	Cm. 195.0	Cm. +250	Cm. 8.5	Cm. 32.0
Blend of AC-1 and 7.5 percent of—				
R-1.....	20.0	11.0	3.5	3.5
R-2.....	16.0	10.0	5.0	8.0
R-6.....	19.0	9.5	4.5	6.0
R-7.....	42.0	60.0	239.0	123.0
R-10.....	18.0	8.0	2.5	3.3
R-13.....	34.0	32.0	+250	110.0
R-14.....	19.0	9.0	3.0	3.0
Unblended AC-2	159.0	80.0	5.3	8.0
Blend of AC-2 and 7.5 percent of—				
R-1.....	8.0	5.0	3.0	3.5
R-2.....	8.5	6.5	4.0	5.2
R-6.....	14.5	6.0	3.5	3.8
R-10.....	7.8	5.0	2.3	2.5
R-13.....	32.0	30.0	75.0	22.0
Unblended AC-3	+250	+250	0	+250
Blend of AC-3 and 7.5 percent of—				
R-1.....	+250	+250	70.0	158.0
R-2.....	19.0	20.0	7.0	15.5
R-6.....	21.0	22.0	1.0	13.0
R-10.....	36.0	36.0	7.0	20.0
R-13.....	+250	+250	+250	+250

total depth of 0.6 inch under a superimposed load of 10 pounds. Immediately after the cylinder had penetrated the material to a depth of 0.6 inch, the 10-pound load was removed and change in the depth of penetration of the cylinder was determined at 1-minute intervals for a total of 5 minutes. The results of these tests are given in table 11.

A plot of the depth of penetration against the time of penetration, both on logarithmic scales, resulted in linear relation for the unblended asphalt and for various rubber-asphalt blends. This relation is shown in figure 10 for asphalt AC-1 and the blends containing 5 and 10 percent of rubbers R-1, R-2, R-6, R-10, and R-13. Although the straight lines are approximately parallel, they show the wide effect of the various amounts and types of rubber on the resistance to penetration of the cylinder. For instance, it took 38

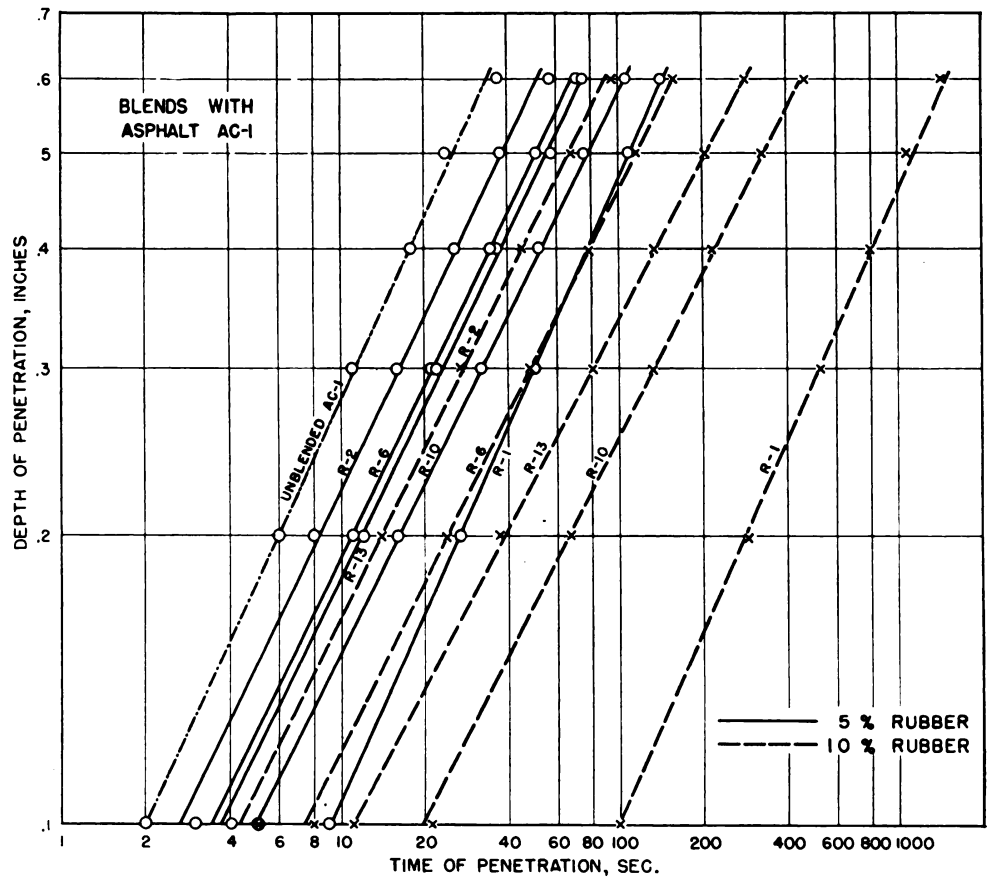


Figure 10.—Effect of time on penetration of a 1-inch, 200-gram cylinder under a 10-pound load into blends of asphalt AC-1 and various powdered rubbers (tested at 77° F.).

times as long for the cylinder to penetrate 0.6 inch in the blend containing 10 percent of rubber R-1 as it did in the asphalt itself. Blends containing rubber R-2 showed the least resistance to penetration, the time of penetration of the 10 percent blend being only 2.6 times that of the asphalt.

In figure 11 the change in depth of the cylinder after removing the 10-pound load is plotted against the time of recovery for asphalt AC-1 and the blends containing 5, 7.5, and 10 percent of the various rubbers. Although the

data for the blend containing 7.5 percent of R-13 were incomplete, the curve is assumed as shown by the broken line. For the asphalt, the weight of the cylinder was sufficient to cause continued penetration while for all the rubber-asphalt blends there was an immediate recovery or rebound, the extent and duration of which varied with the type and amount of rubber in the blend. For the 5-percent rubber blends, this recovery was only temporary and was followed by a renewed settlement of the plunger at some period within the 5-minute interval except for the R-1 blend which remained in a static position. For the blends containing 7.5 and 10 percent of rubbers R-1, R-10, and R-13, the recovery increased during the entire 5 minutes, while for blends containing the same amount of rubbers R-2 and R-6 the recovery decreased after the 1- or 2-minute periods.

This study shows that there was a wide difference in the amount of recovery of the cylinder which further indicates the varying degree of elasticity imparted by the various rubbers. It is apparent that rubbers R-1, R-10, and R-13 impart a considerable amount of elasticity to the asphalt.

Effect on Flow of Asphalts

It has been stated by other investigators that the addition of rubber to asphalts changes the flow properties and thereby increases the resistance to distortion of paving mixtures containing this type of binder under high temperatures and heavy traffic. Endres, et

Table 11.—Results of special penetration and recovery tests¹ on asphalt AC-1 and rubber-asphalt blends

Blend identification	Time for loaded cylinder to penetrate—						Recovery of unloaded cylinder after—				
	0.1 inch	0.2 inch	0.3 inch	0.4 inch	0.5 inch	0.6 inch	1 minute	2 minutes	3 minutes	4 minutes	5 minutes
Unblended AC-1	Sec. 2	6	11	18	24	37	0.001 in. -16	0.001 in. -30	0.001 in. -47	0.001 in. -59	0.001 in. -75
Blend of AC-1 and—											
R-1, 5 percent.....	9	27	50	78	108	142	45	53	57	57	57
R-1, 7.5 percent.....	38	116	215	324	447	580	30	38	44	46	49
R-1, 10 percent.....	99	296	535	800	1,090	1,413	30	37	40	44	47
R-2, 5 percent.....	3	8	16	26	38	57	18	10	3	-15	-28
R-2, 7.5 percent.....	4	13	25	43	65	94	33	34	31	27	23
R-2, 10 percent.....	5	14	27	45	68	95	44	45	41	38	33
R-6, 5 percent.....	4	11	21	35	51	71	10	15	7	-1	-10
R-6, 7.5 percent.....	6	17	32	53	78	109	32	29	27	22	17
R-6, 10 percent.....	8	24	48	78	115	159	33	34	33	30	27
R-10, 5 percent.....	5	16	32	52	76	106	38	40	40	37	33
R-10, 7.5 percent.....	12	35	70	113	168	235	43	56	58	61	64
R-10, 10 percent.....	21	67	133	219	327	462	41	51	58	64	67
R-13, 5 percent.....	4	12	22	36	54	75	40	43	42	39	30
R-13, 7.5 percent.....	8	24	49	83	125	174	---	---	---	---	62
R-13, 10 percent.....	11	39	81	135	204	287	60	74	81	88	91

¹ Penetration is that of a 1-inch diameter, 200-gram cylinder, loaded with a 10-pound weight. Recovery is determined after removal of the 10-pound weight. Tests were made at 77° F.

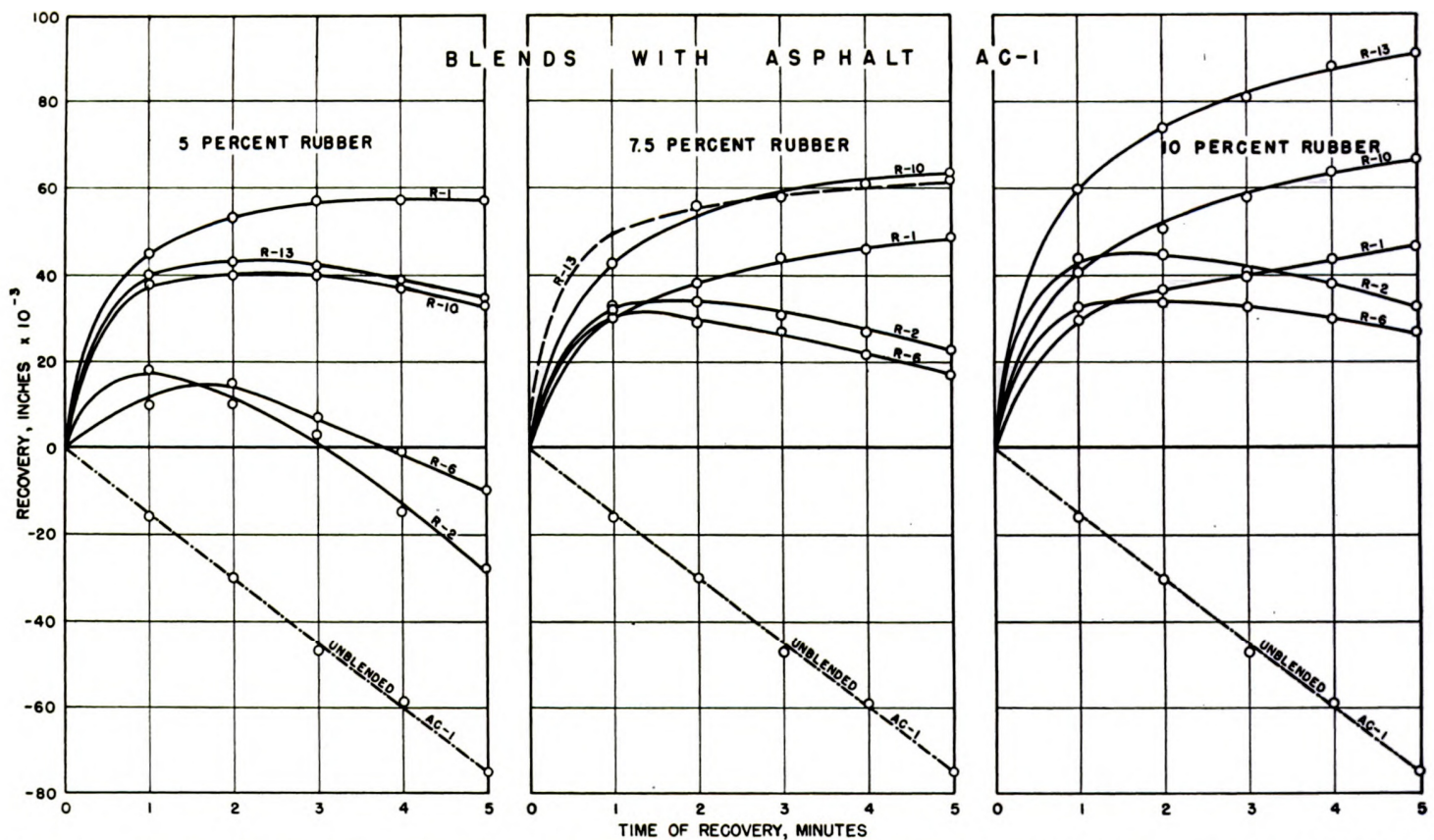


Figure 11.—Recovery of 1-inch, 200-gram cylinder after removing 10-pound load, for blends of asphalt AC-1 and various powdered rubbers.

al., (12) have shown that the addition of rubber affects the flow properties of asphalts and the amount of flow varies with the different types of rubber.

The method used in this study for determining the flow was similar to the method used for measuring the flow of blown asphalts (20). In this test the material was heated to a fluid condition and poured into an amalgamated brass mold, $\frac{3}{8}$ inch in inside diameter and $\frac{3}{4}$ inch in height. After cooling, the excess material was cut from the top and the cylindrical specimen removed. This specimen was then placed on a corrugated brass plate, supported at an angle of 45 degrees with the lower end of the cylinder on a line 15 cm. above the end of the plate. The apparatus is shown in figure 12. For blown asphalts the amount of flow is determined by heating the specimen at 150° F. for 4 hours but, due to the much higher rate of flow of the rubber-asphalt blends studied here, it was necessary to modify the temperature and time of heating. It was found that all the mixtures were within the range of 15 cm. when tested at 140° F. for 1 hour. The results of the flow test under these conditions are given in tables 5 and 7.

The results of the tests show that, except for the blend of asphalt AC-1 with 5 percent of rubber R-15, flow of all the blends containing rubber was less than the flow of the unblended asphalts. For the same rubber content the amount of flow varied with the different asphalts and rubber used. For the same rubber and asphalt, the amount of flow decreased as the rubber content was increased.

In order to show the relation between flow and softening point of the various mixtures,

the softening point was plotted against the log of the flow for the three unblended asphalts and five of the rubber-asphalt blends, as shown in figure 13. Although there is some spread among the points, the average curves for the three asphalts are almost identical. In general, the relation between softening point and flow of the rubber-asphalt blends was similar to that found in testing rubber-asphalt compounds used for sealing concrete expansion joints (19). In this previous work it was found that the rate of flow of the joint sealing materials was proportional to their softening points and it was recommended that the softening point determination be used to evaluate the flow properties of these materials instead of the flow test.

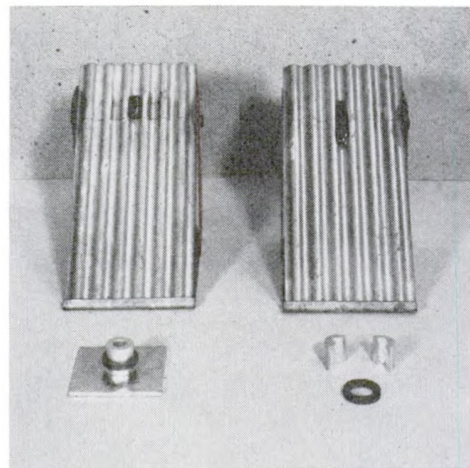


Figure 12.—Apparatus used in determining flow.

The flow test is a measure of the susceptibility to temperature change of the material as can be seen in figure 14 where the slope of the log-penetration-temperature curve is plotted against the log-flow of the blends prepared with asphalt AC-2 and the various rubbers. Except for three blends the points fall close to a straight line.

Thin-Film Oven Tests

For several years the thin-film oven test (21, 22) has been advocated as a means of measuring the amount of change that may occur in asphalt cements when mixed with an aggregate at high temperature. This test is more severe than the standard test for loss on heating due to the larger surface area of the test sample that is exposed. The thin-film oven test is made by exposing a $\frac{1}{8}$ -inch film of asphalt in an aluminum pan 5.5 inches in diameter and $\frac{3}{8}$ inch in height in an oven at 325° F. for 5 hours. The loss in weight is determined and the residue tested for penetration, ductility, and softening point. The results of the thin-film oven test on the rubber-asphalt blends are given in tables 5 and 7.

In general, when asphalt cements are exposed to the thin-film oven test, there is a slight loss in weight and a varying decrease in penetration and ductility and increase in softening point. For asphalts containing rubber, this was not found to be true for all the blends tested. As compared with the original blends, the thin-film residues of asphalts AC-1 and AC-2 containing the three percentages of rubber R-1 had approximately the same or higher penetration, much higher ductility, and much lower softening point. The thin-film

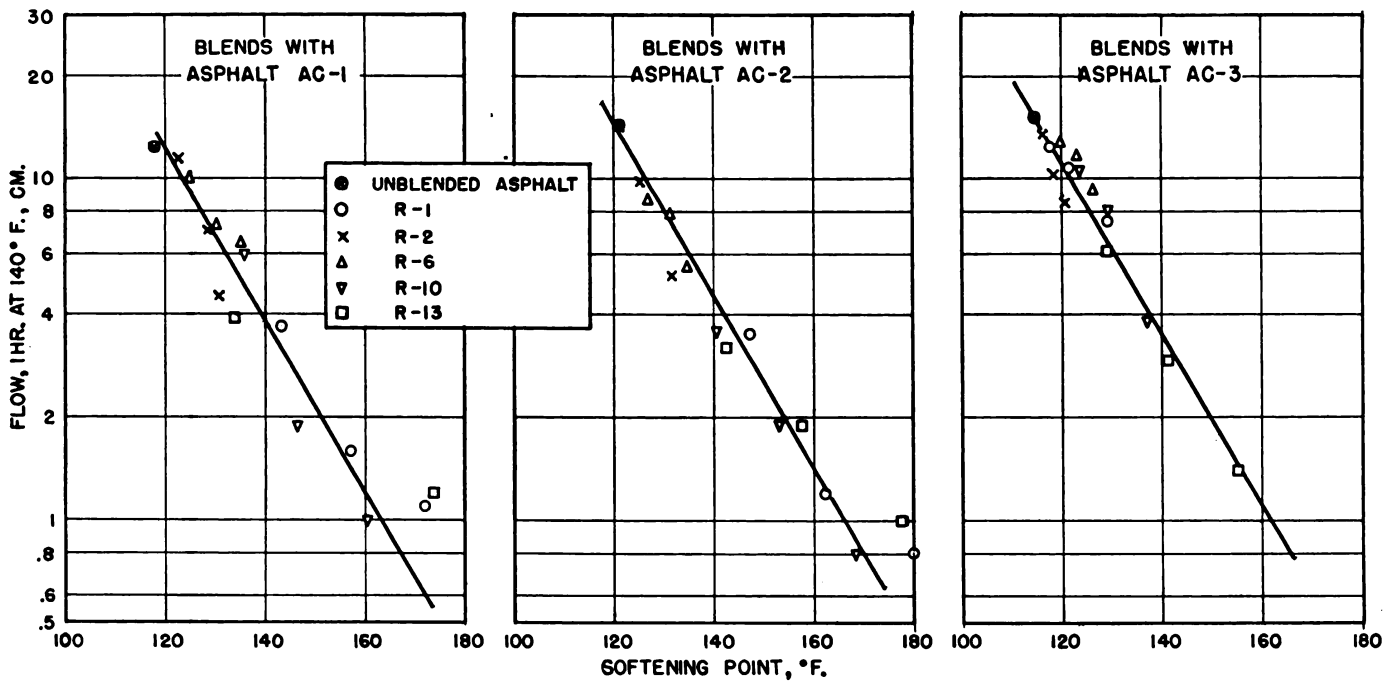


Figure 13.—Relation between softening point and flow of rubber-asphalt blends.

residues of asphalt AC-1 with 7.5 percent rubber R-13 and asphalt AC-3 with 7.5 and 10 percent rubber R-1 had lower penetrations and somewhat lower softening points than did the corresponding original blends. The ductility of the thin-film residues from blends made with the three asphalts with rubbers R-2 and R-6 was approximately the same or was lower than the ductility of the corresponding original blends. The ductility of all the residues containing rubber R-10 was higher than, or approximately the same, as the ductility of the corresponding original blends.

The results of the thin-film oven tests indicate that there could be a wide difference in the changes which would take place in the properties of the various rubber-asphalt blends when subjected to high temperatures, such as those encountered in the processing of hot mixtures.

Solubility in Carbon Disulfide

In order to obtain some information on the blending action of the various rubbers in asphalts, the test for solubility in carbon disulfide was made on the various rubber-asphalt blends. Due to the inability to filter some of the blends after dissolving with carbon disulfide, it was necessary to reduce the size of sample to approximately 0.5 gram and also use celite as a filter aid. Even with these aids the blends containing rubbers R-1 and R-13 were extremely slow to filter and results of tests showed poor reproducibility. The results of the tests for solubility in carbon disulfide are given in tables 5 and 7.

The results show a wide difference in the solubility of the blends prepared with different rubbers. In general, it can be seen that those rubbers (R-1 and R-13) that produced the greatest changes in the physical characteristics of the asphalts were also the most soluble in carbon disulfide. Since in no case is the

added rubber entirely soluble in carbon disulfides, it is indicated that the characteristics of the asphalts extracted and recovered from paving mixtures containing rubber may differ greatly from the asphalt blends as they actually exist in the pavement.

Effect of Heating Time on Viscosity

In order to obtain additional information on the changes that occur during the mixing of the rubbers with the asphalts, viscosity tests were made on blends containing 5 percent rubber heated at 300° F. for 4 hours. During

this period of heating, viscosity determinations were made every 30 minutes with a Brookfield Syncho-Lectric viscometer, shown in figure 15.

The principle of this instrument is the measurement of the drag produced on a spindle rotating at a constant speed while immersed in the material being tested. The amount of drag is indicated by a pointer attached to the spindle shaft which measures the tension produced in a spiral spring connected between the shaft and the outside of the dial which is connected to the motor shaft. The range in viscosity is obtained with a

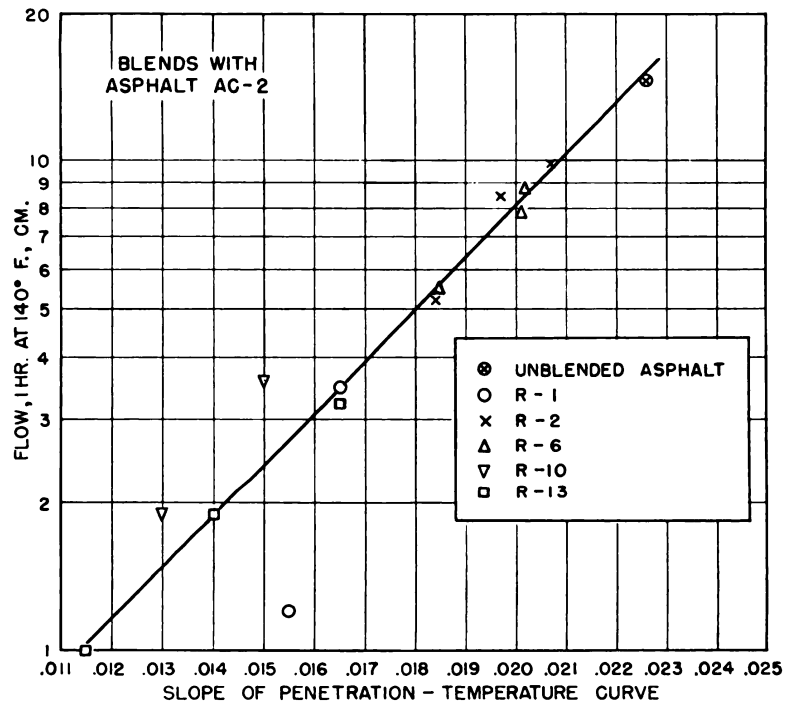


Figure 14.—Relation of slope of log-penetration-temperature curve to the flow of blends of asphalt AC-2 and various powdered rubbers.

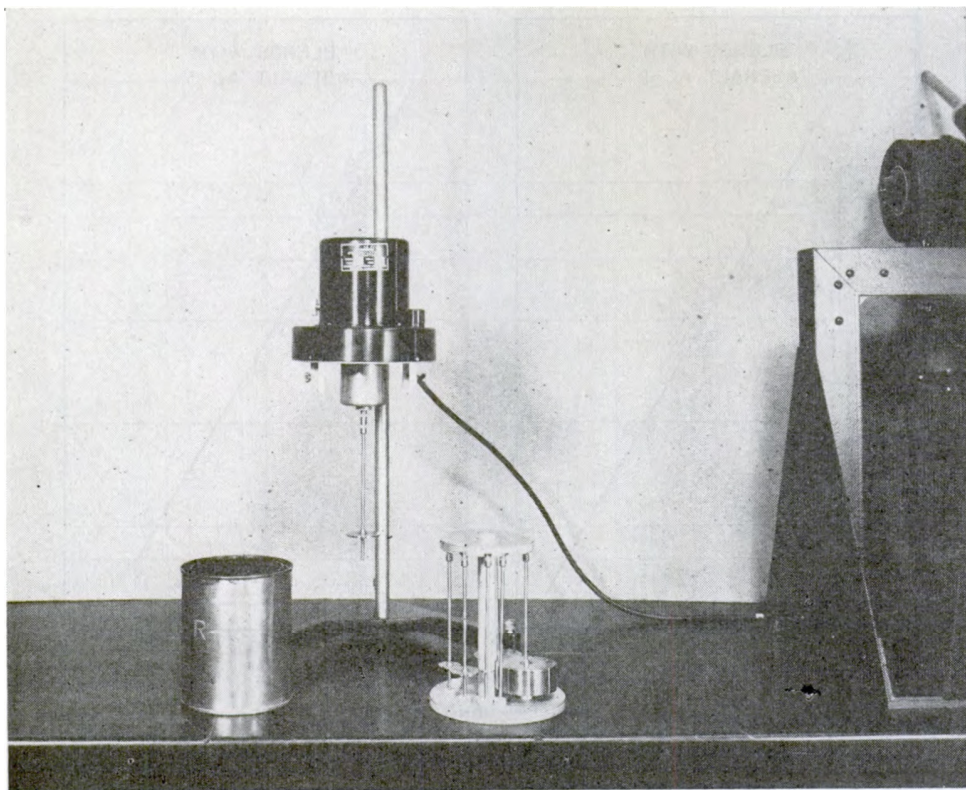


Figure 15.—Synchro-Lectric viscometer used to determine viscosity of rubber-asphalt blends.

series of spindles, each covering a part of the range. Viscosity is calculated by multiplying the reading on the dial by a factor, depending upon the spindle and speed of rotation used. The results of the viscosity determinations are given in table 12 for the blends prepared with each of the three asphalts and 5 percent of each of the rubbers. The effect of the time of heating on the viscosities of these blends is shown in figure 16.

There was a very wide range in the change in viscosity of the various mixtures during the 4-hour period. For all asphalts, blends with rubbers R-1 and R-13 developed the highest viscosities and blends with rubbers R-2 and

R-6 the lowest viscosities. Considering the maximum viscosity reached during the 4 hours, the order of the five rubbers is the same for the three asphalts and this order is the same as was found for the increase in softening point. Here also the change in viscosity was effected by the source of the asphalt.

Viscosity-Temperature Relations

Consistency is a property of asphaltic road materials that is of extreme importance from the standpoint of their application to road surfaces or in plant mixing with an aggregate. Since it was evident from earlier work that

there was a wide difference in the consistency of the various rubber-asphalt blends, the viscosity-temperature relations of blends of asphalt AC-1 with 5 percent of rubbers R-1, R-2, R-6, R-7, and R-13 were determined. The blends were prepared by mixing the rubber with the asphalt at 300° F. for 2 hours. At the end of the period, the mixing paddle was removed and viscosities determined on the material with the Brookfield viscometer, described earlier in this report.

Viscosity determinations were made first at 300° F. and then at lower temperatures as the material cooled. In order to reduce the time required for testing, tests were not made at predetermined temperatures. For viscosity determinations above 300° F., the blends were reheated after the test at the lowest temperature had been completed. It was apparent from the results obtained that very little change in viscosity occurred in the blends during the time they were maintained at these elevated temperatures.

The results of the viscosity determinations of the various rubber-asphalt blends over a range in temperature are given in table 13. These results are plotted in figure 17 on a log-temperature log-viscosity basis. By plotting in this manner, straight-line relations were obtained.

The viscosity-temperature relations show a very wide difference in the viscosities of blends containing the various rubbers over the entire range in temperatures. As was indicated previously, blends with rubbers R-1 and R-13 produced the greatest change in viscosity and blends with rubbers R-2 and R-6 the least change. All blends had viscosities well above the viscosity of the unblended asphalt.

In order to compare these viscosity values with Saybolt Furol viscosity, which is more commonly used, an approximate conversion of absolute viscosity to Furol viscosity can be obtained from the standard method of conversion of kinematic viscosity to Saybolt Furol viscosity (ASTM designation D 666-44), as follows:

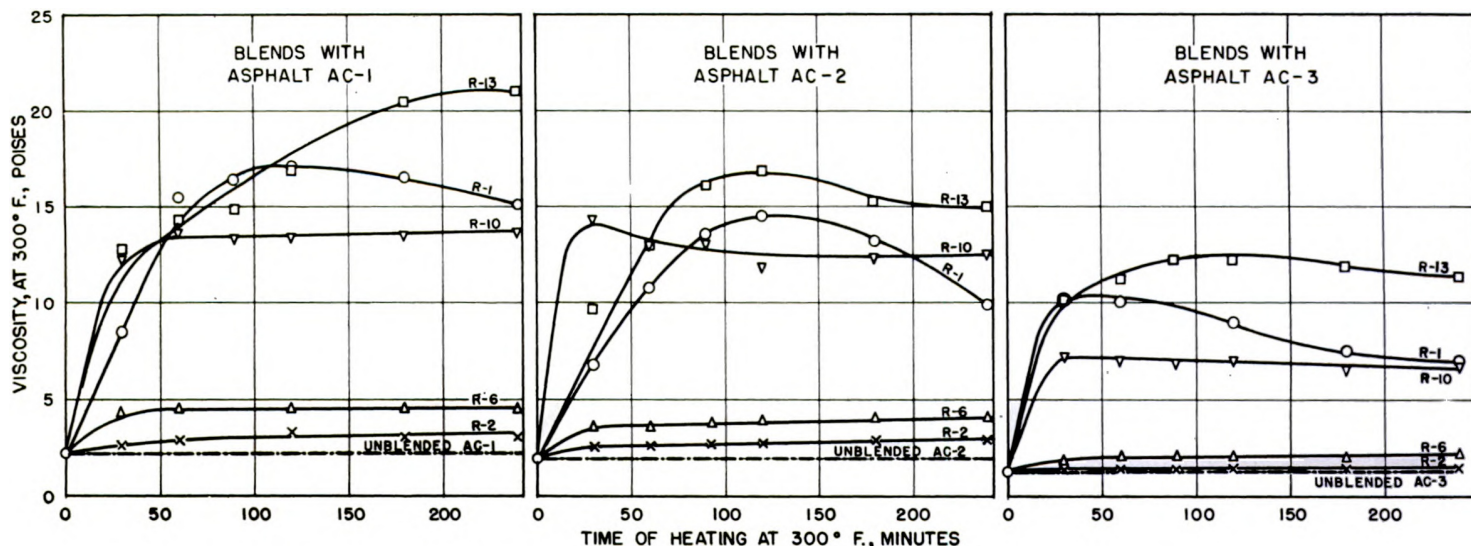


Figure 16.—Effect of time of heating on viscosity of 5 percent rubber-asphalt blends.

Table 12.—Effect of time of mixing at 300° F. on viscosity at 300° F. of asphalts and blends containing 5 percent rubber

Blend identification	Viscosity after heating and mixing for—						
	0 min.	30 min.	60 min.	90 min.	120 min.	180 min.	240 min.
Unblended AC-1.....	Poises 2.37	-----	-----	-----	-----	-----	-----
Blend of AC-1 and 5 percent of—	-----	-----	-----	-----	-----	-----	-----
R-1.....	-----	8.50	15.55	16.40	17.10	16.55	15.20
R-2.....	-----	2.65	2.90	-----	3.30	3.10	3.10
R-6.....	-----	4.35	4.50	-----	4.50	4.55	4.60
R-10.....	-----	12.38	13.70	13.35	13.30	13.55	13.75
R-13.....	-----	12.85	14.35	14.90	16.95	20.50	21.05
Unblended AC-2.....	2.00	-----	-----	-----	-----	-----	-----
Blend of AC-2 and 5 percent of—	-----	-----	-----	-----	-----	-----	-----
R-1.....	-----	6.85	10.80	13.55	14.60	13.20	10.00
R-2.....	-----	2.65	2.63	2.70	2.75	2.90	2.90
R-6.....	-----	3.70	3.65	3.80	3.95	4.10	4.10
R-10.....	-----	14.35	13.00	13.10	11.85	12.40	12.55
R-13.....	-----	9.65	12.95	16.20	16.90	15.30	15.05
Unblended AC-3.....	1.25	-----	-----	-----	-----	-----	-----
Blend of AC-3 and 5 percent of—	-----	-----	-----	-----	-----	-----	-----
R-1.....	-----	10.20	10.10	-----	9.05	7.50	6.95
R-2.....	-----	1.30	1.35	1.35	1.35	1.40	1.40
R-6.....	-----	1.90	2.05	2.15	2.10	2.05	2.15
R-10.....	-----	7.30	7.10	6.90	7.10	6.60	6.65
R-13.....	-----	10.05	11.25	12.30	12.25	11.90	11.40

Saybolt Furol viscosity = $V_{cs} \times 0.470$

where V_{cs} is the viscosity in centistokes.

Also: $V_{cs} = \frac{V_p}{\text{density}} \times 100$

where V_p is the viscosity in poises.

Since the density of the asphalts and rubber-asphalt blends is approximately 1.00,

$V_{cs} = V_p \times 100.$

Thus the viscosity data in poises as given in table 13 and shown in figure 17 can be converted to Furol viscosity, as follows:

Furol viscosity = $V_p \times 47.0.$

For plant mixing of hot asphaltic concrete, a Furol viscosity range of 75 to 150 seconds

has been considered as optimum. Converted by the equation just derived, the optimum is 1.60 to 3.19 poises. This range is indicated in figure 17, and it will be noted that the temperatures at which the asphalt and rubber-asphalt blends have this optimum viscosity are as follows:

- Unblended asphalt AC-1... 285-305° F.
- AC-1 with 5 percent R-2... 300-325° F.
- AC-1 with 5 percent R-6... 315-340° F.
- AC-1 with 5 percent R-7... 320-350° F.
- AC-1 with 5 percent R-1... 355-380° F.
- AC-1 with 5 percent R-13... 370-395° F.

The temperature ranges for use in plant mixing the different rubber-asphalt blends are indicated in figure 17.

The use of preblended rubber asphalts may not only require higher mixing temperatures but also some additional equipment to handle the more viscous binder. In the Massachusetts project, previously referred to (9), the GR-S synthetic rubber powder was prepared from standard GR-S synthetic rubber latex in such a manner as to produce a dry powder at least 50 percent of which passed the No. 40 sieve and 100 percent the No. 20 sieve. No information was given as to the degree of vulcanization of the synthetic latex. The rubber-asphalt blend was prepared at the plant of the asphalt producer and the very viscous condition of the rubberized blend presented a handling problem as additional pumps were necessary to circulate the rubberized asphalt in the distributor during transportation of the material to the storage tank at the paving plant and to provide satisfactory flow between the plant storage tank and the mixer box.

Road construction practice has shown that the selection of the proper temperature of application of bituminous materials to aggregate, either on the road or in a mixing plant, to give proper coating of the aggregate and workability of the mixture, is dependent upon the consistency of the material at the time of application or mixing. For plant mixing this consistency depends to a large extent upon the temperature of the aggregate. For the materials studied here it would appear that

Table 13.—Viscosity of asphalt AC-1 and rubber-asphalt blends at various temperatures¹

Test temperature ° F.	Viscosity of blend of asphalt AC-1 and 5 percent of rubber indicated					
	None	R-1	R-2	R-6	R-7	R-13
162.....	-----	-----	-----	630.0	-----	-----
175.....	256.5	-----	-----	-----	-----	-----
180.....	-----	-----	287.5	-----	-----	-----
185.....	-----	1,800.0	-----	353.0	433.5	-----
200.....	74.0	-----	140.8	177.0	220.0	1,400.0
210.....	-----	840.0	-----	-----	-----	-----
220.....	-----	-----	48.8	-----	88.8	-----
225.....	25.4	-----	-----	-----	-----	577.0
235.....	-----	200.0	-----	40.4	46.0	-----
240.....	14.0	-----	-----	-----	-----	-----
250.....	9.2	-----	-----	21.2	28.5	216.0
255.....	-----	104.0	13.4	-----	-----	-----
275.....	4.1	-----	-----	-----	12.9	74.0
280.....	-----	38.0	-----	-----	-----	-----
290.....	-----	-----	4.0	-----	-----	-----
300.....	2.0	17.1	3.2	4.8	6.0	30.4
320.....	-----	-----	-----	-----	-----	14.4
330.....	-----	7.0	-----	-----	-----	-----

¹ Blends prepared by heating at 300° F. for 2 hours.

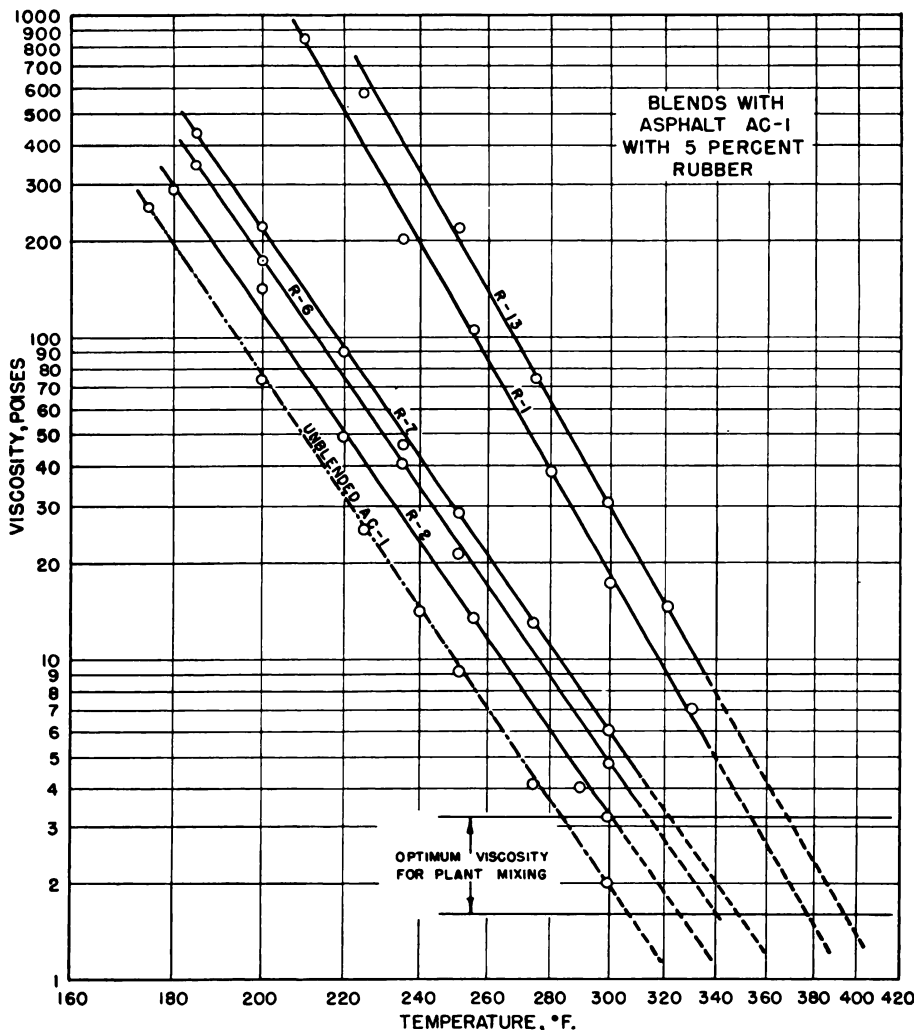


Figure 17.—Viscosity-temperature relation of rubber-asphalt blends.

Table 14.—Results of tests on blends of asphalt AC-1 and 5 percent of various rubbers mixed at various temperatures

	Blend with R-1, mixed at—			Blend with R-2, mixed at—			Blend with R-6, mixed at—			Blend with R-13, mixed at—		
	300° F.	338° F.	425° F.	300° F.	375° F.	425° F.	300° F.	375° F.	425° F.	300° F.	338° F.	425° F.
Mixing time.....hrs..	2	2	2	4	4	4	4	4	4	2	2	2
Softening point after mixing:												
5 min.....° F.	125.0	-----	133.3	117.0	-----	-----	125.2	-----	-----	127.2	130.5	133.8
30 min.....do	133.5	142.3	134.3	122.7	120.0	124.0	124.9	128.3	129.0	132.0	138.0	144.0
60 min.....do	140.0	140.5	132.8	124.5	122.1	125.0	127.0	129.0	130.0	134.0	139.1	142.0
90 min.....do	143.0	137.7	130.0	121.3	123.5	125.0	125.6	-----	131.5	134.3	141.4	149.0
120 min.....do	142.5	137.3	128.8	122.9	124.3	126.3	125.0	129.8	132.5	134.0	141.7	152.1
240 min.....do	-----	-----	-----	123.8	127.3	129.9	126.5	132.4	136.4	-----	-----	-----
Penetration—												
At 50° F.....	22	20	18	18	17	15	16	16	15	22	23	17
At 77° F.....	66	69	65	73	66	63	66	62	55	73	72	58
At 95° F.....	139	160	153	157	146	137	146	139	121	157	150	109
Ductility, 77° F.....cm.	28	61	111	23	15	14	22	21	18	66	66	67
Rebound..percent	63	46	-----	48	40	42	13	20	27	66	73	64
Residue from thin-film oven test:												
Penetration, 77° F..	65	57	49	47	43	40	47	47	43	57	54	49
Softening point ° F.	129.0	134.5	140.0	137.8	141.0	145.0	140.3	140.5	145.5	151.0	154.0	158.0
Ductility, 77° F..	-----	-----	45.0	10.0	9.5	9.0	11.8	11.0	10.5	48	43	41.5
Rebound..percent	-----	-----	29	52	47	50	43	42	48	59	63	71

in order to apply or mix the various rubber-asphalt blends under the same viscosity conditions as for the unblended asphalt AC-1, it would be necessary to raise the mixing temperature approximately 20° F. for the R-2 blend and 90° F. for the R-13 blend.

Effect of Mixing Temperature

The previous data given in this report has been for blends of asphalt and rubber prepared at 300° F. It seemed of importance to get some information concerning the effect of mixing at other temperatures on the properties of the rubber-asphalt blends. For this study asphalt AC-1 and rubbers R-1, R-2, R-6, and R-13 were used. Mixing temperatures of 300°, 338°, 375°, and 425° F. were employed to obtain the information desired.

Since rubbers R-1 and R-13 had been found to produce wide changes in the properties of asphalt, the mixing time for these was limited to 2 hours at 300°, 338°, and 425° F. Rubbers R-2 and R-6, which showed little change in the properties of the asphalts when mixed for 2 hours at 300° F., were mixed for 4 hours at 300°, 375°, and 425° F. Softening-point tests were made during the mixing periods, and the blends after being mixed for 2- or 4-hour periods were tested for penetration, ductility, and effect of heating in thin films at 325° F. The results of tests showing the effect of mixing temperature on the rubber-asphalt blends are given in table 14. The effect of heating at various temperatures on the softening point during the mixing period is shown in figure 18.

The blend containing rubber R-1 is of particular interest. When heated at 300° F. the softening point increased during mixing over the full 2-hour heating period, but when mixed at 338° and 425° F. there was a gradual decrease in softening point after the first 30 minutes. This reversal is apparently due to the instability of the natural rubber when subjected to the higher temperatures. The blend containing rubber R-13 showed an increase in softening point during mixing at the three temperatures with the rate of increase

being greater with increases in mixing temperature. At all temperatures, blends containing rubbers R-2 and R-6 showed a relatively low rate of change in softening point during the mixing period.

Figure 19 shows the effect of mixing temperature on the penetration, softening point, and ductility of the blends after 2- and 4-hour periods. Except for rubber R-1, the penetration of the blends decreased as the temperature of mixing was increased. The blend containing the natural rubber R-1 had a

higher penetration when mixed at 338° F. than at 300° F., and then decreased at 425° F.

Except for rubber R-1, the softening points of the blends were increased by raising the mixing temperature. As previously stated, the decrease in softening point for the blends made with the natural rubber R-1 shows the instability of this rubber when subjected to high temperatures. The greatest increase in softening point occurred with rubber R-13.

The ductility of the blends containing rubbers R-2, R-6, and R-13 was affected only slightly by increasing the temperature of mixing. The ductility of the blend containing rubber R-1 was increased greatly by mixing at the higher temperatures.

Effect of Rubber on Various Penetration Grades of the Same Asphalt

All of the rubber-asphalt blends which have been discussed previously in this report were prepared with 85-100 penetration asphalts. In order to get some information on the effect of rubber on other grades of asphalt cement, blends were prepared using 50-60, 85-100 and 120-150 penetration asphalts, refined from Venezuelan crude by the same producer. The 85-100 penetration grade is the same as the asphalt designated in this article as AC-1. Blends of these three asphalts containing 5 percent of the natural rubber R-1 were made by heating at 300° F. for 2 hours. Softening-point tests were made on samples taken during the mixing period and the resulting blends tested as in the previous studies. The results

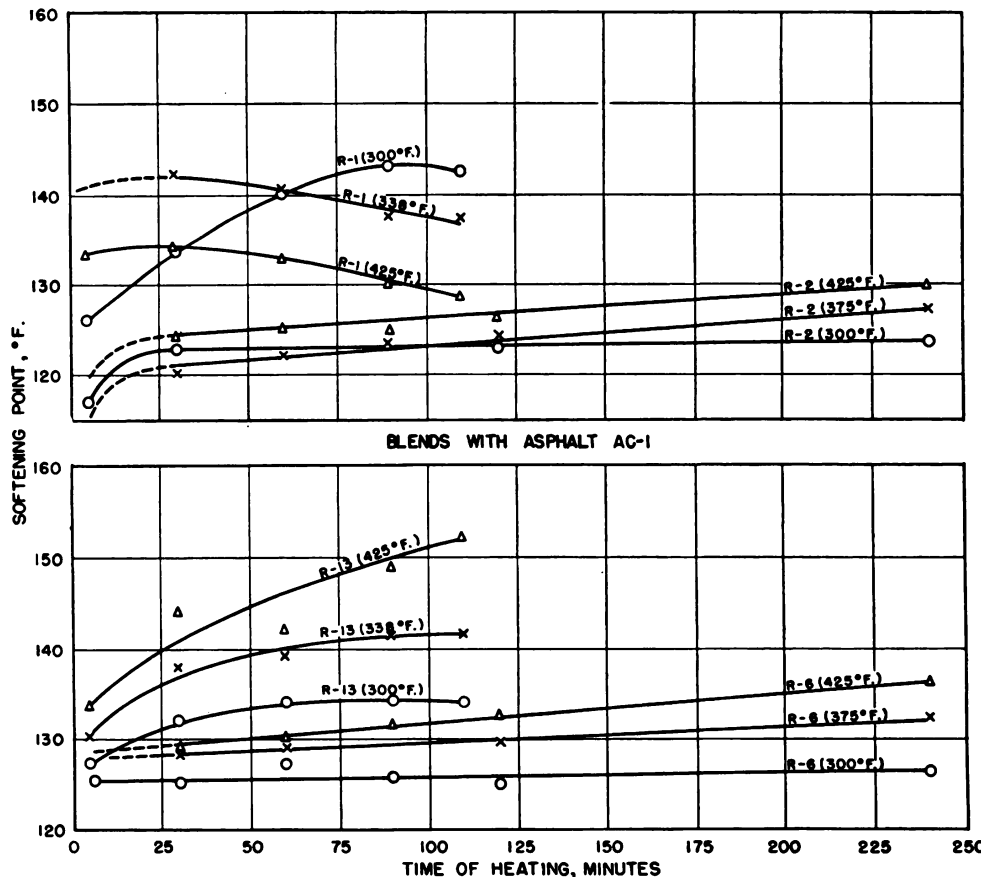


Figure 18.—Effect of temperature and time of heating on the softening point of rubber-asphalt blends.

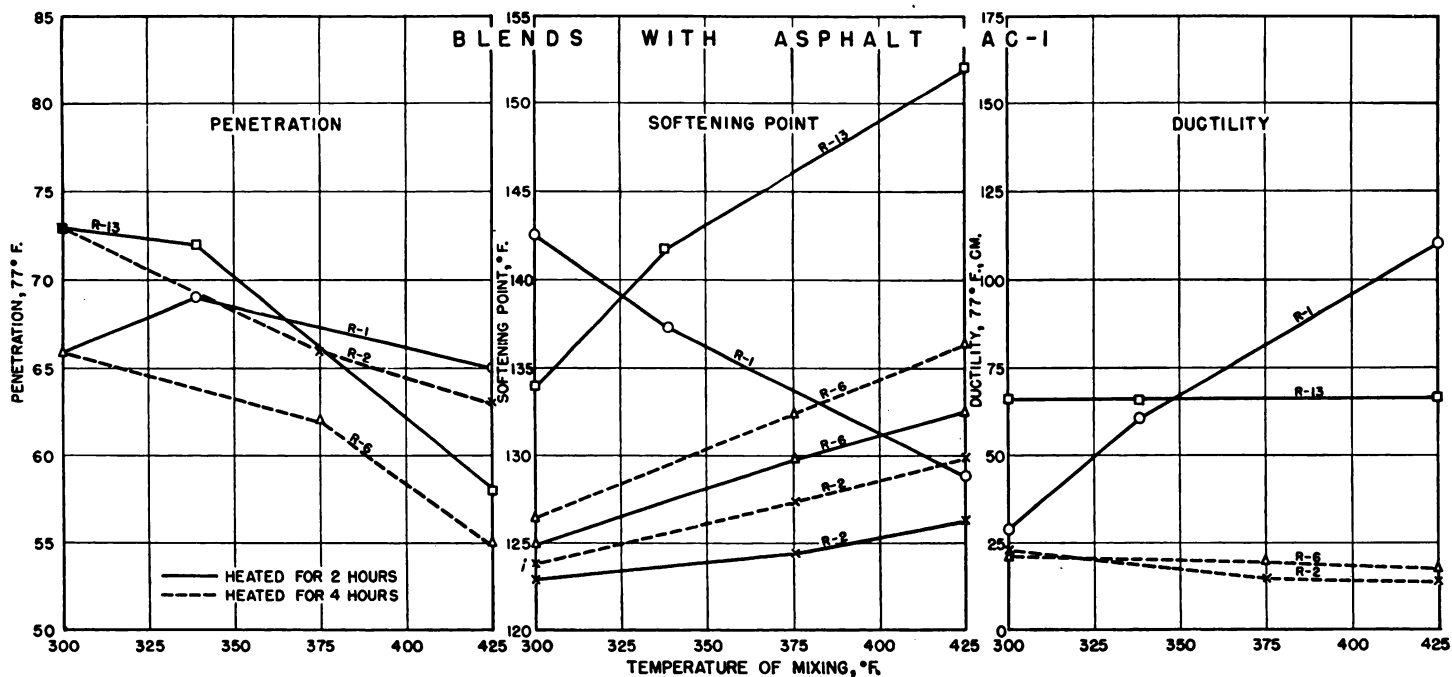


Figure 19.—Effect of mixing temperature on penetration, softening point, and ductility of rubber-asphalt blends.

of tests on the unblended asphalt and the rubber-asphalt blends are given in table 15.

Figure 20 shows the changes in softening point during the 2-hour mixing period for the blends prepared with the three grades of asphalt. The curves are of the same general shape and the difference in softening point remained fairly constant during the heating period.

In figure 21 the penetration, softening point, and ductility of the unblended asphalts are plotted against the penetration, softening point, and ductility of the corresponding rubber-asphalt blends. This figure indicates

for these asphalts and the one rubber used that as the penetration of the unblended asphalt was increased, the blends increased in penetration and had lower softening points and higher ductilities.

An analysis of the changes that were caused by the addition of rubber to the three grades of asphalt can be made from figure 22 where the penetration-softening point relations are plotted for the unblended asphalts and the rubber-asphalt blends before and after the thin-film oven test. For each of the above conditions the points for the three grades of asphalt are approximately linear and the curves thus

formed are nearly parallel. The relative position of the curves for the original asphalts and for the rubber-asphalt blends shows the high increase in softening point with a corresponding decrease in penetration. After the thin-film oven test, the curve for the rubber asphalt blends shows a large decrease in softening point accompanied by a slight increase in penetration. The position of this curve is only slightly above the curve for the thin-film oven residues on the unblended asphalts. This again demonstrates the variable properties that rubber-asphalt blends of this type might have when subjected to heat and oxidation in the mixing and laying of hot asphalt mixtures.

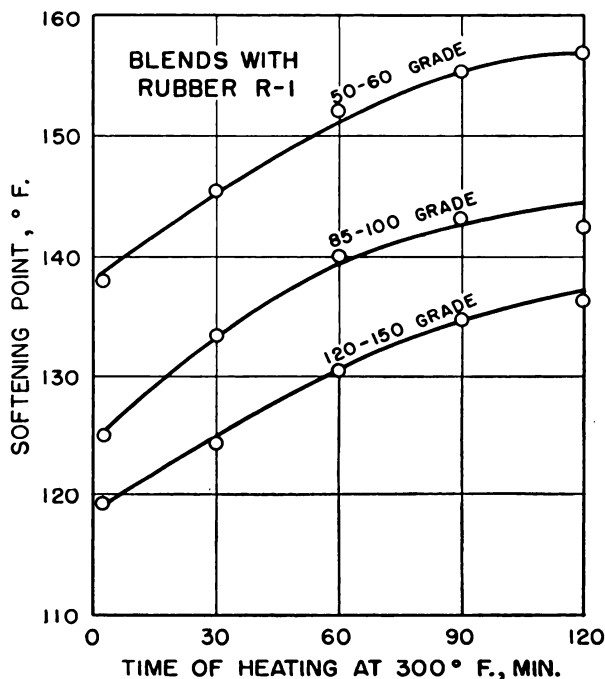


Figure 20.—Effect of time of heating on blends of 5 percent rubber R-1 with various grades of asphalt from the same source.

Recovery Tests on Mixtures

Tests on bitumens extracted and recovered from asphaltic paving mixtures have been useful in studying the changes that the contained asphaltic materials undergo during plant mixing with hot aggregate and during the exposure of bituminous pavements to service conditions. Usually these tests are made by extracting the soluble portion of the mixture with benzene and recovering this material by a method of test developed by Abson or by a modification thereof. Investigations have shown that asphalts are hardened during the hot mixing process or by exposure, and the amount of this hardening varies with the asphalt used and the conditions, such as temperature and the time of mixing or the climatic conditions, to which the mixture is subjected.

Tests on Recovered Bitumen

Since it has been shown that many of the rubbers included in this study are relatively insoluble in benzene, it was of interest to determine the effect of extraction and recovery tests on bitumens from asphalt mixtures in which rubber was used. Samples were obtained of the original asphalts and of paving

Table 15.—Effect of 5 percent natural rubber on asphalts of different penetration grades from the same source when mixed at 300° F. for 2 hours

	Unblended asphalt of penetration grade—			Blend of 5 percent R-1 with asphalt of penetration grade—		
	50-60	85-100	120-150	50-60	85-100	120-150
Softening point after mixing—						
5 minutes..... ° F	131.0	118.0	109.0	138.0	125.0	119.3
30 minutes..... do				145.5	133.5	124.3
60 minutes..... do				152.0	140.0	130.5
90 minutes..... do				155.5	143.0	134.8
120 minutes..... do				157.0	142.5	136.3
Tests on material after mixing for 2 hours:						
Penetration—						
At 50° F.....		20		13	22	22
At 77° F.....	50	89	136	39	66	85
At 95° F.....	122	232		85	139	195
Ductility, 77° F..... cm	230	+250	152	17	28	40
Rebound..... percent				65	63	79
Thin-film oven test:						
Loss..... do	0.18	0.28	0.36	0.19	0.19	0.71
Tests on residue:						
Penetration, 77° F.....	33	51	74	43	65	99
Softening point..... ° F	143	131	123	138.8	129.0	118.8
Ductility, 77° F..... cm	63	237	207	30	+250	240

mixtures in which these asphalts were used with and without rubber from several of the experimental pavements laid in the United States. These paving mixtures contained natural, reclaimed, synthetic, and plasticized rubbers and the powdered rubbers were the same as, or similar to, the rubbers R-1, R-2, R-5, and R-6 used in this study.

Extraction tests were made on these paving mixtures, using benzene, and the soluble material was recovered by the Abson method. The recovered bitumens were tested for penetration, softening point, and ductility. The results of tests on the original asphalts and on the bitumens recovered from the paving mixtures without rubber and corresponding mixtures which contained rubber are given in table 16.

Except for the mixtures containing the plasticized rubber, it was noticed that the extracted aggregates contained particles of rubber which had not been dissolved by the asphalt in the mixture or by the benzene used in the extraction test. Since it has been shown that the solubility of the rubber powders and rubber-asphalt blends in benzene are not the same, it was not possible to determine the exact amount of rubber actually contained in the bitumens recovered from the asphaltic concretes. It has also been shown that a wide range in test characteristics can be obtained with the natural rubber-asphalt blends, depending upon the asphalt used and the time and temperature used in the blending or mixing.

Comparisons of the characteristics of the original asphalts with those of the same asphalts recovered from the paving mixtures show that all the asphalts were hardened during the mixing process as evidenced by decreased penetration and increased softening point. Also, the ductilities of the recovered asphalts were lower than those of the original asphalts.

Comparisons of the characteristics of the bitumens recovered from the mixtures containing rubber with those of the bitumens recovered from the mixtures without rubber show that, in many cases, the presence of rubber increased the penetration; that in some cases it lowered the softening point;

and that in most cases it increased the ductility. This apparent effect of rubber is contrary to its effect in the blends of rubber and asphalt prepared in the laboratory where, as compared with the unblended asphalts, the blends generally had lower penetration, higher softening point, and lower ductility.

These differences between the characteristics of rubber-asphalt blends prepared in the laboratory and the characteristics of bitumens extracted and recovered from paving mixtures containing powdered rubber are attributed partly to the fact that the mixtures of rubber powder and asphalt in the pavement are not directly comparable to the laboratory blends and partly to the fact that the bitumen recovered from the pavement is not the same as the mixture of rubber powder and asphalt as it exists in the pavement.

In the District of Columbia experiment two types of paving mixtures were laid (23). Except where the plasticized rubber was used, 60-70 penetration asphalt was used in the sand asphalt mixtures. Except for the control section, 85-100 penetration asphalt was used in the sheet-asphalt mixtures. The 60-70 penetration asphalt was used in the control sections for both sand-asphalt and sheet-asphalt mixtures and 85-100 penetration asphalt was used in the plasticized rubber sections for both types of mixtures. The amount of each kind of rubber used was the same in both types of mixtures.

Except where the plasticized rubber was used, all of the rubbers were incorporated into

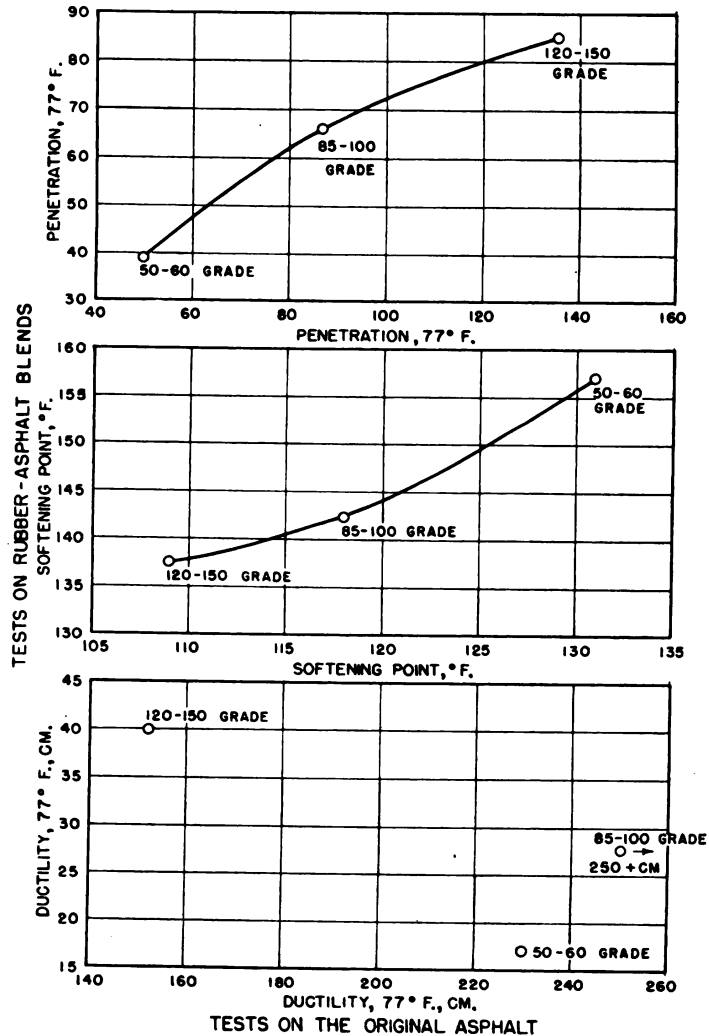


Figure 21.—Relation between tests on various grades of asphalt from the same source and tests on the same asphalt containing 5 percent rubber R-1.

Table 16.—Results of tests on asphalts and rubber-asphalt blends before and after recovery from paving mixtures

Type of mixture	Original material			Asphalt recovered from paving mixture		
	Penetration, 77° F.	Softening point	Ductility, 77° F.	Penetration, 77° F.	Softening point	Ductility, 77° F.
Non-skid mixture (Ohio):		°F.	Cm.		°F.	Cm.
Plain asphalt.....	70	122.0	175	47	132.4	136
Asphalt with natural rubber.....				43	135.5	78
Asphaltic concrete (Ohio):						
Plain asphalt.....	75	122.7	170	45	135.0	98
Asphalt with natural rubber.....				46	135.9	103
Asphalt with reclaimed rubber A.....				64	131.9	100
Asphalt with reclaimed rubber B.....				64	131.9	99
Asphalt with synthetic rubber.....				44	137.0	65
Asphaltic concrete (Texas):						
Plain asphalt.....	94	120.7	164	59	129.9	130
Asphalt with natural rubber.....				66	128.5	134
Asphalt with reclaimed rubber.....				62	129.9	175
Asphaltic concrete (Virginia):						
Plain asphalt.....	89	114.4	214	74	122.7	163
Asphalt with natural rubber.....				89	118.0	250
Sand-asphalt mixture (D. C.):						
Plain asphalt, 60-70 penetration ¹	64	123.0	+250	58	126.0	187
Asphalt with natural rubber ²	45	141.5	32	43	131.9	+250
Asphalt with synthetic rubber ²	53	135.0	25	61	126.3	+250
Asphalt with reclaimed rubber ²	47	133.8	18	53	128.0	+250
Asphalt with plasticized rubber ³	78	126.4	34	63	132.0	188
Sheet-asphalt mixture (D. C.):						
Plain asphalt, 60-70 penetration ¹	64	123.0	+250	53	128.6	225
Plain asphalt, 85-100 penetration ¹	93	117.0	+250			
Asphalt with natural rubber ²	63	134.0	33	65	125.8	+250
Asphalt with synthetic rubber ²	70	129.1	22.5	88	118.5	+250
Asphalt with reclaimed rubber ²	66	126.3	16	78	120.8	222
Asphalt with plasticized rubber ³	78	126.4	34	61	133.5	198

¹ Used in all sections of sand asphalt, except in plasticized rubber blends, and in control sections for sheet asphalt.
² Rubber-asphalt blend prepared in laboratory by mixing at 300° F. for 2 hours.
³ Plasticized rubber blended with asphalt at refinery and added to aggregate at mixing plant.
⁴ Used in all rubber-asphalt blends for sheet asphalt and in plasticized rubber blend for sand asphalt.

the mixtures by adding them to the aggregate prior to the asphalt. The plasticized rubber was blended with asphalt at the refinery. Therefore, the characteristics of the powdered rubber-asphalt blends were not known as they existed in the asphalt concrete. In order that some comparison could be made between the powdered rubber-asphalt blends before and after recovery, laboratory blends were prepared with the rubber powders and asphalt cements used in the District of Columbia experiment in the same proportions as in the paving mixtures. These blends were made by mixing the asphalt and rubber for 2 hours at 300° F. The test characteristics of these

materials, together with those for the plasticized rubber blend, are given in table 17. Figure 23 shows the effect of the time of heating on the softening point of the blends of the 60-70 and 85-100 penetration asphalts with the powdered rubbers. The results of the penetration, softening point, and ductility tests on the laboratory-prepared rubber-asphalt blends also are shown in table 16 for comparison with the same tests on the recovered bitumens.

A comparison of the laboratory-prepared rubber-asphalt blends with the bitumens recovered from the paving mixtures shows that, in general, the recovered bitumens had higher

penetrations, lower softening points and very much higher ductilities than did the laboratory-prepared blends. It is recognized that the blends prepared in the laboratory are not necessarily comparable with the combinations of rubber powders and asphalts as they existed in the pavement. If it can be assumed that they had somewhat similar characteristics, the differences in penetration, softening point, and ductility which have been noted could be accounted for, at least partially, by the fact that free particles of rubber are lost from the blend during extraction.

In the case of the plasticized rubber blend there is opportunity for a direct comparison between the original blend and the blends extracted from the paving mixture. In this case, in contrast to the powdered rubber blends, the recovered bitumen had a lower penetration and a higher softening point than did the original blend. However, as in the case of the laboratory blends, the ductility of the recovered bitumen was much higher than the ductility of the original blend.

From the data given in tables 16 and 17 on the extraction and recovery tests, on the laboratory-prepared blends, and on the plasticized rubber blend prepared at the refinery, it can be seen that there was little or no correlation between the properties of rubber-asphalt blends and the properties of the blends recovered from the asphaltic paving mixtures, as measured by the penetration, softening point, and ductility tests.

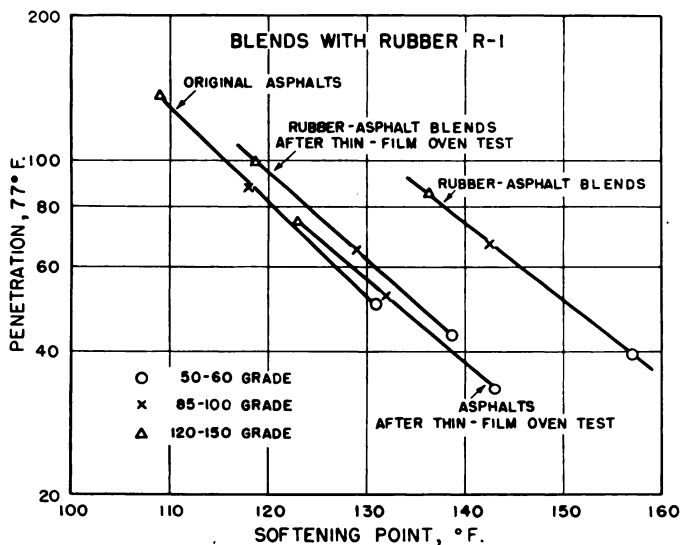


Figure 22.—Relation between softening point and penetration of various grades of asphalt from the same source with and without 5 percent rubber R-1, before and after thin-film oven test.

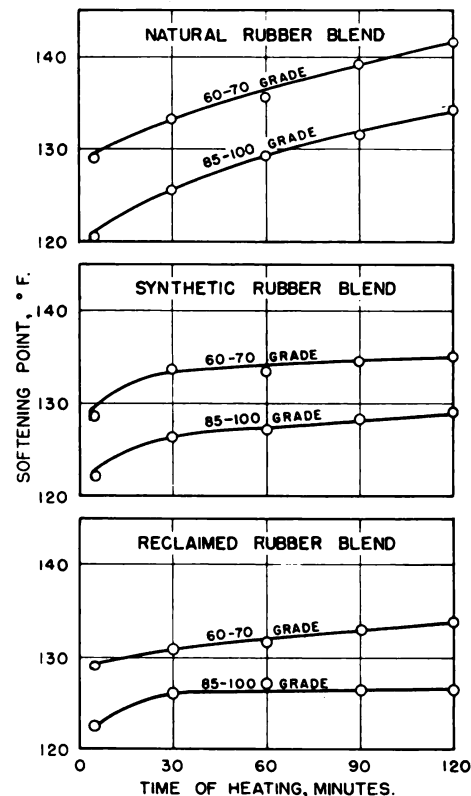


Figure 23.—Effect of time of heating on softening point of blends of various rubbers with 60-70 and 85-100 penetration grades of asphalt (used in District of Columbia experimental pavement).

Table 17.—Results of tests on laboratory blends of asphalt and various rubbers used on District of Columbia experimental pavements

	60-70 penetration asphalt blended with rubber indicated				85-100 penetration asphalt blended with rubber indicated				
	None (un-blended)	5.2 percent natural	5.2 percent synthetic	7.0 percent reclaimed	None (un-blended)	5.2 percent natural	5.2 percent synthetic	7.0 percent reclaimed	25.0 percent plasticized ¹
Softening point after mixing:									
5 min. °F	123.0	129.0	128.6	129.0	117.0	120.3	122.0	122.5	126.4
30 min. °F	-----	133.0	133.6	130.8	-----	125.3	126.5	126.0	-----
60 min. °F	-----	135.5	133.5	131.5	-----	129.2	127.0	127.0	-----
90 min. °F	-----	139.0	134.5	132.8	-----	131.5	128.5	126.3	-----
120 min. °F	-----	141.5	135.0	133.8	-----	134.0	129.1	-----	-----
Tests on mixture after heating 2 hours:									
Penetration, 100 g., 5 sec.:									
At 50° F	13	12	16	11	18	16	16	16	21
At 77° F	64	45	53	47	93	63	70	66	78
At 95° F	192	105	120	121	275	137	174	162	190
Ductility, 77° F, cm	+250	32	25	18	+250	33	22.5	16	34
Rebound, percent	-----	78	60	31	-----	58	50	27	32
Thin-film oven test:									
Loss, 5 hr., 325° F, percent	0.15	0.14	0.14	0.19	0.27	0.24	0.24	0.27	0.39
Tests on residue:									
Penetration, 77° F	38	54	36	33	54	69	48	45	50
Softening point, °F	132.8	128.0	146.0	148.5	126.5	124.5	141.0	142.0	139.0
Ductility, cm	+250	+250	30.5	14.5	188	+250	42	17.0	24.5
Rebound, percent	-----	-----	66	62	-----	-----	70	64	27

¹ Tests made on rubber-asphalt blend prepared at refinery with 85-100 penetration asphalt.

Table 18.—Viscosities of blends of SC-3 liquid asphalt and 5 percent of various rubber powders after periods of aging at room temperature

	Viscosity ¹ at 95° F. after—						
	1 day	3 days	7 days	16 days	56 days	127 days	400 days
Unblended SC-3	Poises 160	Poises 157	Poises 155	Poises 162	Poises 155	Poises 155	Poises 155
Blend of SC-3 and—							
R-1	285	335	390	383	443	555	425
R-2	210	228	230	230	240	240	235
R-6	310	313	310	350	335	330	280
R-10	605	550	580	605	675	750	665
R-13	350	610	780	1,360	1,500	1,510	1,530

¹ Determined by Brookfield Synchro-Lectric viscometer with spindle No. 6 and speed of rotation of 2 r.p.m.

Therefore, to obtain at this time a definite idea as to the effect of rubber powders on the physical properties of asphalt, recourse must be made to tests of rubber-asphalt blends prepared in the laboratory. It should be noted, as indicated in table 16 and as has been shown by other investigations, that the properties of normal asphalt cements may be considerably altered during the mixing and laying operation. If similar changes take place in the characteristics of the rubber-asphalt blends during the mixing and laying operation, they cannot be determined at present because no extraction and recovery method available can recover the rubber-asphalt blend as it exists in the pavement.

Effect of Rubber on Liquid Asphalt

This report so far has been confined to the effect of rubber on asphalt cements when combined at relatively high temperatures. It has been demonstrated that variations in these high mixing temperatures produced changes in the characteristics of some of the rubber-asphalt blends. In order to determine the effect of the various rubbers on asphaltic materials when mixed and stored at normal atmospheric temperatures, a separate study was made with a nonvolatile, slow-curing, liquid asphaltic material of the SC-3 grade. The test characteristics of this material were as follows:

Specific gravity, 77°/77° F..... 0.987
 Saybolt Furol viscosity, 140° F..... 511 sec.
 Distillation test:
 Volume of distillate to 680° F... 0.0 percent
 Tests on distillation residue:
 Float test of 122° F..... 88 sec.
 Residue of 100 penetration..... 79.4 percent
 Tests on residue:
 Penetration, 77° F... 102
 Ductility, 77° F... 88 cm.

Blends were prepared at room temperature with this material and 5 percent of rubber powders R-1, R-2, R-6, R-10, and R-13. After thorough mixing, the blends were sealed in 1-quart friction-top cans and stored in the laboratory. After periods of 1, 3, 7, 16, 56, 127, and 400 days the blends were heated to 95° F., stirred to insure uniformity, and their viscosity determined at 95° F. by means of the Brookfield viscometer. The results of these tests on the original SC-3 liquid asphalt and the various rubber blends are given in table 18. The changes in the viscosity of these materials are shown in figure 24, where the time of storage is plotted against the viscosity.

There was a very large difference in the change in viscosity for the various rubber blends during storage. After 1-day storage, all the blends had higher viscosity values

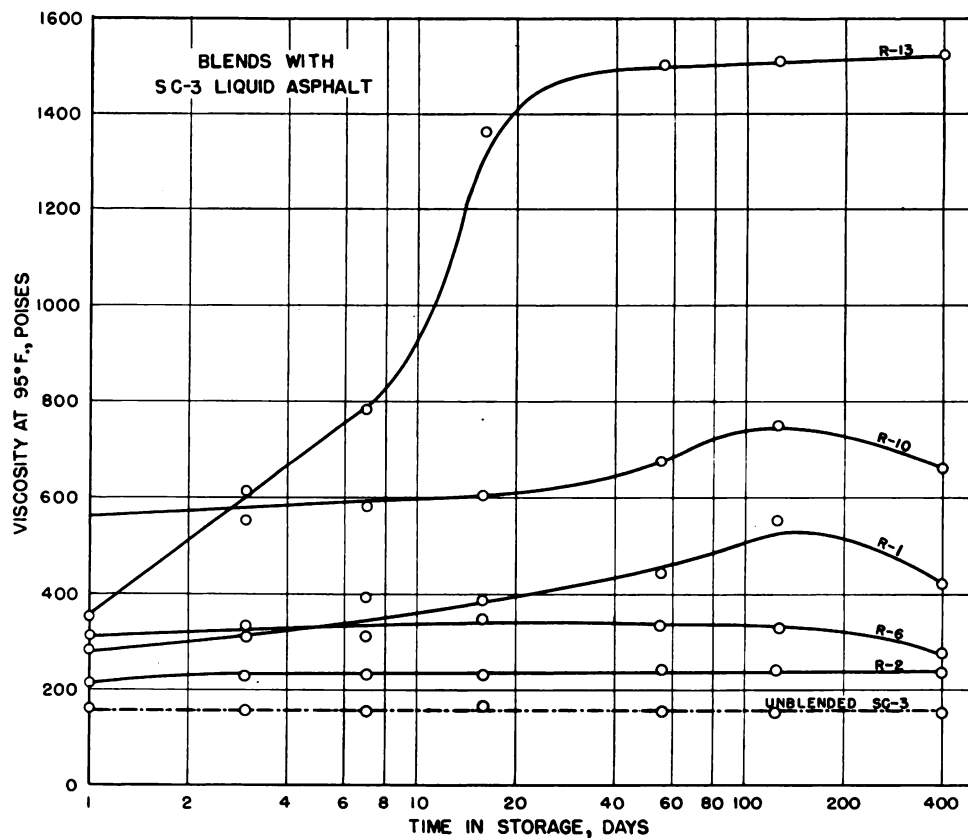


Figure 24.—Change in viscosity of blends of SC-3 liquid asphalt with 5 percent of various powdered rubbers during storage at room temperature.

flow and elastic properties of the SC-3 material.

Theories about Rubber-Asphalt

During the development of the use of rubber powder as a modifier for asphaltic materials, several theories have been advanced as to what happens when these two materials are combined. In a report by van Der Bie and Kain (1) in 1938, the following theory was advanced: Asphaltic bitumens are regarded as a colloidal system of particles, rich in asphaltenes, in a medium of malthenes. When rubber is added, the asphaltenes remain unchanged while a portion of the rubber is dissolved by the malthenes, thus increasing their viscosity and, consequently, that of the entire system. Initially the greater part of the rubber remains in the form of granules and absorbs a portion of the malthenes which cause them to swell. This causes the remaining bitumen phase to become harder.

In another report, van Rooijen (1) in 1941 gave the following explanation of the effect of natural rubber on asphaltic bitumens: The addition of rubber powder to asphaltic bitumen creates a disperse system in which the rubber particles, which have swollen, are dispersed in the bituminous medium. When the swelling of the rubber is sufficiently great, the volumes of the two phases may be about equal. A reversal of phases may then occur in which the rubber becomes the continuous phase. This may be accompanied by a coagulation of the asphaltenes by the depolymerized rubber. This theory was used to explain why rubber-asphalt mixtures first become softer on heating to high temperatures and with continued heating again become harder.

Coltof (24) in 1937 studied the solubility properties of certain highly polymeric substances, paying special attention to the phenomenon of dissolution in regard to dispersion, swelling, and ballast action. He

observed that the primary phenomenon is swelling. The swollen material grows and changes into a gelatinous mass and ultimately becomes completely miscible with the solvent. Coltof stated that there are two kinds of interaction between a liquid (simple or mixture) and a highly polymeric substance: Miscibility in all proportions (resulting in a solution or in a jelly) according to the fluidity of the mixture, and limited swelling (part of the liquid being absorbed by the particles while a certain part of the substance passes into the remainder of the liquid). He states further that heating tends to increase dispersion and decrease swelling.

De Decker (25) in 1951 stated that the behavior of dispersed rubber powders which causes the changes in the physical properties of rubber-asphalt blends is not yet fully explained and the research in the behavior of the rubber-asphalt binding material in a complete asphalt mixture is only in the first stage.

Photomicrographs of Blends

During the preparation of the rubber-asphalt blends, it was evident that many of the rubber powders used in this study retained their particle form even when subjected to very severe heat treatment, while blends containing other rubber powders became homogeneous under less severe conditions of mixing. A microscopic study of materials of this nature is dependent upon the ability to prepare films sufficiently thin to transmit light. It was found that for some of the rubber powders, which were of relatively large particle size and did not break down in the presence of asphaltic materials during mixing and heating, suitable films of the blends could not be prepared. In preparing the slides, a small drop of the rubber-asphalt blend was placed on a glass microscope slide, a cover glass was placed on

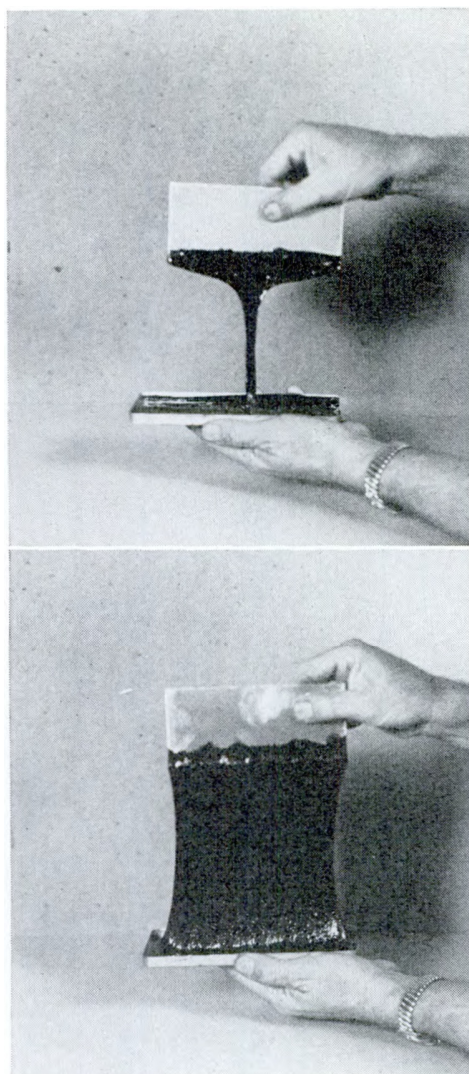


Figure 25.—Effect of rubber on flow and elastic properties of SC-3 liquid asphalt: above, unblended asphalt; below, rubber-asphalt blend.

than the original SC-3 material. The range in viscosity was from 210 to 605 poises. Increasing the storage period to either 56 or 127 days increased the viscosities of all the blends, after which some of the blends showed a slight decrease in viscosity. At 16 days storage the range in viscosity was 230-1,360 poises and at 127 days 240-1,510 poises. The reclaimed rubber R-2 showed the least effect of the storage period and rubber R-13 the greatest effect.

The viscosity of the blend containing rubber R-1 increased gradually during storage up to 127 days but did not develop the high viscosity that would be expected when compared with the viscosity of the blends prepared with the same rubber and the asphalt cements. This may be attributed to the effect of temperatures at which the respective blends were prepared. The relative order of the viscosity developed in storage by the other blends of SC-3 asphalt and rubber is the same as for the blends of asphalt cements with the same rubbers. Figure 25 shows the effect of the GR-S Type II rubber, R-13, on the

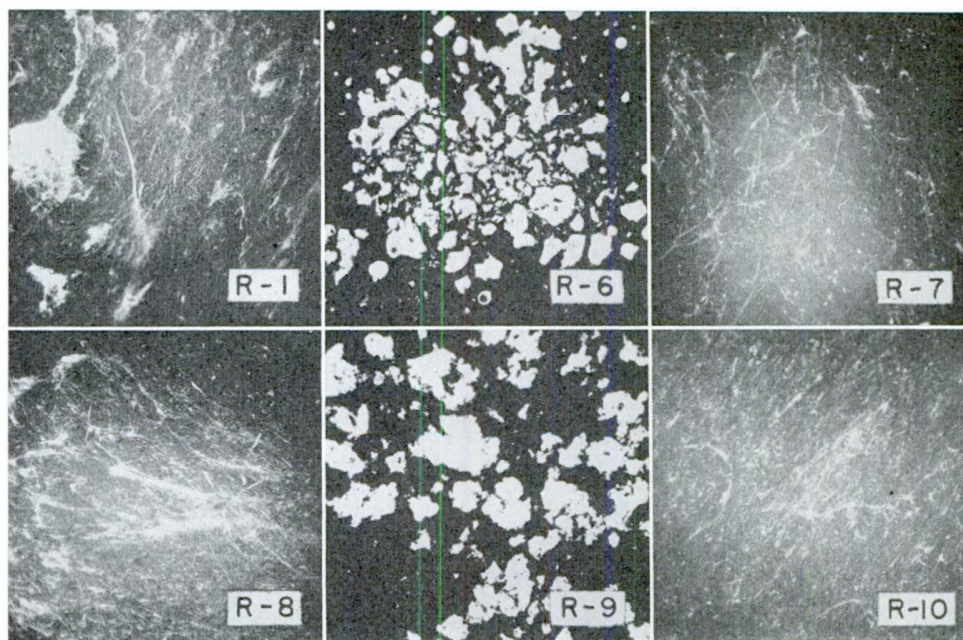


Figure 26.—Photomicrographs of blends of asphalt AC-1 with various powdered rubbers after heating and mixing at 300° F. for 2 hours (×34).

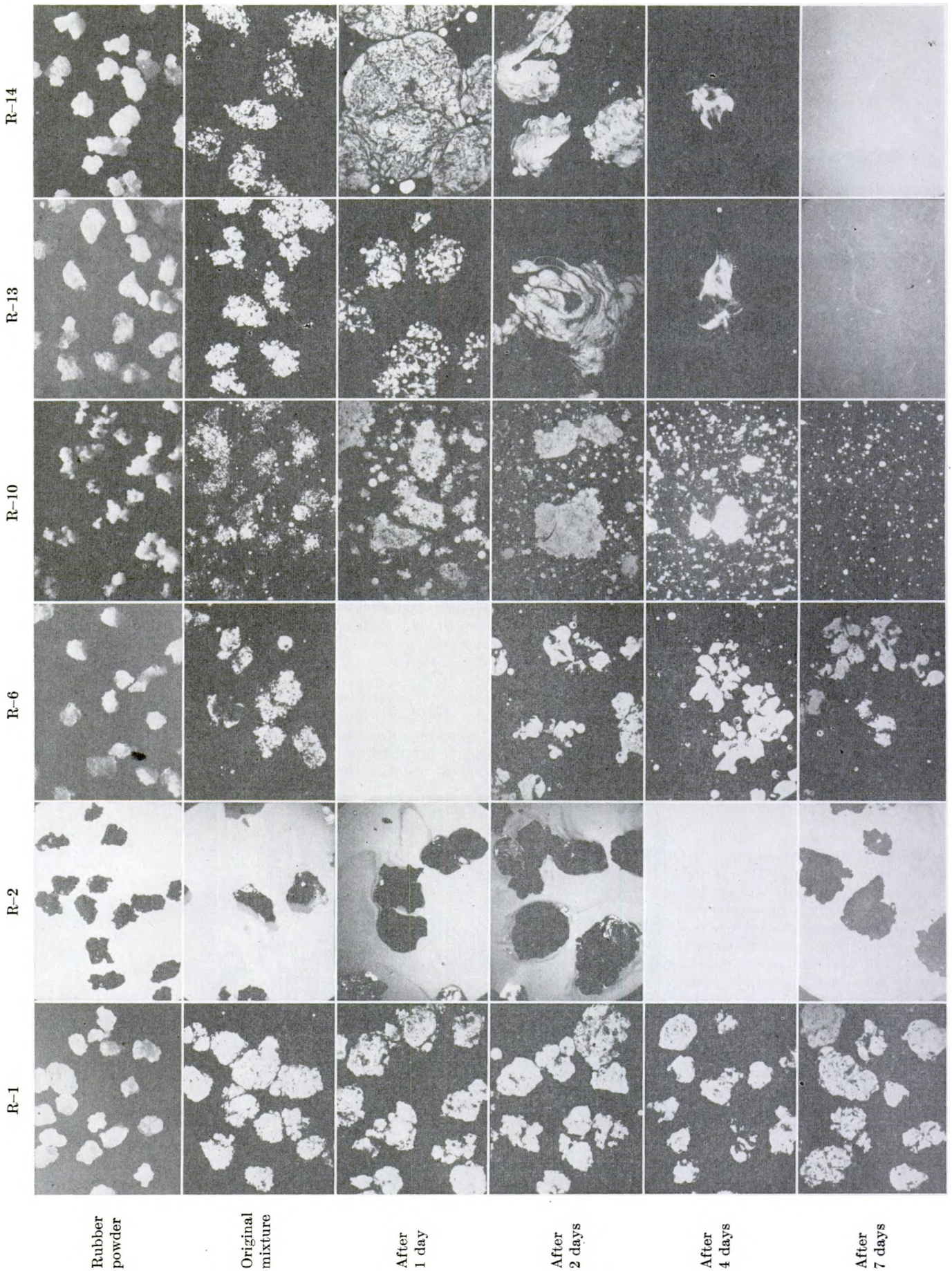


Figure 27.—Photomicrographs of various powdered rubbers before and after mixing with SC-3 liquid asphalt ($\times 17\frac{1}{2}$).
 (No photomicrographs were available for R-2 after 4 days and R-6 after 1 day.)

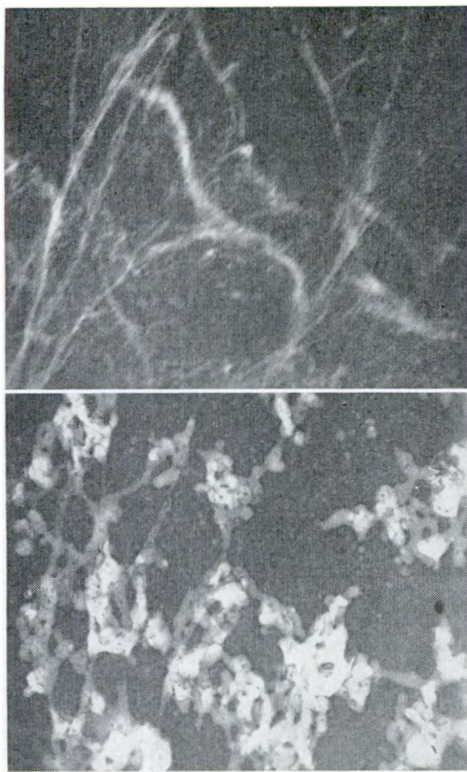


Figure 28.—Photomicrographs of blend of rubber R-14 with SC-3 liquid asphalt ($\times 33$). Above: Blend after 8 days, after standing 1 day without stirring before slide was made. Below: The same slide, 24 hours later, showing development of rubber structure on standing undisturbed.

top, and the assembly was warmed sufficiently so that light pressure applied to the cover glass caused the material to flow into a thin film. As mentioned above, where large particles of rubber were present between the cover glass and slide it was not possible to make the film sufficiently thin to transmit light.

Where satisfactory slides could be made, photomicrographs were taken of some of the rubber-asphalt blends prepared by heating for 2 hours at 300° F. The state in which the rubber existed in the asphalt at this time is illustrated by figure 26. Although photomicrographs of some of the rubber-asphalt blends are not shown here, the various rubbers appeared to fall into two groups depending upon their behavior. The natural rubber R-1 and the synthetic rubbers R-7, R-8, R-10, R-13, and R-14 appeared to have softened and were dispersed throughout the asphalt. The reclaimed, processed, and ground scrap rubbers R-2, R-3, R-4, R-5, R-15, and R-16 and the synthetic rubbers R-6 and R-9, except for some swelling, appeared to be relatively unaffected in the asphalt blend. It is of interest to point out the fact that those rubbers that showed the

greatest change in particle structure when blended with the hot asphalt also produced the greatest changes in the properties of the rubber-asphalt blends as measured by the physical tests.

Detailed Photomicrographic Study

Since the first photomicrographic study showed a wide difference in appearance of the various rubbers when mixed with asphalt, a more detailed study was undertaken to determine the relative behavior of some of the rubber powders. To reduce the influence of the particle size, only that portion of powdered rubber passing a No. 50 sieve and retained on a No. 80 sieve was used. To eliminate the effect of heat, as used in preparing the blends with asphalt cements, the SC-3 liquid asphalt previously referred to was used so that blends could be made at room temperature. Blends were prepared with the SC-3 asphalt containing 5 percent of rubbers R-1, R-2, R-6, R-10, R-13, and R-14. Films of the blends were made immediately after mixing and after 1, 2, 4, and 7 days storage at room temperature. Photomicrographs were taken of these films and also of the rubber powder, as shown in figure 27.

During the 7-day period, the particles of rubbers R-1, R-2, and R-6 showed some swelling. There was some disintegration of individual particles of R-6 but none of R-1. The streaks shown in the blend with rubber R-2 at 1- and 2-day periods probably were due to some of the carbon black flowing from the rubber particles through the asphalt.

Rubber R-10 appeared to break into smaller particles during the initial mixing. After 1 day there was considerable swelling of the rubber, followed by a gradual breakdown and disappearance of the large particles. At 7 days, there were only a few small rubber particles visible.

The particles of rubbers R-13 and R-14 seemed to soften and swell very rapidly. After this condition the rubber appeared to be dissolved or dispersed in the asphalt, and at 7 days only slight traces of the rubber were visible.

The striking difference in the behavior of the natural rubber R-1 when mixed with asphalt cement (fig. 26) and with the SC-3 liquid asphalt (fig. 27) probably was due to the difference in mixing temperature, as previous work has shown this rubber to be very unstable when subjected to high temperatures.

As previously indicated, the changes in particle structure during the heating of the rubber powders could not be followed by photomicrographs, although it was apparent that those rubbers which formed homogeneous mixtures did swell to some extent, softened, and dissolved or were finely dispersed. The

reclaimed and processed rubber and ground vulcanized scrap, as well as the GR-S Type V rubber R-6, did not swell to a great extent but did break down to smaller particles in the hot asphalt. When mixed with SC-3 liquid asphalt, natural rubber R-1, which formed a homogeneous mixture with the hot asphalt, swelled but slightly and retained its particle structure in the same manner as the more inert rubbers in the SC-3 liquid asphalt.

During the blending of rubbers R-13 and R-14 with the SC-3 liquid asphalt, it was noticed that these blends developed a high degree of gelation during storage and on stirring they became very rubbery. In an attempt to show this change in condition, slides of the blended rubber R-14 were prepared on the eighth day without stirring the mixture for 24 hours. Definite changes in the rubber structure were found to have occurred in these materials, as illustrated in figure 28, for the blend of SC-3 asphalt and rubber R-14.

The photomicrograph taken of the blend without stirring shows considerable more rubber structure than does the photomicrograph of the same blend after 7 days, shown in figure 27. The photomicrograph of the slide after 24 hours (figure 28, bottom) shows the rubber to have separated or coagulated to a much greater extent. These conditions no doubt account for the physical changes occurring in the blends of rubbers R-13 and R-14 with the SC-3 liquid asphalt. Changes such as these with the SC-3 liquid asphalt have not been noticed with the blends prepared with asphalt cements.

References to various theories that have been advanced (1) as to what happens when rubber powders are blended with asphaltic materials indicate that some investigators believe that the rubbers are soluble only in the malthene portion of the asphalt. Considering the variable solubilities of the rubber powders in simple solvents, such as those normally used in the examination of bituminous materials, and considering the changes in particle size and structure of the rubber blends with the asphalt and SC-3 slow-curing liquid asphalt, as shown in the photomicrographs, it might well be assumed that these asphaltic materials act as a solvent mixture. According to Coltof (24), therefore, these rubber powders, depending upon the degree of vulcanization, upon the presence of non-rubber bodies, and upon the temperatures involved in effecting solution, might act in the same manner as other highly polymeric substances in simple or complex solvents. The amount of dissolution, the dispersion, and the swelling that occur when blending the various rubbers with asphaltic materials may be due to the action of the asphaltic material itself and not to the selective action of its malthene fraction.

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A Laboratory Study of Rubber-Asphalt Paving Mixtures

BY THE PHYSICAL RESEARCH BRANCH
BUREAU OF PUBLIC ROADS

Reported by HARRY M. REX, Supervising Highway Physical Research Engineer and ROBERT A. PECK, Highway Physical Research Engineer

DURING recent years, the use of several types of rubber admixtures in bituminous roads has been promoted intensively. The principal advantages claimed for bituminous road surfaces containing rubber over conventional pavements are lower susceptibility to temperature change, being less likely to crack in cold weather and less likely to be displaced by traffic in hot weather, greater resistance to the action of water, greater resistance to abrasion by traffic, higher resistance to skidding, and longer life, with lower maintenance costs.

Considerable interest in this idea has been shown by many States and cities in the United States, and has resulted in the installation of test sections on a number of city streets and State highways for the purpose of determining the value of adding rubber under actual service conditions. The Bureau of Public Roads participated in observing the construction of test sections in several of the States, through the courtesy of the respective highway departments. Skid-resistance measurements are being made periodically on some of these test sections by the State highway departments. Also, it is hoped that laboratory testing of samples cut from the test roads from time to time will show the comparative degree of progressive alteration in other properties of the mixtures that occurs with age.

In the field experiments, several different forms of rubber have been used: rubber latex, rubber powders or crumbs, and so-called plasticized rubber. The rubber latex, as used in the United States, has been a synthetic product. The rubber powders used have consisted of natural and synthetic materials, and of processed reclaimed rubber. Two methods of incorporating the rubber powders into the final paving mixture have been used: adding the powder directly to the aggregate in the mixing box just before adding the bituminous material, and preblending the rubber with the bituminous material and then mixing the blend with the aggregate. The so-called plasticized rubber is a proprietary commercial compound which has been used widely as a joint- and crack-filler. While its exact composition is not known, this product is believed to consist essentially of synthetic rubber and bitumen, and for the purpose of this study has been considered as a preblend of rubber and bituminous material.

Decisions as to the value of additive rubber derived from the relative service behavior of

test roads must necessarily await the passage of considerable time. Study of the literature indicates that to date most of the laboratory research on the subject has been devoted to work with blends of asphalt and rubber, and very little to investigations of asphalt-rubber-aggregate mixtures. In order, therefore, to determine to what extent the addition of rubber to bituminous mixtures would change certain laboratory test properties of these mixtures, and thereby to arrive at conclusions, of a tentative nature at least, with respect to the value of adding the rubber, this laboratory study was initiated.

It was realized when planning the study, that interest in the development of new types and forms of rubber for use in bituminous paving is continuing. Likewise, new methods of incorporating the rubber materials now in use experimentally may be developed, or perhaps it may be found advantageous to combine the rubbers with types of bituminous materials other than those presently employed for the purpose. Meanwhile, this study was designed with a view to evaluating the materials and methods of incorporation that have been most widely used in this country to date.

Conclusions

Bearing in mind the limited scope of this study with respect to the number and kinds of rubber materials, the single proportion of rubber, and the single grade and source of asphalt employed, the test results are believed to warrant the following comments.

1. When added in the form of powder, the incorporation of rubber lowers the compactibility of an asphaltic paving mixture. In this regard the results of the laboratory tests were consistent with results of density tests that have been made on samples taken from several experimental road surfaces shortly after their construction. As tested in the laboratory, mixtures containing such rubber powders, when compacted under standard conditions, have lower stability and higher susceptibility to temperature change than control mixes without rubber.

2. In most of the field experiments installed in this country to date, the rubber has been incorporated by adding it in powder form to the aggregate before mixing with asphalt. Results of the laboratory tests show that mixtures prepared by preblending the rubber with

asphalt are much more compactible and stable than corresponding mixtures containing rubber that has been added in the form of powder. In fact, mixtures containing three of the four rubber materials tested in preblended form showed higher stabilities than the control mixture without rubber.

3. In the results of compression tests of mixtures containing rubber powders molded under varied pressures to produce equally low densities, and especially in the results of mixes containing preblended rubber and asphalt, it is possible to discern a degree of relation between the changes in stability, plasticity, and susceptibility to temperature change of the mixtures in this study and the changes in penetration, softening point, and susceptibility obtained in previous laboratory studies made of blends of asphalt and rubber. Such relation is entirely lacking in results of compression tests on mixtures containing rubber powders compacted under standard pressure.

4. Although the results show that the plastic properties of pavements containing preblended synthetic, natural, and plasticized rubber and asphalt would, in their early life at least, respond at a slower rate to temperature change than surfaces without rubber, the data hold no indication that pavement surfaces containing any of the rubber materials tested would be both substantially more plastic at lower temperatures and substantially less plastic at higher temperatures than surfaces without rubber. Mixtures containing plasticized rubber and preblended natural rubber were less plastic at 140° F. than the control mix, but they were also less plastic at 77° F. In general, mixtures containing synthetic and reclaimed rubber in either powder or preblend form were more plastic at 77° F. than the control mix, but they were also more plastic at 140° F. The exception to this generality was the mixture containing preblended synthetic rubber which, after oven exposure for 21 days, was slightly less plastic at 140° F. and slightly more plastic at 77° F. than the control mix.

5. The addition of rubber in either powder or preblend form did not increase the resistance of the mixture to the action of water.

6. Mixtures consisting of Ottawa sand and preblended asphalt and natural rubber were found to be more resistant to abrasion than the control mix without rubber, mixes con-

taining the other preblended rubbers tested, and mixes containing the same natural rubber tested in the form of powder.

Planning the Study

Two general lines of approach have been used in planning laboratory and field studies of asphalt mixtures containing rubber. In one approach, mixtures consisting of aggregate and combinations of rubber and asphalt have been compared directly with control mixtures containing asphalts, the viscous properties of which were equivalent to those for the rubber-asphalt combinations as predetermined by laboratory tests on the latter materials. For example, if, when a certain rubber was added to a certain asphalt in the 85-100 penetration range, it was found that the penetration of the resulting combination was between 60 and 70, then an asphalt in the 60-70 penetration range would be selected for the asphalt-aggregate control mixture.

This approach entails a number of practical difficulties. In the first place, it has been found that different types of rubber vary with respect to their solubility in asphalt, and thus with respect to their effect on consistency. A test program involving several types of rubber might, therefore, require several control mixtures. In any case, the degree of mutual solubility of rubber and asphalt actually attained in any given blend or combination is very difficult to determine. Thus it is very difficult to decide whether observable differences in physical characteristics are attributable to properties of a complex substance (mutually dissolved asphalt and rubber) or to properties of asphalt in which an essentially inert material is dispersed.

Again, one of the claims made for pavements containing rubber is that they are less prone to reflect cracks in underlying rigid pavements. If, in a field experiment laid over such a pavement, cracking is found in a control section containing 60-70 penetration asphalt and is not found in adjacent sections containing blends of rubber and 85-100 penetration asphalt, the question logically arises as to whether cracking would have occurred in the control section had 85-100 penetration asphalt been used there as well as in the rubber section.

The other approach, and the one used in planning this study, confines the scope to consideration of one question only: namely, what is the effect of adding a small quantity of rubber to a bituminous mixture consisting of a given aggregate and a given asphalt?

Table 1.—Results of sieve analysis of rubber powders

	R-1 Natural	R-2 Re- claimed	R-6 Syn- thetic
Percentage passing by weight:			
No. 10 sieve....	100	99	100
No. 20 sieve....	97	69	100
No. 30 sieve....	83	33	98
No. 40 sieve....	57	14	90
No. 50 sieve....	31	4	83
No. 80 sieve....	8	1	71
No. 100 sieve....	3	-----	61

By using the same grade of asphalt in the control mixture as is used in the mixtures to which the rubber is added, variables other than the addition of rubber are eliminated, thus permitting clear-cut and rational comparisons.

Laboratory Tests Used

The principal objectives of this study, together with the test methods selected for the attainment of each, were as follows:

To determine the effect of the manner in which the rubber is added to the asphalt mixture, two methods were employed. In one, the rubber powder was added to the hot aggregate in the mixer prior to the addition of the asphalt. In the other, the rubber was preblended prior to mixing with the aggregate, by heating and stirring the rubber and asphalt for a period of time.

To determine the effect of rubber on the temperature susceptibility (the rate at which the consistency of the asphalt changes with temperature) of the mixture, and to determine the effect of aging on this susceptibility, unconfined compression tests were made at two test temperatures, 77° and 140° F., after the specimens had been cured for 1 day in an oven at 140° F. and after they had been exposed to this temperature in the oven for 21 days.

To determine the effect of rubber on the resistance of the mixture to the action of water, the immersion-compression test (ASTM designation D 1075-49T) was made on specimens that had been cured for 1 day in an oven at 140° F. and on similar specimens after they had been aged in the oven at this temperature for 21 days. Static immersion tests were also made.

To determine the effect of rubber on resistance to abrasion, the modified California abrasion test was made.

Details of Test Procedures

Specimens used in the compression testing were cylinders 3 inches in diameter and 3 inches high. Two specimens were molded from each batch. Except for the size of specimens, size of batch, and molding pressures used, the mixing and molding procedures followed were the same as in ASTM designation D 1074-52T.

In the immersion-compression testing, 12 test cylinders were prepared and placed in an oven maintained at 140° F. They were removed from the oven 24 hours later, allowed to cool to a temperature of 77° F., and then measured for bulk specific gravity, using the water-displacement method. They were then divided into four sets of three specimens each on the basis of the specific gravity data, so that the average specific gravity of each of the four sets was approximately the same as the average for the twelve specimens.

Of the four sets of test specimens, set 1 was tested in compression at 77° F. in a dry condition. Set 2 was placed in water at 120° F. for 4 days, at the end of which time the three specimens in the set were measured again for bulk specific gravity and tested in compression

at 77° F. Sets 3 and 4 were replaced in the 140° F. oven immediately after the original density determinations had been made and kept there for 20 additional days. At the expiration of this oven-exposure period the specimens of sets 3 and 4 were removed from the oven and treated in the same manner as just described for sets 1 and 2, respectively. The ratio resulting from dividing the average compressive strength of the specimens of set 2, after immersion, by the average compressive strength of the specimens of set 1, tested dry, was taken as a measure of the effect of water on the mixture after 1 day of oven exposure. The ratio of average compressive strengths of specimens comprising sets 4 and 3 were taken as the measure of the effect of water on the mixture after 20 additional days of oven exposure at 140° F. The effect of the simulated aging provided by the additional oven exposure was obtained by comparing the two ratios, which represent retained strength values.

In the compression tests to measure stability, plastic properties, and susceptibility to temperature change, one set of three test specimens molded as described above was brought to a temperature of 77° F. in an air bath and tested in unconfined compression. A second set of three specimens was brought to a temperature of 140° F. and tested while immersed in water maintained at that temperature. Both of these two sets of specimens had been exposed to warm air in a 140° F. oven for 24 hours before testing. In order to determine the effect of aging on the properties of stability and plasticity of the mixture, two companion sets of specimens were kept in a 140° F. oven for 20 additional days, at the expiration of which period they were tested as just described.

All compression testing was done at a vertical-deformation rate of 0.05 inch per minute per inch of specimen height. Load deformation curves were obtained by means of an electrically actuated automatic recorder attached to the hydraulic testing machine.

The basic or control mixture used in all of the stability, temperature susceptibility, and immersion-compression tests consisted of hydrophilic crushed granite, concrete sand, commercial limestone dust, and 85-100 penetration asphalt.¹ These materials were combined to form a mixture containing (by weight) 5.5 parts of asphalt to 100 parts of aggregate graded as follows:

Passing:	Percent
¾-inch sieve.....	100
No. 4 sieve.....	82
No. 10 sieve.....	37
No. 40 sieve.....	14
No. 200 sieve.....	5

As has already been indicated, only one asphalt was used in this study. As has also been stated in this report, asphalts and rubbers alike appear to differ with respect to their mutual solubility, so that, had additional

¹ This material is the same as that designated as AC-2 in the report, *The effect of various rubbers on the properties of petroleum asphalts* by R. H. Lewis and J. Y. Welborn, appearing on pp. 64-89.

asphalts from other sources been included in the study, a wider range of results might have been obtained. The test characteristics of the asphalt used are as follows:

Specific gravity, 77°/77° F.....	1.012
Penetration 100 g., 5 sec.—	
At 50° F.....	24
At 77° F.....	94
At 95° F.....	238
Softening point.....°F..	120.0
Ductility, 77° F.....cm..	195
Standard oven test, 5 hr., 325° F.:	
Loss.....percent..	0.02
Tests on residue:	
Penetration, 77° F.....	76
Softening point.....°F..	123.8
Ductility, 77° F.....cm..	160
Thin-film oven test, 5 hr., 325° F.:	
Loss.....percent..	+0.01
Tests on residue:	
Penetration, 77° F.....	56
Softening point.....°F..	134
Ductility, 77° F.....cm..	52
Bitumen soluble in CS ₂percent..	99.94
Organic insoluble.....do.....	0.02
Inorganic insoluble.....do.....	0.04
Oliensis spot test.....	Negative

In preparing the control mix for the static-immersion test, the aggregate, which consisted of quartzite (a hydrophilic material) passing the 3/8-inch sieve and retained on the No. 4 sieve, was washed and heated to 300° F. The asphalt, which was also heated to 300° F., was mixed with the hot aggregate by hand over a hot plate until the best possible coating was obtained. The proportions used for the control mixture were 95 parts of aggregate to 5 parts of the asphalt, by weight. The mixture was then placed in an oven at 140° F. for 24 hours, after which it was cooled to room temperature and divided into three approximately equal portions. One of these portions was immersed in distilled water for 24 hours at a temperature of 100°F. The other portions were similarly immersed in water maintained at temperatures of 120° and 140° F., respectively. Upon completion of the water-immersion period, each sample was examined visually and the extent of stripping estimated. This examination was made without disturbance or agitation of the sample, and was made while the sample was still immersed in water. The area of the aggregate remaining coated with bitumen at the end of the test was reported as a percentage of the total surface area of the aggregate.

The basic or control mixture used for the abrasion test consisted of 100 parts of standard Ottawa sand (No. 20–No. 30) and two parts of asphalt, by weight. Both the sand and the asphalt were heated to 325° F. before mixing in the laboratory mixer. After mixing, the batch was spread out in shallow pans to a depth of about one-half inch and allowed to cool to air temperature. After cooling, 30-grams of the mixture were placed in each of eighteen 2-ounce ointment tins. These tins were then placed in an oven at 325° F. to warm the mix for molding.

The tins and contents were placed in the oven one at a time at 3-minute intervals.

Molding was started after 9 minutes and continued at the rate of one specimen each 3 minutes so that the preheating time for each 30-gram lot was uniformly 9 minutes. The test specimens were formed and tested in steel cups having an inside diameter of 2 inches and a depth of 3/8 inch. Each batch of exactly 30 grams of warm mixture was placed in one of the warm molds and compressed under a load of 1,000 pounds per square inch maintained for 1 minute. After molding, the specimens in their steel cups were allowed to cool to 77° F. prior to being placed in the 325° F. oven for weathering.

Weathering periods of 1/4, 1, 2, 4, and 8 hours were used. Three specimens were tested without oven exposure and at the expiration of each weathering period. After removal from the oven, the weathered specimens together with their supporting cups, were cooled to room temperature, weighed, and brought to test temperature of 77° F. in an air bath. The unweathered specimens were similarly weighed and brought to test temperature.

The apparatus used in the abrasion test was one that conformed essentially to the California design. The apparatus controls the fall of lead shot at the rate of 2,000 grams of shot per minute through a distance of 1 meter onto the surface of the test specimen. During the test the specimen is rotated at the rate of 340 r. p. m. The temperature of the test is controlled by placing the machine in an air bath held at 77° F. The shot is stored in the air bath between tests. The abrasion loss is normally reported on the basis of loss per 1,000 grams of shot after a total of 4,000 grams of shot has been dropped. After the test is stopped, the specimen is weighed and the loss determined to hundredths of a gram. Additional details of the test procedure are given in a previous report.²

Types of Rubber Studied

Three of the rubber materials used in this study were in powder form, and the fourth was a meltable rubber compound or plasticized rubber. The powdered materials consisted of a natural rubber from Indonesia, a processed reclaimed rubber, and a synthetic rubber.³ Sieve analyses of these powders are given in table 1.

Two different methods were used to incorporate the powders in the various test mixtures: adding them to the hot aggregate before adding the asphalt, and preblending them with the asphalt. In all of the test mixtures, regardless of the method of adding the rubbers, the proportion of rubber powder used was 5 percent of the asphalt, by weight.

In preparing the test mixtures containing the plasticized rubber, the rubber compound and the 85–100 penetration asphalt were preblended in the proportion of 25 and 75 percent, respectively. Although information regard-

² *Studies of the hardening properties of asphaltic materials*, by J. T. Pauls and J. Y. Welborn. PUBLIC ROADS, vol. 27, No. 9, Aug. 1953.

³ These materials correspond to the rubbers designated as R-1, R-2, and R-6, respectively, in the report cited in footnote 1.

ing the exact rubber content of the plasticized material itself has not been made available by the manufacturer of this commercial product, it has been estimated that the amount of rubber hydrocarbons in the blend of asphalt and plasticized rubber compound combined in the foregoing proportions is approximately 5 percent by weight of the asphalt.

In preparing the preblends of rubber and asphalt, the temperature of the asphalt was held at 300° F. and the various rubbers were stirred with the asphalt at that temperature for the following time periods:

Natural rubber powder....	1½ hours
Synthetic rubber powder....	2 hours
Reclaimed rubber powder...	2 hours
Plasticized rubber compound.	1 hour

The blends were then allowed to cool, and thereafter were heated again to 300° F. just before mixing with the aggregate, as needed.

In preparing all of the test mixtures containing the rubber powders, the proper amounts of asphalt, rubber, and aggregate for each batch were weighed separately and then combined in the order of their admission to the laboratory mixer, as follows: aggregate (preheated to 325° F.), rubber powder, and asphalt (preheated to 300° F.).

Comparing Temperature Susceptibility of the Mixtures

In 1949 and 1950, experimental asphalt-rubber road sections were built by several State highway departments. A number of samples of the mixtures from some of these field experiments were brought to the Bureau's laboratory for testing. In the course of these investigations, molded specimens of the mixtures were tested for unconfined compressive strength at 77° and 120° F., with the thought in mind that comparison of the compressive strengths of a particular mixture at the two test temperatures would provide some measure of its susceptibility to temperature change. At the same time, load-deformation curves were obtained by means of an automatic recorder attached to the testing machine. Study of these curves was made with a view to relating the character of the curve with the degree of plasticity of the mixture, and by this means to develop additional information as to the effect of temperature change on the flow properties of the mixture.

The behavior of compacted bituminous mixtures when subjected to vertical load without lateral support may differ widely, depending upon how closely they resemble rigid, elastic materials at the one extreme or plastic, easily deformable materials at the other. When tested at low temperatures, and where deflections or deformations of small magnitude are involved, bituminous mixtures may assume quasi-elastic properties; at high temperatures the same mixtures may exhibit extremely plastic properties.

Speed of testing (rate of loading or rate of vertical displacement) and ratio of height to diameter of the test specimen are other procedural factors that influence greatly the load-deformation relation with respect to any

one mixture. When these various factors are held constant in a given series of tests, however, differences in the load-deformation relation as between different mixtures may be used to compare the flow properties of the mixtures.

For example, the leading slope of the load-deformation curve shown in figure 1 is assumed to reflect the flow characteristics of the compacted specimen of bituminous mixture when tested in compression without lateral restraint. The curve shown in this figure is a typical one for mixtures tested at 77° F., and the basic elements as they were used in analyzing the curves for this report are as indicated in the figure. Some mixtures, however, are so plastic that no straight-line segment is obtainable. This latter type of curve is very often obtained in testing mixtures at temperatures of 120° or 140° F. In any case, a load component equal to one-third the maximum load is laid off on the middle section of the curve. The projection of this segment on the horizontal axis is carefully measured, and this quantity is taken as the deformation component. Unit vertical load (pounds per square inch of end-area of the test specimen) divided by the unit vertical deformation (inches per inch of specimen height) is termed the modulus of plastic deformation.

The computation, using the load-deformation curve in figure 1, obtained with a specimen 3 inches in diameter and 3 inches high, is as follows:

$$\begin{aligned} \text{Unit load} &= \frac{\text{load (lb.)}}{\text{cross-sectional area of specimen (sq. in.)}} \\ &= \frac{577}{7.069} = 81.62 \text{ lb. per sq. in.} \end{aligned}$$

$$\begin{aligned} \text{Unit deformation} &= \frac{\text{deformation (in.)}}{\text{height of specimen (in.)}} \\ &= \frac{0.026}{3} = 0.00867 \text{ in. per in.} \end{aligned}$$

$$\begin{aligned} \text{Deformation modulus} &= \frac{\text{unit load}}{\text{unit deformation}} \\ &= \frac{81.62}{0.00867} = 9,420 \text{ lb. per sq. in.} \end{aligned}$$

A steep slope of the curve (high numerical deformation modulus value) indicates a mixture having stiff, hard, or even brittle properties; a shallow slope (low numerical modulus value) indicates a very plastic, easily deformed mixture. In the study of temperature susceptibility, temperatures of 77° and 140° F. were used in the unconfined compression tests.

In the laboratory study of blends of asphalts and rubbers⁴ relative temperature susceptibility of the blends was based on a comparison of the slopes of lines connecting points plotted on semi-log graph paper to show penetration of the blends versus test temperatures. The numerical values for the slopes of such lines may be calculated from the following equation:

$$\text{Slope} = \frac{\log P_2 - \log P_1}{T_2 - T_1}$$

⁴ See report cited in footnote 1, p. 92.

where P_1 and P_2 are the penetrations of the blends at the two temperatures T_1 and T_2 .

It is generally agreed that the strength of a compacted bituminous mixture tested in unconfined compression at 77° F. is largely a function of cohesion. In turn, cohesion of the mixture tested at that temperature is largely a function of the viscous properties (penetration, melting point, ductility) of the bituminous cement. The compressive strength of a mixture containing a low-penetration asphalt is greater than a similar mixture containing a high-penetration asphalt. Increasing the temperature at which the unconfined compression test is made has the effect of reducing the viscosity of the asphalt with corresponding reduction in cohesive strength, and increase in plastic flow.

Therefore, since the temperature susceptibility of bituminous binders or blends of such binders and rubbers can be measured by the log penetration-temperature relation for such materials, it is logical to assume that temperature susceptibility of paving mixtures containing such binders, or blends of binders and rubbers, may be measured similarly by evaluating the rate of change in compressive strength and plastic flow resulting from temperature variation. Since both compressive strength and plastic flow are functions of the deformation modulus adopted for this study, a temperature-susceptibility index, calculated as follows, was used to compare susceptibility of the various mixtures to temperature change:

$$\text{Temperature-susceptibility index} = \frac{\log DM_1 - \log DM_2}{T_2 - T_1} \times 10^4$$

where DM_1 and DM_2 are deformation modulus values obtained in compression tests at the temperatures T_1 and T_2 , respectively, expressed in degrees F. The 10^4 factor is used simply as a convenience.

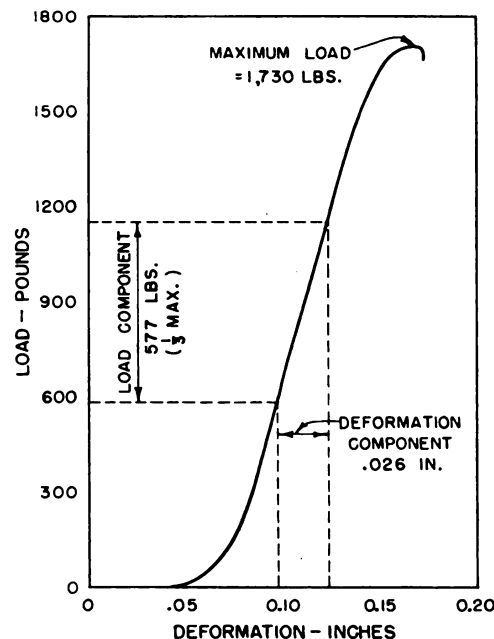


Figure 1.—Typical load-deformation curve and elements used in calculating deformation modulus.

In such comparisons, a relatively low index is construed as indicating a low temperature susceptibility—that is, a high resistance to temperature change. A high index is construed as indicating a high temperature susceptibility—that is, a low resistance to temperature change.

Differences in Density, Strength, and Temperature Susceptibility

Results of the unconfined compression tests made on specimens cured in an oven at 140° F. for 1 day, in conformity with standard compression-test procedure, are given in the left half of table 2. Each of the values shown is the average for three test specimens. In the first group of results shown in this table are a control mixture, and mixtures in the preparation of which reclaimed, synthetic, and natural rubber powders were added to the hot aggregate in the mixer before adding the asphalt. In molding test cylinders in this group of mixtures, the standard molding pressure of 3,000 pounds per square inch was used. This resulted in a wide range of densities for the several mixtures, with corresponding variations in values for compressive strength and plastic deformation. All the mixtures containing rubber powder were less compactible than the control mixture, and in general this observation based on tests of laboratory-prepared mixtures is consonant with the data available from tests previously made on a limited number of samples cut from newly laid experimental road installations. Table 3 shows data obtained on samples from three of these test roads. Of course, in studying these data, comparisons of bulk specific gravity are valid only as between mixtures of similar type.

In the first group of mixtures (the mixes with A in their designations) in table 2, in which powdered rubber was added to the aggregate and asphalt in the mixer, and in which the standard molding pressure was used, mix 1A (the control) was the most stable as judged by the compressive strength values at either test temperature, with the rubber mixes 3A (synthetic), 2A (reclaimed), and 4A (natural) following in descending order. The deformation modulus values at either test temperature showed the same rating for the mixtures in this group. Temperature-susceptibility ratings also had the mixtures in the same order, with the less stable mixtures being most susceptible.

These temperature-susceptibility evaluations of the mixtures were in disagreement with what might have been expected on the basis of results of tests made by a number of laboratories, including that of the Bureau of Public Roads, on blends of asphalt and rubber alone. Based on comparisons of the slopes of the log penetration-temperature curves mentioned in the previous discussion, it has been shown that the temperature susceptibility of blends of some rubbers and some asphalts is lower than that of the respective base asphalts.⁵

With a view to ascertaining to what extent this apparent discrepancy was attributable to

⁵ See report cited in footnote 1.

Table 2.—Results of unconfined compression tests of bituminous concrete mixtures after exposure in 140° F. oven for 1 day and 21 days

Mix No.	Type of rubber	Form of rubber	Molding pressure	Tests after 1 day						Tests after 21 days					
				Density	Tests at 77° F.		Tests at 140° F.		Temperature susceptibility index	Density	Tests at 77° F.		Tests at 140° F.		Temperature susceptibility index
					Compressive strength	Deformation modulus	Compressive strength	Deformation modulus			Compressive strength	Deformation modulus	Compressive strength	Deformation modulus	
1A	None		Lb./sq.in.	Gm./cc.	Lb./sq.in.		Lb./sq.in.		Gm./cc.	Lb./sq.in.		Lb./sq.in.			
2A	Reclaimed	Powder	3,000	2.240	245	8,830	69	4,190	51	2.240	315	10,150	87	4,650	
3A	Synthetic	do	3,000	2.120	149	3,500	21	655	115	2.121	178	3,830	37	995	
4A	Natural	do	3,000	2.204	199	5,925	44	1,885	79	2.208	275	7,310	73	2,710	
			3,000	2.058	134	2,500	14	345	136	2.057	164	2,620	23	485	
1B	None		200	2.053	80	4,725	6	380	174	2.059	131	7,590	14	890	
2B	Reclaimed	Powder	1,000	2.061	129	4,260	12	560	140	2.064	156	4,420	24	815	
3B	Synthetic	do	400	2.061	126	7,010	13	690	160	2.061	173	8,770	29	1,320	
2C	Reclaimed	Preblend	3,000	2.104	175	4,900	23	825	123	2.106	229	5,250	50	1,600	
3C	Synthetic	do	3,000	2.217	261	7,590	61	3,820	47	2.217	317	10,130	90	4,900	
4C	Natural	do	3,000	2.228	257	13,640	102	7,165	44	2.232	368	17,810	124	6,540	
5C	Plasticized	do	3,000	2.237	320	11,450	92	6,270	42	2.237	400	17,520	125	8,220	

the fact that the compacted mixtures varied widely with respect to density, tests were made on a second group of specimens (group B) in the preparation of which the molding pressure was varied so that the resulting densities would be approximately equal. Since mix 4A (natural rubber) in the first test group had the lowest density, molding pressures of 200, 1,000, and 400 pounds per square inch were used in preparing mixes 1B, 2B, and 3B, respectively, to bring the densities in these mixtures to approximately the same density as that of mix 4A.

With the density of the compacted mixtures removed as a variable, the compressive strength of mix 4A at either test temperature was highest. At 77° F. the compressive strengths for mixes 2B, 3B, and 1B in the equal-density group followed 4A in descending order. At 140° F. the compressive-strength rating position of mixes 3B and 2B were reversed, but mix 1B (control) again had the lowest rating.

Although the results of tests at 77° F. showed that mix 4A had slightly higher compressive strength than mix 1B, 2B, or 3B, they also showed that this mixture was the most plastic at that temperature, based on

comparison of deformation modulus values. At this test temperature mix 3B was the least plastic, although it did not have the highest compressive strength. At 140° F., although the compressive strengths of mixes 4A and 3B were essentially the same, the deformation modulus value of mix 3B indicates that this mixture was twice as stiff (or half as plastic) as mix 4A. In this test group, all of the mixtures containing rubber powders were somewhat more resistant to temperature change than the control mixture for the group (1B). In comparisons limited to this group, it is thus possible to discern a degree of relation between the effect of adding rubber to asphalt as measured by laboratory tests of the blends of asphalt and rubber, and the effect as measured by laboratory tests of corresponding mixtures consisting of aggregate and the same asphalt and rubber when the rubber is added in the form of powder. The higher compressive strengths and lower temperature-susceptibility index values obtained for mixtures 2B (reclaimed), 3B (synthetic), and 4A (natural), as compared to the control mix (1B), reflect to a perceptible degree the reduction in penetration, increase in softening point, and reduction in temperature susceptibility noted in the

results of tests made on the same asphalt and the same rubbers in the form of a blend.

Table 4 is arranged to facilitate the foregoing comparisons.

In studying the results of tests on the equal-density mixtures, it should be borne in mind that their importance is perhaps only academic, and lies chiefly in emphasizing the difference in effectiveness between adding the rubber to the mixture in the form of powder and adding it as part of the binder. In order to obtain the effects noted it was necessary, in molding the specimens of mixtures in which the rubber had been added in powder form, to compensate for the variations in compactibility characterizing the several mixtures by arbitrarily using molding pressures which, in two cases at least, would be considered wholly unrealistic.

From the foregoing discussion it is apparent that, under conditions of standard laboratory compaction, mixtures containing rubber that has been added to the aggregate in the form of powder are less compactible, are more plastic and less stable at both 77° and 140° F., and, within the temperature range 77°-140° F., are more susceptible to temperature changes than comparable control mixtures containing no rubber. Furthermore, in order to develop favorable comparisons as between the mixtures containing such rubber powders and the control mix, it was necessary to eliminate the pronounced compactibility differences by using unequal and unrealistic compactive pressures in molding the specimens for test.

Rubber More Effective When Preblended

The binders used in mixes 2C, 3C, and 4C consisted of blends of asphalt and reclaimed, synthetic, and natural rubber, respectively, prepared as has already been described. The binder in mixture 5C consisted of a blend of plasticized rubber and asphalt. Since the test specimens for the C group of mixtures were formed using 3,000 pounds per square inch molding pressure, test results for this group are directly comparable with those for the A group of mixtures.

The effect of the method of adding the rubber on the test results of the mixtures is

Table 3.—Density of samples cut from roadway test sections

Type of pavement and rubber	Form of rubber	Density at time of construction		Density at subsequent testing	
		Year constructed	Bulk specific gravity	Year tested	Bulk specific gravity
Bituminous concrete (Tex.):					
None		1949	2.19		
Natural rubber	Powder	1949	2.04		
Reclaimed rubber	do	1949	2.15		
Sand asphalt (Va.):					
None		May 1949	1.81	1951	2.17
Natural rubber	Powder	May 1949	1.71	1951	2.12
None		Sept. 1949	(¹)	1951	1.99
Reclaimed rubber	Powder	Sept. 1949	(¹)	1951	1.99
Sand asphalt (D. C.):					
None		1951	2.20	1952	2.23
Natural rubber	Powder	1951	2.00	1952	2.19
Synthetic rubber	do	1951	2.12	1952	2.20
Reclaimed rubber	do	1951	2.04	1952	2.20
Plasticized rubber	Preblend	1951	2.10	1952	2.24
Sheet asphalt (D. C.):					
None		1951	2.11	1952	2.15
Natural rubber	Powder	1951	2.06	1952	2.13
Synthetic rubber	do	1951	2.02	1952	2.06
Reclaimed rubber	do	1951	2.03	1952	2.10
Plasticized rubber	Preblend	1951	2.07	1953	2.17

¹ No data available regarding density as constructed.

clearly apparent, in the left half of table 2, in the higher densities obtained for the mixes containing preblended synthetic and natural rubber (3C and 4C) than were obtained for the corresponding mixes (3A and 4A) in which the rubbers were introduced in the form of powder. In the case of reclaimed rubber, this improvement in compactibility was not observed.

Similarly, the compressive strengths and the temperature-susceptibility index values show the relative effect of the two different methods of preparation, with higher stability and higher resistance to temperature change being obtained for preblended synthetic and natural rubber mixtures as compared with their rubber-powder counterparts. Although the stability of the preblended reclaimed rubber mix (2C) at both test temperatures was higher than that obtained with the same rubber in powder form (2A), the temperature susceptibility was about the same for this rubber regardless of the method of preparation.

Comparisons confined to the mixes comprising the C group and their control mix (1A) serve to indicate the relative value of the four different types of rubber with regard to their effect on the test properties of the mix after 1 day of oven curing. In the tests at 77° F. in the C group of mixtures, the compressive strength of mix 5C (plasticized) was highest, with the values for mixes 3C (synthetic), 4C (natural), 1A (control), and 2C (reclaimed) following in descending order. Comparative values for deformation modulus indicate that at this temperature mix 2C was the most plastic and 4C the least plastic. At 140° F., the compressive strength of mix 4C was highest with mixes 5C, 1A, 3C, and 2C following in descending order. At this temperature, as at 77° F., mix 4C was the least plastic and 2C the most plastic, based on deformation modulus values. Judged by the temperature-susceptibility index values, mix 2C was most susceptible to temperature change. Comparisons of index values indicate that mixes 3C, 4C, and 5C were slightly more resistant to the change in temperature than mix 1A.

As has been mentioned previously in discussing the results of compression tests of the equal-density (B) group of mixes, tests on

Table 5.—Changes in compressive strength, deformation modulus, and temperature susceptibility resulting from 20 additional days exposure to air in oven at 140° F.

Mix No.	Type of rubber	Form of rubber	Tests at 77° F.		Tests at 140° F.		Temperature susceptibility index ¹
			Compressive strength	Deformation modulus	Compressive strength	Deformation modulus	
			Percent	Percent	Percent	Percent	Percent
1A	None.....		+29	+15	+26	+11	+6
2A	Reclaimed.....	Powder.....	+19	+9	+76	+52	-19
3A	Synthetic.....	do.....	+38	+23	+66	+44	-14
4A	Natural.....	do.....	+22	+5	+64	+41	-15
1B	None.....		+64	+61	+134	+134	-15
2B	Reclaimed.....	Powder.....	+21	+4	+100	+45	-17
3B	Synthetic.....	do.....	+37	+25	+123	+91	-19
2C	Reclaimed.....	Preblend.....	+31	+7	+117	+93	-33
3C	Synthetic.....	do.....	+21	+33	+48	+28	+6
4C	Natural.....	do.....	+43	+31	+22	-8	+57
5C	Plasticized.....	do.....	+25	+53	+36	+31	+24

¹ Negative values indicate a gain in resistance to temperature change.

blends of asphalt and rubber have indicated that in some cases the addition of the rubber resulted in lower penetration and reduced temperature susceptibility. In the comparison of mixes 2C, 3C, 4C, and 5C with the corresponding control mix 1A, it is possible to discern some relation between the changes observed in the tests of asphalt and rubber blends, and the slight changes observed in tests of the mixtures of aggregates and corresponding blends. That is, the higher compressive strengths of mixes 3C (synthetic), 4C (natural), and 5C (plasticized), as compared to the control mix 1A, are consistent with the higher viscosity resulting from blending corresponding rubbers with asphalts. Likewise, the reduction in temperature susceptibility resulting from blending rubbers and asphalt is reflected in the lower temperature-susceptibility index values obtained for mixes 3C, 4C, and 5C as compared to that of the control mix 1A. Reference is again made to table 4, in which related materials are compared directly.

The data in the left half of table 2 indicate, nevertheless, that although the rate of change in plastic properties as measured by temperature-susceptibility index values is slightly lower for the mixtures containing preblended rubber and asphalt than for the control mix without rubber, the mixes containing the rubber preblends are not substantially more plastic at lower temperatures and at the same time substantially less plastic at higher

temperatures than mixes without rubber, at least in the 77°-140° F. temperature range. Deformation modulus values indicate that mixes 2C (reclaimed) and 3C (synthetic) were more plastic at 77° F. than mix 1A, but at the same time they were more plastic at 140° F. On the other hand, while mixes 4C (natural) and 5C (plasticized) were less plastic at 140° F. than the control mix, they were less plastic also at 77° F. The indications implicit in these test results are not in agreement with claims that paving mixtures containing rubber are more plastic at low temperatures and less plastic at high temperatures than similar mixtures without rubber.

Effect of Prolonged Oven Exposure

The right half of table 2 gives the results of tests made on molded specimens that were held in a 140° F. oven for 21 days. These specimens were molded and placed in the oven at the same time as those represented in the left half of the table, the oven-exposure period for which had been 1 day in conformity with the usual procedure for the unconfined compression test. Since the densities of corresponding sets of specimens were in close agreement, differences in other physical properties as between 1-day and 21-day oven exposures may be fairly attributed to the effect of the extended heat treatment. Table 5 was prepared to show, in percentage form, the changes in numerical values for the several properties evaluated.

In the control mixture specimens molded at 3,000 pounds per square inch (1A), extended exposure to warm air resulted in higher compressive strengths and modulus values at both test temperatures. However, it is interesting to note that the temperature susceptibility of this mixture was little changed by the extended heating. The specimens containing this same mixture, molded at 200 pounds per square inch (1B) showed pronounced percentage increases in compressive strengths and modulus values. As shown in table 5, changes occurred in all of the mixtures containing rubber powders regardless of the pressure used in the molding operation. Changes in compressive strength and modulus values appear to be more marked in the results of tests made at 140° F. In studying the values given in table 5, it should be realized

Table 4.—Characteristics of asphalt AC-2 and blends of 5 percent rubber powders with this asphalt compared to characteristics of compacted mixtures of aggregate and these same materials

Type of rubber	Characteristics of rubber-asphalt blends ¹				Equal-density mixtures, with powdered rubber ²		Equal-molding-pressure mixtures, with preblended rubber ³	
	Rubber identification	Penetration at 77° F.	Softening point	Temperature susceptibility ⁴	Mix. No.	Temperature susceptibility index	Mix. No.	Temperature susceptibility index
None.....		87	° F. 122	226	1B	174	1A	51
Reclaimed.....	R-2	80	126	207	2B	140	2C	123
Synthetic.....	R-6	74	127	202	3B	160	3C	47
Natural.....	R-1	67	147	165	4A	136	4C	44

¹ From *The effect of various rubbers on the properties of petroleum asphalts*, by R. H. Lewis and J. Y. Welborn. Tables 7 and 8 (see pp. 69 and 70).

² Mixtures 1B, 2B, and 3B were molded under variable pressures to the same density as was obtained for mix 4A molded under 3,000 lb. per sq. in. pressure. Mixtures 1A, 2C, 3C, and 4C were molded under 3,000 lb. per sq. in. pressure.

³ Slope of log penetration-temperature curves $\times 10^4$.

Table 6.—Results of immersion-compression tests of bituminous concrete mixtures after exposure in 140° F. oven for 1 day and 21 days

Mix No.	Type of rubber	Form of rubber	Molding pressure	Tests after 1 day								Tests after 21 days							
				Characteristics of specimens as molded				After immersion at 120° F.				Characteristics of specimens as molded				After immersion at 120° F.			
				Density	Air voids	Compressive strength at 77° F.		Absorption	Swell	Compressive strength at 77° F.	Retained strength	Density	Air voids	Compressive strength at 77° F.		Absorption	Swell	Compressive strength at 77° F.	Retained strength
			Lb./sq. in.	Gm./cc.	Percent	Lb./sq. in.	Percent	Percent	Lb./sq. in.	Percent	Gm./cc.	Percent	Lb./sq. in.	Percent	Percent	Lb./sq. in.	Percent		
1A	None		3,000	2.249	10.6	238	2.4	0.8	177	74	2.248	10.7	309	2.0	0.3	269	87		
2A	Reclaimed	Powder	3,000	2.125	15.3	162	4.4	.7	107	66	2.121	15.4	210	3.5	(1)	179	85		
3A	Synthetic	do	3,000	2.206	12.0	206	2.9	.8	162	79	2.207	11.7	289	2.8	.6	233	81		
4A	Natural	do	3,000	2.061	17.8	133	4.9	0	101	76	2.055	18.0	173	4.0	(1)	134	77		
1B	None		200	2.043	18.8	72	6.4	(1)	69	96	2.051	18.5	140	5.9	1.4	108	77		
2B	Reclaimed	Powder	1,000	2.048	18.4	115	5.2	(1)	94	82	2.060	17.9	166	5.4	(1)	121	73		
3B	Synthetic	do	400	2.058	17.9	127	5.3	(1)	96	76	2.064	17.6	157	5.4	(1)	130	83		
2C	Reclaimed	Preblend	3,000	2.122	15.4	194	4.3	1.0	128	66	2.114	15.7	215	4.4	.4	187	87		
3C	Synthetic	do	3,000	2.219	11.5	258	2.7	1.3	177	69	2.220	11.4	324	2.6	.9	251	77		
4C	Natural	do	3,000	2.236	10.7	254	2.5	1.0	184	72	2.237	10.7	330	2.8	.9	266	81		
5C	Plasticized	do	3,000	2.235	10.9	303	2.7	1.1	207	68	2.238	10.8	391	2.4	1.0	280	72		

1 No swell.

Table 7.—Results of static immersion stripping tests

Mix No.	Type of rubber	Form of rubber	Estimated area remaining coated after 24-hour immersion at temperature indicated		
			100° F.	120° F.	140° F.
1	None		90	85	75
2	Reclaimed	Powder	90	80	70
3	Synthetic	do	90	75	50
4	Natural	do	80	75	60
5	Reclaimed	Preblend	95	65	40
6	Synthetic	do	85	70	30
7	Natural	do	100	85	80
8	Plasticized	do	95	60	45

that increases in resistance to temperature change would be indicated by negative percentage values in the temperature-susceptibility index column, and lowered resistance to temperature change by positive values, since in table 2 high index values indicate high susceptibility to temperature change and low index values indicate low susceptibility.

All of the mixtures containing rubber added in powder form gained in resistance to temperature change during the 21-day exposure period. This could be construed as indicating that the full effect of rubber added in this manner may not be obtained immediately after construction of the pavement, and that some improvement in resistance to temperature change could be expected with the passage of time. Nevertheless, it should be noted that, according to the test results in table 2, the control mixture molded at 3,000 pounds per square inch was superior in resistance to temperature change to any of the mixtures containing rubber powder even at the end of the exposure period.

The effect of extended heating on the group of mixtures containing preblended rubber was quite variable. Marked increase in compressive strength at both test temperatures was noted for all four preblended mixes, but at 140° F. the change in values of the deformation modulus ranged from a 93-percent increase for the reclaimed rubber (2C) to an

8-percent reduction for the natural rubber mix (4C). The changes in temperature susceptibility varied from marked improvement in resistance to temperature change for the mixture containing reclaimed rubber (2C) to regression for the mixtures containing preblended natural, synthetic, and plasticized rubber.

Resistance of the Mixtures to Water Action

The results of immersion-compression tests made on the mixtures after 1-day exposure in the 140° F. oven are given in the left half of table 6. The retained strength values for the mixes containing synthetic and natural rubber in powder form (3A and 4A) were slightly higher than those for the corresponding control mix (1A). Retained strength values for all of the preblended rubber mixes (2C, 3C, 4C, and 5C) were lower than for the control mix. In the equal-density group, all of the mixes containing rubber (2B, 3B, and 4A) showed consistently lower retained strength values than the control mix (1B).

Results of immersion-compression tests made on companion specimens kept in an oven at 140° F. for 21 days after molding are given in the right half of table 6. Judging from the retained strength values, extended oven exposure increased the resistance to water action of all the mixes except the control mix molded at 200 pounds per square inch (1B) and the reclaimed rubber mix molded to equal density (2B). The mix containing synthetic rubber powder in the equal density group (3B) showed a higher retained strength value than the corresponding control

mix (1B). All the other mixes containing rubber showed retained strength values equal to or lower than the corresponding control mixes.

Static Immersion Stripping Tests

In table 7 are given the results of the static immersion stripping tests on mixtures of quartzite and asphalt, both with and without rubber. These results can be compared, qualitatively at least, with those for the immersion-compression tests on mixtures that had been kept in the 140° F. oven for 1 day, shown in table 6. No stripping tests were made on mixtures held in the oven for 21 days.

The results of the stripping tests at the 100° F. immersion temperature showed marked improvement over the control mix (No. 1) for the preblended natural rubber (No. 7) only. When added as a powder, the results at 100° F. indicate that natural rubber was the least effective. In the tests at 120° F., only the preblended natural rubber (No. 7) appeared to be the equal of the control mix (No. 1). At that temperature the plasticized rubber preblend (No. 8) appeared to be least resistant to stripping. In the tests at 140° F., the natural rubber preblend (No. 7) was the most resistant to stripping and the synthetic rubber preblend (No. 6) the least resistant. At that temperature the natural rubber preblend mix (No. 7) was the only other mixture as resistant to water action as the control mix (No. 1).

In general, the results of the static immersion stripping tests confirm the indications based on the results of the immersion-compression test: namely, that the addition of rubber to bituminous mixtures containing hydrophilic

Table 8.—Results of modified California abrasion test

Mix No.	Type of rubber	Form of rubber	Average loss † after exposure at 325° F. for—					
			0	¼ hr.	1 hr.	2 hrs.	4 hrs.	8 hrs.
1	None		0.23	0.03	0.02	0.03	0.16	0.57
2	Natural	Powder	.64	.40	.11	.19	.25	.44
3	do	Blended	0	0	0	.01	.09	.30
4	Synthetic	do	.81	.14	.20	.24	.29	.53
5	Reclaimed	do	.93	.30	.23	.35	.49	.83
6	Plasticized	do	.21	.09	.22	.29	.64	1.42

† In grams per 1,000 grams of shot.

aggregate was ineffectual in improving the resistance of such mixtures to the action of water.

Effectiveness of Rubber in Abrasion Test

In table 8 are given the results of the modified California abrasion tests on mixtures consisting of Ottawa sand and asphalt, with and without rubber. In the test made on mix 1, the loss occurring in the specimen that had not been exposed to the 325° F. temperature at all would be considered fairly high, although a certain amount of loss on similarly uncured or unexposed fresh mixtures is usual in this test.

A sharply reduced loss was noted for mix 1 in the specimen that had been exposed for

¼ hour at 325° F., and this improvement in resistance to abrasion conforms to the general pattern for similar mixtures containing asphalts having histories of good service behavior. This same pattern of relatively high loss for specimens consisting of fresh mixture and reduced loss after ¼-hour exposure was followed also by mixes 2, 4, 5, and 6, but the reductions were of different order. The deviation from this pattern shown by mix 3 was notable; there was no loss either in the fresh specimen or in the specimen exposed in the oven for ¼ hour. Indeed, the first measurable loss for this mixture was noted only after 2 hours at 325° F.

After 4 hours exposure, the abrasion loss on mix 1 increased sharply, and after 8 hours the loss amounted to 0.57 grams per 1,000 grams of shot. After 4 hours exposure mix 3 was

most resistant to abrasion and mix 6 least resistant. After 8 hours exposure mix 3 was still the most resistant to abrasion, with mixes 2, 4, 5, and 6 following in descending order of resistance.

The results of this very limited number of tests indicate that the natural rubber, when added to the mixture as a blend of rubber and asphalt, increased the resistance of the mixture to abrasion. The marked difference in results between mix 2 and mix 3 offers additional evidence supporting the belief that to obtain maximum effectiveness from the rubber materials they should be preblended with the asphalt before mixing with the aggregate. The abrasion test results also indicate that the effectiveness of additive rubber in improving resistance of asphaltic mixtures to abrasion varies with the type of rubber.