MODIFICATION OF PAVING ASPHALTS BY DIGESTION

WITH SCRAP RUBBER

by

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The service performance of sprayed surface treatments laid where traffic stressing is severe or where the existing pavement is cracked can be significantly improved if comminuted scrap rubber is digested in the asphaltic cement before spraying. Work has been done to identify the factors which are of importance in optimising asphalt performance. Measurement of the deformation response of the digestions to sinusoidal loading indicated that the modified binder had improved response under the loading produced by traffic at high pavement temperatures and that produced by thermal contraction at low pavement temperatures. A simple and rapid test procedure was developed to measure the response under loading conditions approaching these. The procedure is to subject a prism of the binder at 60°C to a shear strain of 1.0 in creep and then determine the elastic recovery when the stress is removed. The most important factor affecting elastic recovery was found to be the morphology of the rubber particles as determined by the comminution process used in their manufacture. A simple bulk density test was used to characterise this morphology. Digestions of natural (truck tire) rubber are generally superior to those incorporating synthetic (car tire) rubber but are more affected by changes in the time or temperature of digestion. Where a cryogenic comminution process had been used only digestions of natural rubber particles produced a significant improvement in asphalt properties. Elastic recovery of strain is linearly related to rubber concentration. As rubber particle size decreases elastic recovery of the digestions increases.
Rubber modifiers have been used in bituminous materials for many years. They have usually been specially prepared natural and synthetic rubbers and their concentration has been limited to less than 5 per cent by mass of the asphaltic cement because greater concentrations have given problems in handling (pumping and spraying) and because of their high cost. At these concentrations the improvement in binder performance obtained in the pavement service situation has been marginal unless a satisfactory polymer network has been formed in the asphalt.

A major improvement in this situation occurred as a result of the work of McDonald (1) and (2) who introduced the use of digestions of scrap rubber in asphalt containing up to 25 per cent by mass of comminuted tyre tread rubber. A sprayed layer of this material has been widely used in the U.S. to prevent cracks in the substrate being reflected through overlays. It is normally applied as either a chip seal surface treatment, with approximately 20 per cent rubber added to the asphalt, commonly known as a stress absorbing membrane, or as an interlayer of rubber/asphalt binder and aggregate (stress absorbing membrane interlayer) which is overlaid by a thin course of asphaltic concrete.

In Australia, the main use of the scrap rubber/asphalt digestions has been in sprayed surface treatments where the advantages are considered to be:

(a) The sealing of cracked pavements to prevent, or delay the onset of, reflection cracking,
and additionally

(b) The retention of chips in hot weather under severe traffic stress conditions. Such conditions occur where seals are used to provide surface texture on high speed roads where a conventional asphalt seal is unable to provide satisfactory stone retention at bends or in acceleration and deceleration areas.

DEFORMATION TESTING OF RUBBER MODIFIED ASPHALTS

Sinusoidal Loading

A useful means of evaluating the deformation behaviour of asphalts and rubber modified asphalts is by their response to sinusoidal loading in simple shear. This provides basic information on the behaviour of the materials but requires specialised equipment and testing is slow. The sinusoidal loading procedure was therefore only used to determine the appropriate test conditions (temperature, rate of straining, etc.) for the rubber/asphalt digestions and a simpler apparatus, operated near the required conditions, was then used for routine testing.

In the sinusoidal loading procedure, a force applied to the material produces a sinusoidal displacement which lags behind the force (see Fig 1). The magnitude of the phase angle difference between the force and the displacement (φ) is an indication of the partitioning of the response between viscous and elastic behaviour. The phase angle is zero for purely
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elastic behaviour and 90° for purely viscous behaviour. The ratio of the maximum value of the force to the maximum value of the displacement is proportional to the complex shear modulus of the material ($|G^*|$).

The responses of an asphalt alone and when it has been modified by digestion with two different scrap rubbers (15 percent by mass of scrap rubber digested for 1 hour at 200°C (sample 6) and 220°C (sample 1)) are shown in Fig 2. The response at 60°C can be determined by reference to the upper of the two frequency scales on the horizontal axis, and at 5°C by reference to the lower scale. Details of the rubber samples are given in Table 1.

Rubber 6 has depressed the increase of the phase angle at low loading frequencies to a constant value just below 60°. Rubber 1 is even more effective, reducing the angle to about 50°. At these very slow rates of straining, or high temperatures, the response of the unmodified asphalt is that of a viscous liquid, whereas the modified binders show behaviour typical of a low modulus elastic solid.

Relationship with Pavement Loading

Two kinds of loading are of particular importance in relation to the performance of thin bituminous surfacings. The first, due to vehicles passing over the surfacing, is assumed to be periodic and has a loading time of between, say, 20 ms and 50 ms depending on vehicle speed. The second, due to thermal contraction by diurnal temperature change has a duration of the order of 10⁶s. The magnitude of the strains produced in the binder by such loading is not known precisely but the high
stress locations in the surfacing are where the binder films are thin (3). In such locations the strain in the binder will be high.

Vehicle loading can cause distress in a surfacing at either end of the pavement surface temperature range. At high pavement temperatures the binder can be too fluid and not resist the plucking and shearing action of vehicle tires and at low pavement temperatures the binder can be so hard (particularly after a long period of service) that vehicle loading causes brittle fracture of the binder films.

Thermal contraction loading is critical at low pavement temperatures when the binder (again particularly after long term exposure) is at its hardest.

Since both modes of loading induce overall, gross tensile strains in the surfacing they will augment each other to produce the cracking which eventually occurs at low surface temperatures.

These important rate of loading conditions at the appropriate pavement temperatures for Australian conditions are given in Table 2 and indicated by the arrows A and B on Fig 2.

Selection of a Test Procedure and Conditions of Test for Rubber Modified Asphalts

Consideration of Fig 2 indicates that the important modification of deformation response by scrap rubber addition, so far as performance in the pavement surfacing is concerned, is for traffic loading at high road temperatures and thermal contraction at low road temperatures (arrow A). For traffic
loading at 5°C (arrow B) there is no significant change in the phase angle or modulus level.

To compare the effectiveness of different scrap rubber digestions in asphalt it is desirable to have a simple and rapid method of evaluating the deformation response of the product. For assessing relative benefit in pavement service such testing should be done at about 60°C, at a rate of loading equivalent to traffic loading and to relatively high strains.

A simple method of measuring creep and elastic recovery in shear was developed using a modification of the Shell sliding plate rheometer. The instrument enables a higher strain (1.0) to be realised than is possible with sinusoidal loading and permits rapid testing at the test temperature selected (60°C).

The above discussion indicates the desirability of using test methods which indicate the basic deformation and flow behaviour of the rubber/asphalt digestions under the critical pavement service conditions. These materials have properties intermediate between those of asphalt and those of rubber, and empirical procedures used to evaluate asphalts may not be suitable. More detailed discussion of the deformation behaviour of rubber modified asphalts and methods of testing is given in a paper by Dickinson (4).
EXPERIMENTAL PROGRAM

Digestion Procedure

The primary method of evaluation of different rubber/asphalt systems was the laboratory digestion, under controlled conditions, of mixtures of the comminuted scrap rubber and asphalt followed by deformation testing of the product. The laboratory digestion procedure required that the rubber sample be dried in a vacuum oven prior to addition to the hot asphalt in a reaction flask maintained at the desired temperature. The mixture was continuously stirred and samples were withdrawn and cast when hot into sliding plate rheometer test moulds.

Laboratory digestion simulates the heat treatment applied prior to spraying of the product in road construction operations. In Australia this normally takes the form of circulation of the materials in an asphalt sprayer at about 200°C for between 30 minutes and one hour (5).

Deformation Testing of Digestions

An extensively modified sliding plate rheometer was used to measure the deformation properties (creep in shear) of the binder specimens. A diagram of the apparatus is shown in Fig 3. While the instrument is simple to use, it is necessarily delicate and is more suited to research needs than to routine quality control work.

To test a sample, a mass of 20 g was applied to a 10 mm thick specimen until a strain of 1.0 was obtained. The load was then automatically removed by a motor driven mechanism and
the sample permitted to recover under a 'no load' condition. Movement of the free plate was recorded using a displacement transducer.

The parameters calculated for analysis were 'time under stress' (i.e. time to reach a strain of 1.0) and 'per cent "elastic" recovery' (defined as percentage of this strain recovered when the load is removed and after a recovery period of 10 times the straining period). Time under stress can be regarded as a simple measure of resistance to deformation at the test temperature (60°C), while elastic recovery is an indication of the elastic component of this deformation.

Normally a particular asphalt/rubber combination was digested for 2 hours in the reaction vessel at a controlled temperature. Samples were removed for testing after digestion for 0.5, 1 and 2 hours. Three specimens were prepared from material removed after each digestion time and a test result is the mean value obtained for these three specimens. Repeat testing on an asphalt/rubber combination, which was relatively insensitive to changes in time and temperature of digestion, indicated that the confidence limits (95 per cent probability) of a test result were ±1.4 s for 'time under stress' and ±3.1 per cent for 'elastic recovery'.

Materials Evaluated

Two asphalts representative of Australian production were used and both were 85/100 penetration grade. The material used for the bulk of the testing was the vacuum distillation residue from Kuwait crude petroleum, air blown to grade. The second asphalt, which was more aromatic in character, was a blend of
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the vacuum distillation residue from a Kuwait crude petroleum and the propane precipitated asphalt from this residue.

The bulk of the rubber granulate used for asphalt work in Australia is the material produced during the preparation of used tires for retreading. A series of rotating saw blades contact the tread area of the tire and the buffings are drawn off by a vacuum system. Normally the buffings supplied for asphalt work are a mixture of natural (from truck) and synthetic (from passenger cars) rubbers, with the latter predominating.

Products from two other comminution processes supply the remainder of the asphalt market. One of these is the cryogenic method which involves hammer milling of the rubber after it has been cooled with liquid nitrogen. At a sufficiently low temperature the rubber behaves as a brittle solid. Another process, for which full details have not been disclosed, involves softening and swelling of the tire by solvent immersion followed by size reduction and solvent recovery.

Industrially produced scrap rubber particles can be of variable and indeterminate composition. As part of the study, comminuted rubber prepared from cured sheets of vehicle tire feedstock, of known composition, were examined. The laboratory comminution processes used include rasping, drilling, hand cutting and cryogenic embrittlement followed by crushing.
RESULTS

Rubber Particle Morphology

The gross morphology of the rubber particles, as determined by the way they are produced, was found to be the most important factor affecting the elastic properties of the rubber/asphalt digestions. The difference in the morphology of particles produced by four different processes is clearly illustrated in the scanning electron photomicrographs reproduced as Figs 4 to 7. The particles shown all passed a 600 μm sieve and were retained on a 300 μm sieve when sieved dry. A summary of the appearance of the particles and their composition and production method together with the elastic recovery value of an asphalt digestion of each sample is given in Table 3.

Examination in the scanning electron microscope of rubber particles produced by a number of processes indicated that there are two main types of morphology: one where the surface is covered in porous, 'sponge like' nodules, or the other where it is smooth. These two extremes are shown by the photographs in Figs 4 and 7 respectively. Particles with intermediate morphology generally have either a smooth surface with some porous nodules attached or are a mixture of smooth and nodular-surfaced particles.

There appeared to be a relationship between the number of porous nodules present in a sample and the elastic recovery of strain of a digestion of the sample in asphalt. Accordingly, a simple means of characterising particle morphology was devised and the relationship between this
property and elastic recovery of strain examined. The property measured was the bulk density in water of particles separated between the 300 and 600 μm sieves.

To determine the bulk density, 7.5 g of sieved rubber particles was first boiled in 100 mL water to remove trapped air, and then a weak detergent solution was added to ensure reproducible wetting of the particles. The volume of the rubber was measured after the sample had been allowed to settle in the water for 15 minutes. Replicate testing indicated that the confidence limits at the 95 per cent probability level of the mean of two tests was ±8.2 kg/m³.

The relationship between per cent elastic recovery (0.5 h digestion at 200°C of 15 per cent by mass rubber in the air-blown asphalt) and bulk density is shown in Fig 8 for a number of rubbers. The desirable condition, for pavement service, is for the rubber/asphalt digestion to show a high value of elastic recovery. The rubber samples are identified by specimen number and details of their composition and method of preparation are given in Table 1. Separate regression lines are drawn for mainly natural and mainly synthetic rubbers. For the natural rubbers the Pearson correlation coefficient is 0.96 while for synthetic rubbers it is 0.93.

The results show that there is a strong correlation between particle morphology (as measured by the bulk density test) and the elastic recovery of strain of the rubber/asphalt samples. The digestion conditions used are the ones most commonly used for spraying of rubberised binders in Australia.
Digestion Conditions

The effect of time and temperature of digestion on the elastic recovery of synthetic and natural rubber/asphalt digestions, made from industrially produced rubber buffings, is shown in Figs 9 and 10. For both rubber types, elastic recovery increases with both time and temperature of digestion up to 220°C. At 240°C there is no further increase for the 2 h synthetic rubber digestion and a marked reduction in elastic recovery for the 1 and 2 h natural rubber digestions. Fig 11 shows the 'time under stress' results for natural rubber and these suggest that, with this rubber, thermal degradation can occur at temperatures as low as 180°C, but that the elastic properties of the mixture are not immediately affected. The synthetic rubbers tested generally had a 'time under stress' value of between 5 and 10 s regardless of digestion conditions.

The significance of these results, with regard to asphalt spraying operations, is that both natural and synthetic rubbers behave satisfactorily under normal digestion conditions in the sprayer. However, if overheating occurs the properties of natural rubber digestions are more rapidly degraded than those of synthetic rubber. Since time and temperature of digestion are interdependent, the same difficulty can arise from extended digestion times at normal spraying temperatures.

The effect of digestion time and rubber particle production process on digestions of laboratory prepared rubber samples of known compositions is shown in Fig 12. The recovery of the two natural rubber samples increases markedly with increasing digestion time, while for the styrene-butadiene
rubber samples, time of digestion has little effect. This is apparently true, regardless of the method of preparation and, thus, morphology of the rubber samples. Where styrene-butadiene rubber is blended with butadiene and/or natural rubber, Table 4 shows that, for samples of similar bulk density, the behaviour of blends is intermediate between the 100 per cent styrene-butadiene and the 100 per cent natural rubber cases. There is some evidence from other testing to suggest that, for synthetic blends, the increase in elastic recovery with increasing digestion time is greater for low bulk density samples than for high ones.

The trend in Australia is towards the use of 100 per cent styrene-butadiene rubber in passenger vehicle tyre treads. The results clearly show that, if this material is to be used in asphalt, then cryogenic manufacture is unsuitable. Cryogenically prepared 100 per cent styrene-butadiene rubber gave virtually no improvement in asphalt properties even when a sample was reduced in size so that all the rubber passed a 150 μm sieve and 25 per cent passed a 75 μm sieve.

Rubber Composition

Rubber composition has been shown to be an important variable which interacts with both particle texture and digestion conditions. Its effect on rubber/asphalt digestions has been fully covered in previous sections.

Rubber Concentration

The effect of rubber concentration on elastic recovery of strain is shown in Fig 13 for typical spraying conditions (tyre
retreaders buffings digested in air-blown asphalt at 200°C).

Linear relationships, with correlation coefficients of 0.99, apply for the three digestion periods studied. Linear relationships were also found to apply for a high elastic recovery material which could, however, only be tested over a narrow concentration range because the highest concentration samples were impossible to pour.

Rubber Particle Size

Fig 14 shows that elastic recovery tends to increase as rubber particle size decreases. While the difference between successive size ranges is small, a significant improvement in the elastic recovery of rubber digestions can be obtained by using the fine fraction (<300 μm) of tire retreader's buffings instead of the 1.18 mm-600 μm fraction which is currently specified for Australian asphalt work.

Bitumen Composition

There was no significant difference between the air blown and the propane precipitated Kuwait asphalt in respect to elastic recovery of strain. This was true for both natural and synthetic rubber specimens and for rubber particles with porous (low bulk density) and with smooth (high bulk density) appearance.

Curing of Rubber/Asphalt Binders after Application

In order to determine whether structural changes can occur in rubber/asphalt binders after they have been sprayed, the behaviour of specimens during extended laboratory storage was
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observed. A storage temperature of 55°C was selected as typical of the maximum surface temperature likely to be encountered and also to ensure that any changes which occurred did so at a detectable rate.

Two rubber samples were used: industrial retreader's buffings and new car tire buffings. These were typical of rubber samples which gave a low and a high elastic recovery. Each sample was used to prepare specimens digested at (a) conditions which gave optimum elastic recovery and (b) conditions which gave below optimum elastic recovery.

Fig 15 shows the results obtained. For the tyre retreader's buffings, there is no change in elastic recovery with time while for the new car tire buffings there is an indication of a small increase for both sets of specimens. The behaviour of the two materials in this respect is similar to their behaviour during digestion. The new car tire rubber showed significant increases in elastic recovery with increases in time or temperature of digestion whereas the tire retreader's buffings showed a smaller increase.

DISCUSSION

The main factors which affect the behaviour of rubber/asphalt digestions have been identified and studied. However the list is by no means exhaustive and there may be others, such as rubber particle shape and the 'non-rubber' additives in tire rubber, which could be important.

The morphology of the rubber particles has been shown
to play an important role in determining the properties of rubber/asphalt digestions. The form of the particles seems to be determined by the disintegration method used. Tearing apart of the bulk rubber at near ambient temperatures so that stretching of the rubber takes place before fracture, produces a much more 'active' material than brittle fracture at low temperatures. Experimentation with different manufacturing procedures is planned in order to obtain low bulk density products.

Production by the cryogenic process appears unsatisfactory particularly for predominantly styrene-butadiene rubber blends. Either further treatment of the product is required or this method of comminution should be restricted to natural rubber scrap.

The bulk of scrap rubber used in asphalt is predominantly synthetic and digestion conditions are not particularly critical. If a low bulk density product were to be introduced then smaller concentrations might be as effective as high concentrations of currently used scrap rubbers. Digestion conditions could, however, become more important and this would certainly be true if the product contained a high percentage of natural rubber. There is a need for a simple quality control test to evaluate the deformation properties of rubber/asphalt digestions. In the interim, the bulk density test and analysis of the composition of the rubber can be used as a guide to quality.

A separate test will be needed to indicate whether improved digestions can be sprayed using conventional equipment
and procedures. If spraying of these materials proves to be difficult, such a test could be used to evaluate the effectiveness of measures designed to improve sprayability. Since the process of forcing a viscoelastic fluid through an orifice under pressure to produce a regular pattern of small droplets is not well understood, the best approach may be to simulate the field spraying condition in the laboratory. An apparatus has been constructed which allows rubber/asphalt digestions to be sprayed from a regular slotted jet nozzle at the pressure and temperature used in road sprayers. This apparatus will be commissioned shortly.

In Australia, as the demand for scrap rubber has increased, so has the price. It is possible that specially formulated synthetic polymers may soon become competitive. Dispersions of one group of these materials, known as block co-polymers, in asphalt have the advantage of having very little effect on the asphalt at spraying temperatures but developing marked rubber-like properties through the formation of a network structure at service temperatures. New types of block co-polymers are coming onto the market and these should be evaluated to determine the minimum effective concentration in asphalt.

There is little information on the long term durability of rubber/asphalt digestions, although they have given satisfactory service in Australia for over five years now. Laboratory durability tests developed for asphalts (6) may not be appropriate for this type of material, but there could be a need to determine if these modified asphalts maintain their elastic behaviour under the long term exposure of pavement service.
Road trials are planned in Australia to investigate the effect of concentration and type of rubber on long term service performance of sprayed seals, used both in high traffic stress situations and to overlay cracked pavements.

CONCLUSIONS

Modification of asphaltic cements by scrap rubber improves deformation response under traffic loading at high pavement temperatures, and loading due to thermal contraction at low pavement temperatures. A simple and rapid laboratory test procedure was developed to assess the degree of improvement obtained from various rubbers and digestion procedures. This procedure is as near as practicable to the loading and straining conditions described above.

The major findings for digestions of scrap tire rubber in asphalt were as follows:

1. Rubber particle morphology, as determined by the process used to manufacture the particles, is the most important factor affecting the elastic properties of rubber/asphalt digestions. This morphology can be characterised by a simple bulk density test.

2. Natural rubber digestions tend to be superior to those containing synthetic rubber but digestion conditions (time and temperature) are less critical for the latter.
3. Elastic recovery of strain of the digestions is linearly related to the rubber concentration.

4. Elastic recovery of the digestions tends to increase as the size of rubber particles used decreases.

5. Only a small change in the elastic recovery of certain specimens was observed when they were stored at 55°C (imitating curing over an extended period in road service).
REFERENCES


5. J.D. BETHUNE. Use of Rubber in Bituminous Surfacing. Proc. 9th ARRB Conf. 9(3), Session 24, pp. 9-32. 1978.

**TABLE 1.** Composition and Method of Preparation of Samples Used in the Bulk Density Test

<table>
<thead>
<tr>
<th>SAMPLE NUMBER</th>
<th>COMPOSITION AND PREPARATION METHOD</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>100% synthetic blend. Produced by industrial buffing of new passenger vehicle tires during tire testing.</td>
</tr>
<tr>
<td>2</td>
<td>75% SBR*, 25% BR*. Cured tire tread feedstock, laboratory drilled.</td>
</tr>
<tr>
<td>3</td>
<td>65% SBR, 35% BR. Cured tire tread feedstock, laboratory drilled.</td>
</tr>
<tr>
<td>4</td>
<td>100% SBR. Cured tire tread feedstock, laboratory rasped.</td>
</tr>
<tr>
<td>5</td>
<td>30% SBR, 31% BR, 39% NR*. Cured tire sidewall feedstock, laboratory drilled.</td>
</tr>
<tr>
<td>6</td>
<td>Approx. 70% SBR, 25% BR, 5% NR. Mixed buffings from tire retreader's plant.</td>
</tr>
<tr>
<td>7</td>
<td>100% SBR. Cured tire tread feedstock, laboratory drilled.</td>
</tr>
<tr>
<td>8</td>
<td>Mainly synthetic. Tire retreader's buffings industrially embrittled in liquid nitrogen and size reduced in a hammer mill.</td>
</tr>
<tr>
<td>9</td>
<td>100% SBR. Laboratory crushed after cryogenic embrittlement.</td>
</tr>
<tr>
<td>10</td>
<td>100% NR. Cured tire feedstock laboratory rasped.</td>
</tr>
<tr>
<td>11</td>
<td>100% NR. Cured tire feedstock laboratory drilled.</td>
</tr>
<tr>
<td>12</td>
<td>100% NR. Produced by industrial buffing of new truck tires during tire testing.</td>
</tr>
<tr>
<td>13</td>
<td>Mainly natural. Undisclosed industrial process involving solvent swelling of tire rubbers prior to mechanical size reduction and solvent recovery.</td>
</tr>
<tr>
<td>14</td>
<td>100% NR. Laboratory crushed after cryogenic embrittlement.</td>
</tr>
<tr>
<td>15</td>
<td>Approx. 80% NR. Prepared by similar process to sample 13.</td>
</tr>
</tbody>
</table>

*SBR* = Styrene-Butadiene Rubber  
BR = Butadiene Rubber  
NR = Natural Rubber
<table>
<thead>
<tr>
<th>MODE OF LOADING</th>
<th>SURFACING TEMPERATURE</th>
<th>DURATION OF LOADING (s)</th>
<th>APPROXIMATE FREQUENCY OF SINEWavy LOADING (log rad/s)</th>
<th>DISTRESS MODE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moving traffic</td>
<td>High 60°C*</td>
<td>.02-.05</td>
<td>+1.5</td>
<td>Shearing and plucking of aggregate</td>
</tr>
<tr>
<td>Moving traffic</td>
<td>Low 5°C†</td>
<td>.02-.05</td>
<td>+1.5</td>
<td>Brittle fracture of binder films</td>
</tr>
<tr>
<td>Thermal contraction</td>
<td>Low 5°C*</td>
<td>10⁹</td>
<td>-4.0</td>
<td>Cracking of surfacing</td>
</tr>
</tbody>
</table>

*See Fig 2 Arrow A  
†See Fig 2 Arrow B
### TABLE 3. Properties and Appearance of the Four Samples Shown in Figs 4 to 7

<table>
<thead>
<tr>
<th>MATERIAL AND PRODUCTION PROCESS</th>
<th>GROSS MORPHOLOGY</th>
<th>ELASTIC* RECOVERY (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>New car tire buffings, by-product of tire testing. See Fig 4.</td>
<td>Particle surface completely covered with porous nodules.</td>
<td>39</td>
</tr>
<tr>
<td>100% styrene-butadiene, cured tire feedstock hand rasped. See Fig 5.</td>
<td>As above but with some rounded nodules.</td>
<td>30</td>
</tr>
<tr>
<td>100% styrene-butadiene, cured tire feedstock laboratory drilled. See Fig 6.</td>
<td>Generally smooth rounded particles with a few porous nodules attached.</td>
<td>17</td>
</tr>
<tr>
<td>100% styrene-butadiene, cured tire feedstock embrittled in liquid nitrogen and crushed. See Fig 7.</td>
<td>Smooth faced, angular, cracked particles.</td>
<td>3</td>
</tr>
</tbody>
</table>

*15% by mass rubber in air blown asphalt digested at 200°C for 0.5 h.
TABLE 4. Effect of Rubber Composition.

<table>
<thead>
<tr>
<th>RUBBER COMPOSITION*</th>
<th>BULK DENSITY (kg/m³)</th>
<th>ELASTIC RECOVERY (%)**</th>
<th>0.5 h</th>
<th>1 h</th>
<th>2 h</th>
</tr>
</thead>
<tbody>
<tr>
<td>100% SBR</td>
<td>188</td>
<td>30</td>
<td>31</td>
<td>32</td>
<td></td>
</tr>
<tr>
<td>75% SBR 25% BR</td>
<td>190</td>
<td>33</td>
<td>34</td>
<td>45</td>
<td></td>
</tr>
<tr>
<td>65% SBR 35% BR</td>
<td>192</td>
<td>31</td>
<td>32</td>
<td>38</td>
<td></td>
</tr>
<tr>
<td>30% SBR 31% BR 39% NR</td>
<td>183</td>
<td>29</td>
<td>31</td>
<td>39</td>
<td></td>
</tr>
<tr>
<td>100% NR</td>
<td>203</td>
<td>40</td>
<td>52</td>
<td>69</td>
<td></td>
</tr>
</tbody>
</table>

**For samples of 15% by mass rubber in air blown asphalt digested at 200°C.

*SBR = Styrene-Butadiene Rubber
BR = Butadiene Rubber
NR = Natural Rubber
Fig 1 - Deformation response of a viscoelastic material to repeated sinusoidal loading
Fig 2 - Modification of viscoelastic response of asphalt at 5 and 60°C by digestion with scrap rubber
Balance wheel

Displacement Transducer to measure strain

Counterweight

Recorder & Controller

Motor

Load lifting fork

Load (20g mass)

Sliding plate

Fixed plate

Sample in shear

10 mm

Fig 3 - Diagram of apparatus to measure elastic recovery of strain
Fig 4 Electron micrograph of new car tyre buffings.

Fig 5 Electron micrograph of 100% SBR tyre rubber, laboratory rasped.

Fig 6 Electron micrograph of 100% SBR tire rubber, laboratory drilled.

Fig 7 Electron micrograph of 100% SBR tire rubber, cryogenically crushed.
Fig 8 - Relationships between elastic recovery and bulk density for natural and synthetic rubbers
Fig 9 - The effect of time and temperature of digestion on elastic recovery for synthetic rubber tire buffings
Fig 10 - The effect of time and temperature of digestion on elastic recovery for natural rubber tire buffings.
Fig 11 - The effect of time and temperature of digestion on the consistency of digestions of natural rubber tire buffings.
Fig 12 - Effect of rubber composition on change in elastic recovery with digestion time
Fig 13 - Effect of rubber concentration on elastic recovery
Fig 14 - Effect of rubber particle size on elastic recovery
Fig 15 - Storage of scrap rubber modified binders at 55°C