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EFFECTS OF RUBBER–BITUMEN INTERACTION ON THE PERFORMANCE OF IMPACT ABSORBING ASPHALT

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Abstract

This paper describes results from a laboratory investigation that has been undertaken to investigate the effects of the interaction between an SBS modified bitumen and recycled crumb rubber on the mechanical performance of Impact Absorbing Asphalt (IAA) which has sports, safety surface and civil engineering applications. Curing tests at high temperatures have been undertaken using different rubber-bitumen ratios to assess the amount of bitumen absorbed by the rubber. To assess the effect of the rubber-bitumen interaction on the mechanical durability of the IAA an abrasive wear test has been developed to simulate the contact between a twisting foot and the surface. This test has been used to compare the mechanical durability of laboratory prepared specimens that have been artificially aged at high temperatures (to simulate the mixing and transportation period before the material is laid and compacted). Results show that there is an effect on the mechanical durability of the aged material due to the interaction between the rubber and the bitumen. To assess the cause of the reduction in mechanical durability of the material, residual bitumen from the curing tests has been tested using the Dynamic Shear Rheometer (DSR) to assess the effect of the rubber-bitumen interaction on the rheological characteristics of the residual bitumen. The results show that significant absorption takes place and the residual bitumen undergoes alterations in terms of its stiffness and viscoelastic balance.

Introduction

Impact Absorbing Asphalt is a patented technology consisting of a relatively conventional continuously graded bituminous material with a proportion of the aggregate replaced by dry crumb rubber obtained from the recycling of truck tyres. It has many potential applications and, to date, has been used as a surface layer for play areas and a shock-pad underneath artificial sports surfaces. The technology adopted finds its roots from the dry process developed in the late 1960's in Sweden and traded in Europe under the name Rubit (1, 6 and 7). Production of the material involves addition of crumb rubber to hot aggregate prior to mixing with bitumen. The material is then mixed and held at a high temperature until compaction, which is carried out using conventional paving techniques.

Preliminary production trials of the material indicated that the bonding of the material when laid was poor, leaving loose particles of rubber and aggregate from the mixture on the surface of the pavement. Laboratory testing of the material indicated that the rubber was retaining a larger proportion of the bitumen than the aggregate, suggesting an interaction between the bitumen, which can be regarded as a solvent and the rubber, which is a polymer. This paper describes the research undertaken to investigate the reaction between the rubber and the bitumen and the effect it has on the mechanical durability of the material.

Background

Polymers are known to absorb liquids and swell. The amount they absorb is dependent on the nature, temperature and viscosity of the liquid/solvent and the type of polymer (2). Polymers can be spilt into two classes, those which swell in water and those which swell in organic solvents. The first class contains polymers such as cellulose (cotton, wood etc.) and protein (gelatine, wool etc.) while the dominant group in the second class is rubber, both synthetic and natural (2).

The swelling of rubber in organic solvents is a diffusion process. Liquid molecules from the solvent diffuse into the bulk of the rubber, increasing the dimensions of the rubber network until the concentration of liquid is uniform and equilibrium swelling is achieved. The amount of solvent that will diffuse into the rubber depends on the number of cross-links in the rubber and the compatibility of the solvent and rubber on a molecular scale. The greater the number of cross-links in the rubber, the shorter the average length of rubber chains between cross-links and the lower the degree of swelling. The lower the molecular weight of the solvent, the more readily it will diffuse into the rubber (2).

The crumb rubber used in IAA is obtained from the recycling of truck tyres. Tyres are shredded into sequentially smaller gradings to remove wire and fabric reinforcement, producing an end product of rubber crumb. The actual chemical composition of the crumb rubber is difficult to assess because of the large variation of tyre makes and re-treading processes etc. However, the generic form can be treated as a vulcanised rubber containing natural and man-made rubber. An important factor is that the rubber is vulcanised and therefore its molecular structure contains a large number of cross-links (3).

Bitumen is a complex mixture of organic molecules that vary in chemical composition and molecular weight. As bitumen is extracted from crude oil, which has many different compositions according to its origin, the precise breakdown of the hydrocarbon groups in bitumen is difficult to determine. Therefore, four main chemical types are used to classify the composition of the bitumen:

- Asphaltenes
- Resins
- Aromatics
- Saturates

Asphaltenes are black or brown amorphous (without shape) solids. They are highly polar, complex materials of high molecular weight (between 1,000 and 100,000). Within a medium they have a tendency to associate together to form micelles with a molecular weight between 20,000 and 1,000,000 (4). Asphaltenes typically constitute 5 to 25% of the bitumen. Increasing the asphaltene content in a bitumen produces a harder, less fluid bitumen.

Resins are dark brown solid or semi-solid highly polar molecules and make up between 5 and 30% of the bitumen. The high polarity makes the resins very adhesive. The molecules have a molecular weight between 500 and 50,000. The resins act as a peptising agent for the asphaltenes, decreasing the size of asphaltene micelles and thus increasing the fluidity of the bitumen (4).

Aromatics have the lowest molecular weight (between 300 and 2,000) and form the major proportion of the bitumen (40-65%). They have a very low polarity and form a dark brown viscous liquid that acts as a dispersion medium for the asphaltenes (4).

Saturates are straight branch chain aliphatic hydrocarbon molecules. They have a molecular weight between 300 and 20,000 and make up 5-20% of the bitumen (4).

Resins, Aromatics and Saturates form the maltene fraction of the bitumen.

Bitumen is an organic solvent, that is liquid at high temperatures and will diffuse into rubber particles at a rate determined by its temperature, viscosity and molecular composition. Through development of polymer modified bitumens, Vonk and Bull (8) discovered that when rubber is added to bitumen, the elastomer absorbs all the components of the bitumen apart from the asphaltenes. This indicates that when recycled crumb rubber is added to bitumen it absorbs the maltenes leaving the residual bitumen containing a higher proportion of asphaltenes.

Binder absorption tests

Curing tests were carried out to investigate the maximum amount of SBS modified bitumen that the rubber can absorb. The rate of swelling was also monitored to give an indication of the speed of the interaction. A simple test was developed to measure the increase in mass of rubber crumb that was cured at high temperature in bitumen. The rubber was then drained, allowed to cool and then weighed. The increase in mass, as a percentage of its original weight, was then calculated. Different rubber-bitumen proportions were tested to enable extrapolation of swelling rates for the IAA mixture when held at mixing temperature.

Method

Crumb rubber between 6-9mm in size was divided into 5g samples and placed into a 50ml glass beaker. Bitumen was heated to 180°C in a fan assisted oven. A known mass of bitumen was then poured into the beaker containing the rubber. The beaker was then placed back in an oven and held at 155°C. This temperature regime was chosen to simulate mixing and transportation of the material. Material is typically mixed at 180°C and then placed in well insulated trucks where the average temperature, maintained for up to 6 hours, was 155°C.

The proportion of rubber to bitumen in the beaker (termed the rubber-bitumen ratio) was altered by changing the mass of bitumen added, whilst keeping the mass of rubber constant. Quantities of 10, 20 and 40g bitumen were added to 5g of rubber to give percentage of rubber as 33, 20, and 11% respectively. Sets of seven beakers were prepared for each rubber-bitumen ratio and within each set, each beaker was allowed to cure for a different time. After curing, the beaker was removed from the oven, turned upside down on a 2mm aperture wire gauze and placed over a tin which collected the residual bitumen. The whole system was then placed back in the oven for a further hour, to allow the excess residual bitumen to drain off the rubber. Upon completion of draining, the system was removed from the oven and allowed to cool. The swollen rubber was then removed from the gauze and weighed.

Results

The results for the curing tests are shown in Figure 1 where the percentage increase in the mass of the rubber is plotted against curing time. It can be seen from the figure that the amount of swelling increases with time but decreases as the rubber-bitumen ratio is increased.

This confirms that the rubber is absorbing some of the SBS modified bitumen resulting in an increase in mass. The literature has indicated that the rubber will absorb the lighter fractions of the bitumen (maltene fraction) more readily (3), indicating that the proportion of asphaltenes in the residual binder will increase and thus change the rheological properties of the residual binder.

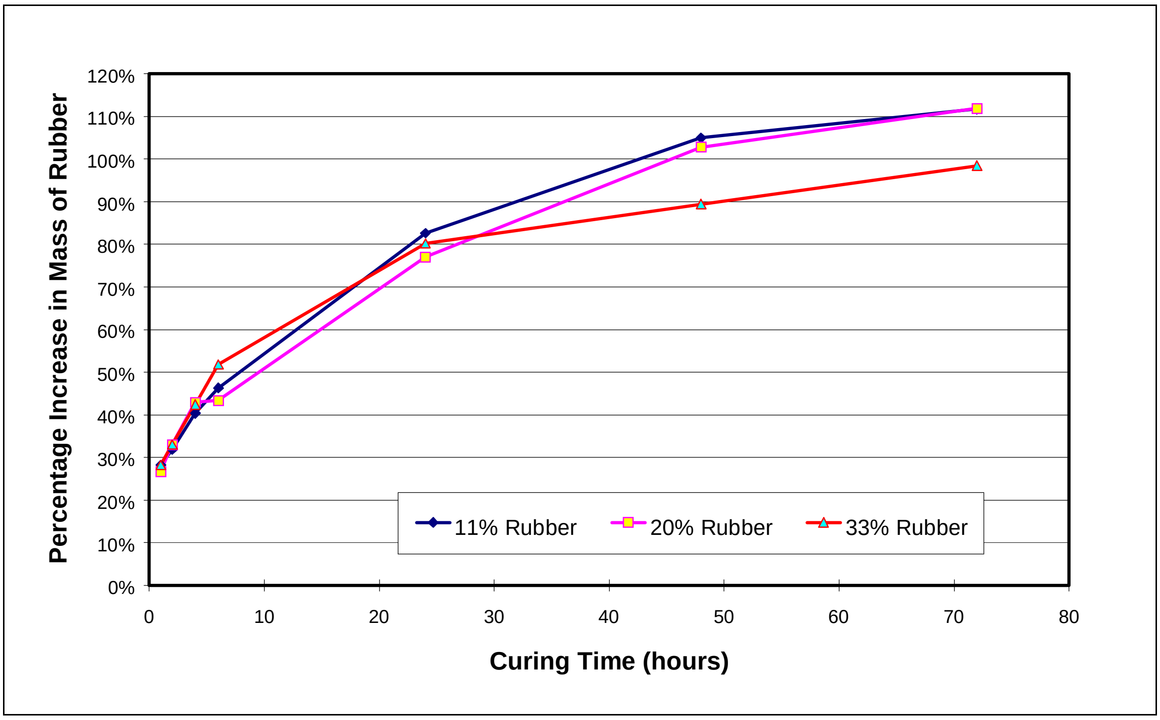

Figure 1 - Increase in mass of rubber cured in SBS modified bitumen at 155^{o}C

Mechanical durability testing

A test was devised to assess the mechanical durability of the material, as an empirical quantitative measure of the adhesion/cohesion of the bitumen within the IAA mixture. The test was designed to abrade the material by 'plucking' out particles of rubber and aggregate from the surface of the material, thus giving an approximate average measure of the strength of the adhesive/cohesive properties of the bitumen. The test was used to compare the change in mechanical durability of the material as it was aged in the oven, simulating the reaction between the bitumen and the rubber.

Method

The test apparatus is shown schematically in Figure 2. The test was developed to represent the twisting and turning motion due to a person moving on the surface. A simple abrasive tool with an abrading surface comprising a series of pyramid shaped studs (5mm high) arranged in a grid formation was rotated on the surface of the material under the action of a normal load. The normal load was chosen to be 1kN and the dimensions of the abrading tool were chosen to simulate the front part of the sole of a typical sports shoe. The sample of material was weighed and placed in a jig, the tool was then rotated through an arc of 60°, 100 times at a frequency of 0.1Hz at a temperature of 20°C. The sample of material was re-weighed, the loose particles were then removed and the remaining sample weighed. The loss in mass was noted and calculated as a percentage of the available mass that could have been removed from the sample.

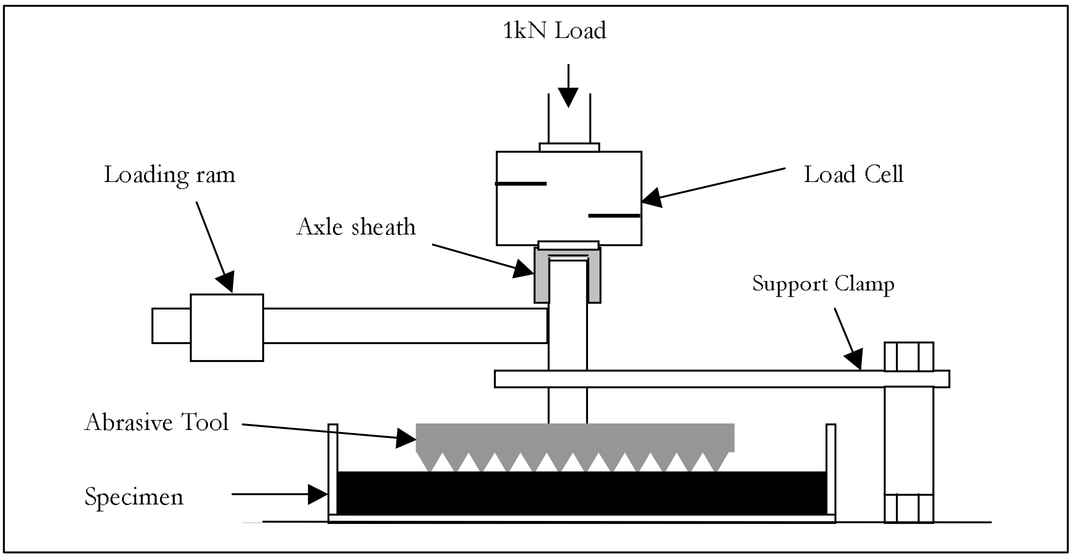

Figure 2 - Schematic of the abrasive wear test developed to measure the mechanical durability of impact absorbing asphalt

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Results

A mixture of IAA containing 15% rubber, 10% SBS bitumen and 75% aggregate (by mass) was compared to a control material which was a bituminous mixture of comparable grading containing no rubber, to investigate the effect of curing the material in the oven at 155°C. Each specimen was mixed in the laboratory, then placed in the oven for 0, 3 and 6 hours. Each batch was then compacted into a slab using a roller compactor. The slab was then cut into 6 samples measuring 135mm x 140mm to fit into the jig. Each sample was then tested and the mass loss recorded. The results are presented in Figure 3.

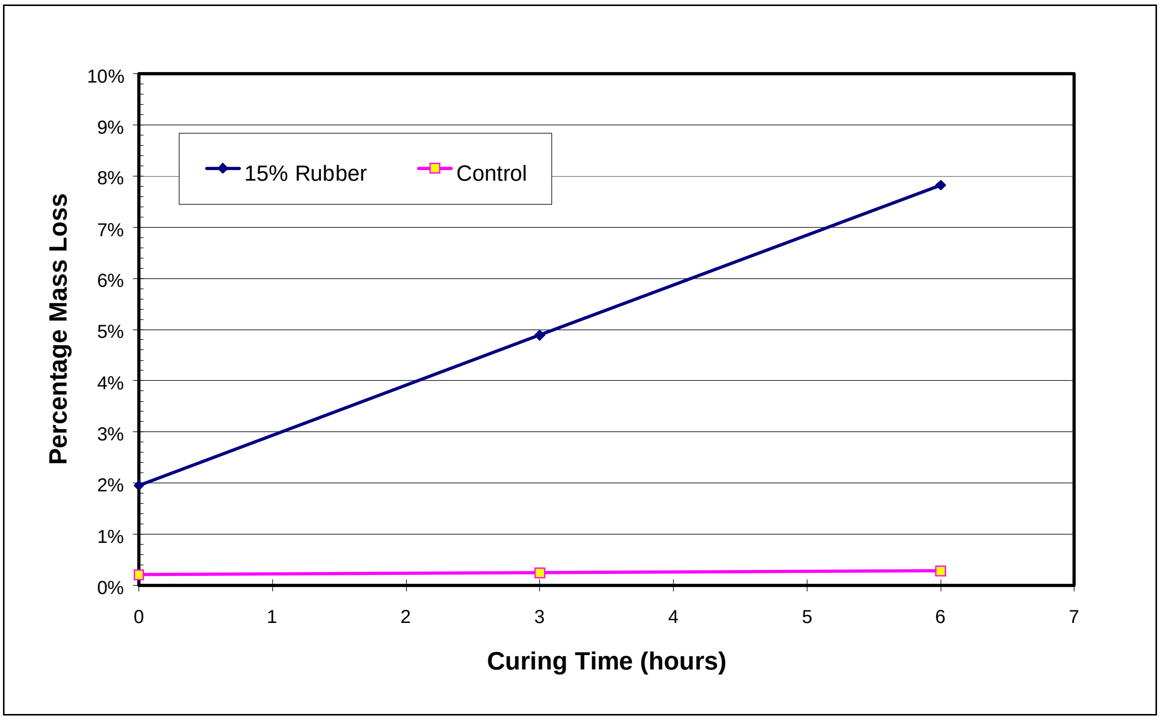

Figure 3 - Percentage mass loss of Impact Absorbing Asphalt cured in the oven for different periods prior to compaction, containing different proportions of rubber and tested in the abrasive wear test

It can clearly be seen from the figure that the curing of the material in the oven causes an increase in mass loss for the mixture containing 15% rubber. The control mixture containing no rubber has a greater resistance to degradation of mechanical durability following curing at high temperatures. Therefore, the interaction between the rubber and the bitumen is reducing the mechanical durability of the IAA with the cohesive/adhesive strength of the material being reduced through the rubber-bitumen interaction. To investigate the magnitude of this change the rheological characteristics of the residual binder were measured. Preliminary results have also shown that a reduction in the proportion of rubber in the mixture greatly improves the mechanical durability of the material.

Rheological characteristics of residual bitumen

The rheological characteristics of the residual bitumen collected after curing with rubber were compared to bitumen cured under the same conditions without rubber using the Dynamic Shear Rheometer (DSR).

The DSR is a dynamic oscillatory test that can be used to measure the linear visco-elastic properties of bituminous binders. It applies a sinusoidal strain to a sample of bitumen sandwiched between two parallel circular disks. The resulting stress is monitored through the torque at the top disk as a function of temperature and frequency. Measurements of shear stiffness and shear viscosity can be obtained at different temperatures, frequencies and strain levels. The two most commonly used parameters obtained from the DSR test are the magnitude of the complex shear modulus ($|G^*|$) and the phase angle (ϕ). The magnitude of the complex shear modulus is the ratio of peak stress to peak strain. It represents the stiffness of the bitumen under the conditions of testing and is independent of the phase angle. The phase angle is defined as the phase difference between the peak stress and peak strain. A material with a high phase angle (approaching 90^o) represents a highly viscous response, whereas a material with a low phase angle (approaching 0^o) represents an elastic response (5).

The major feature of the DSR is that it has the ability to test bitumen over a range of loading times and temperatures. It is possible to measure the stiffness and visco-elastic response of the bitumen at different temperatures and loading times to describe the rheological behaviour of the bitumen throughout its viscoelastic region.

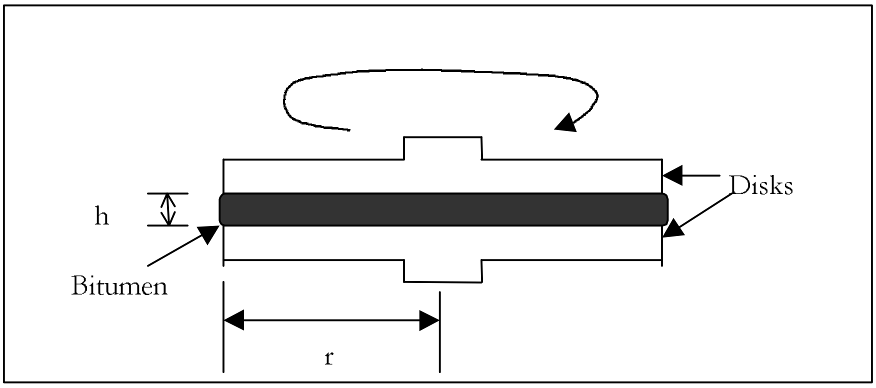

Figure 4 - Schematic of the Dynamic Shear Rheometer (DSR) testing configuration

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Method

Dynamic Testing using the DSR was carried out on specimens cured for 1, 6 and 24 hours in rubber-bitumen ratios of 0, 11, 20 and 33% at 155°C. The following DSR test conditions were used;

Mode of loading:	Strain control
Strain amplitude:	1%
Temperatures:	35, 45, 55 and 65°C
Frequencies:	0.1, 0.2, 0.5, 1, 2, 5 and 10Hz
Bitumen thickness, h:	1.00mm
Spindle diameter, d:	25mm

Results

The measured values of phase angle and values of complex shear modulus at 1Hz and 35°C for the different samples are presented in Figures 5 and 6. The conditions of the DSR testing were chosen using time-temperature equivalency so that the results can be transposed for the same conditions as the Abrasive Wear test (20°C and 0.1Hz). Therefore, the measured values given in Figures 5 and 6 represent the rheological behaviour of the bitumen for the mechanical durability test.

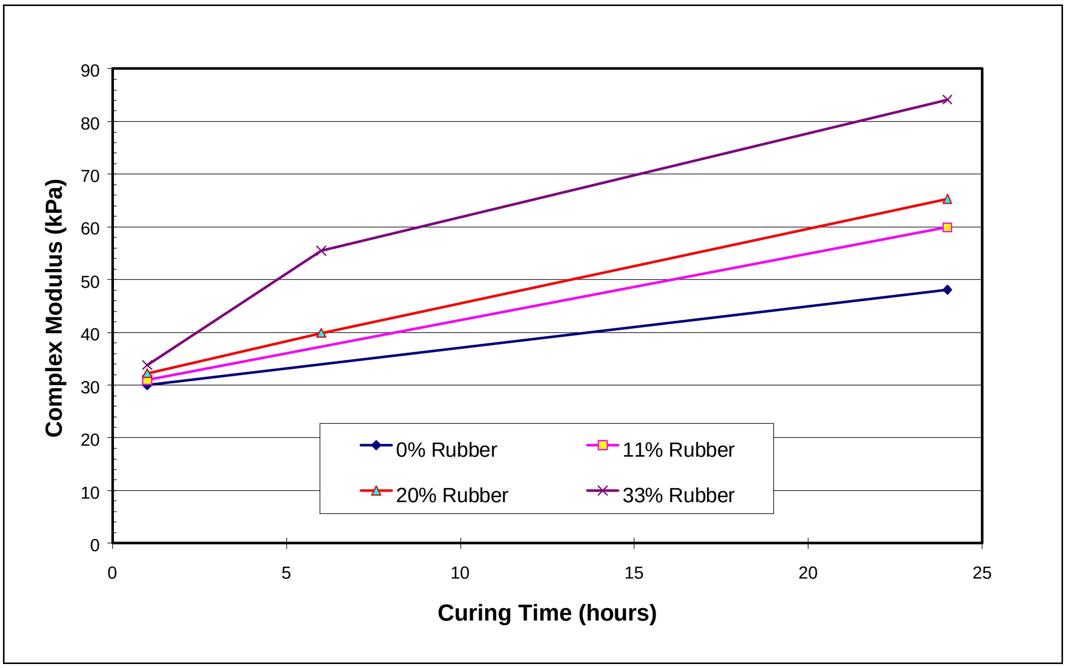

Figure 5 - Measured values of complex shear modulus at 1Hz and 35°C for different cured samples of the residual SBS modified bitumen

It can be seen from Figure 5 that for the sample cured without rubber the stiffness increases with curing time. This is indicative of hardening of the bitumen through oxidation. However, it can also be seen from this figure that the addition of rubber further increases the stiffness of the residual bitumen as the rubber-bitumen ratio increases. This is consistent with an increased proportion of the low molecular weight maltene phase being absorbed by the rubber leaving a greater proportion of asphaltenes in the residual bitumen which results in a harder, less fluid bitumen.

Figure 6 illustrates the affect of curing on the phase angle of the residual bitumen. The samples cured in rubber show a greater decrease in phase angle with curing time compared to the samples cured in air suggesting that the residual bitumen is tending to become more elastic in behaviour. The greater the proportion of rubber, the greater the reduction in phase angle. These results suggest that the inclusion of rubber through the curing process is changing the rheological properties of the residual bitumen, increasing the stiffness and the making it more elastic.

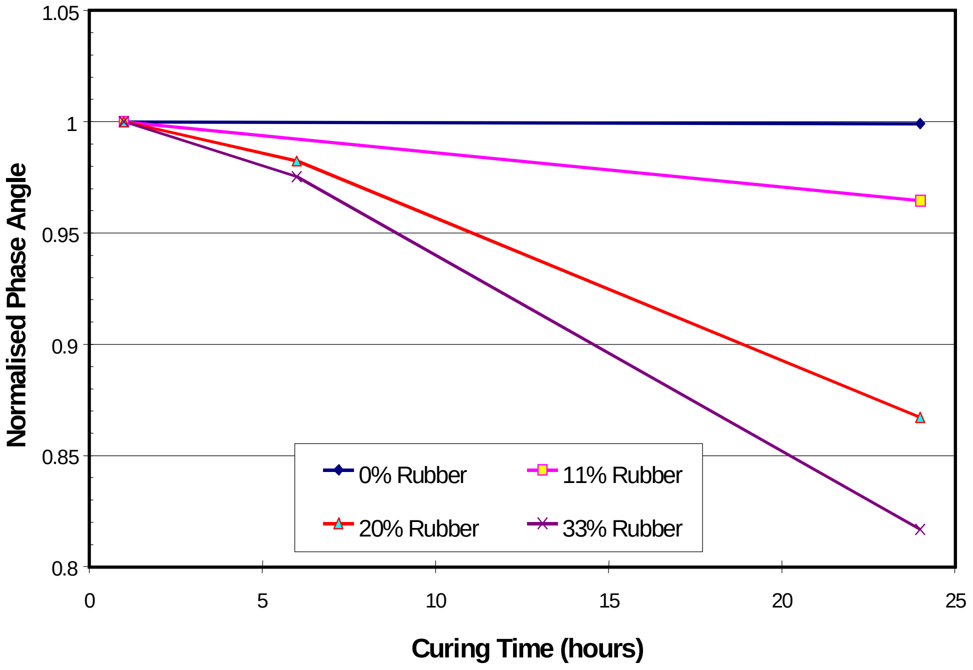

Figure 6 - Measured values of normalised phase angle at 1Hz and 35°C of different cured samples of the residual SBS modified bitumen

Summary and conclusions

This paper has outlined research being carried out into the performance of Impact Absorbing Asphalt (IAA). The main focus of the paper has been the interaction between the crumb rubber and the bitumen. Initial testing has shown that there is a reaction between the rubber and bitumen at mixing temperatures (155-180^{o}C) where the rubber absorbs a proportion of bitumen and swells.

The rubber-bitumen interaction has been shown to decrease the mechanical durability of the material by way of an abrasive wear test. Therefore, the absorption of portions of the SBS modified bitumen by the crumb rubber reduces its cohesion/adhesion in the impact absorbing mixture. Dynamic rheological testing of the residual bitumen has shown that the interaction between the rubber and the bitumen alters the rheological characteristics of the bitumen, increasing the complex modulus and elastic response, essentially making the bitumen stiffer and more brittle. This indicates that the poor mechanical durability of the IAA is due to changes in the mechanical performance of the residual bitumen in the mixture through absorption of portions of the bitumen by the crumb rubber at mixing and transportation temperatures.

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