

Correlating the Rheological Properties of Binders with the Mechanical Properties of their Surface Dressing Systems

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This paper presents rheological data in terms of fundamental material properties of three cut-back binders, one conventional and two modified with different polymer types. The binders were tested at one frequency over a range of temperatures and conditioning periods. They were then used to produce surface dressing samples which were tested in the Mini Fretting Test under the same conditioning period and temperature conditions as the rheology testing. This test simulates the action of traffic on the dressing. The paper then provides correlations between the fundamental binder properties and the Mini Fretting Test results of the dressings containing the three binders. The correlations highlight the usefulness of the Mini Fretting Test in discriminating between different binder types and in predicting the performance of surface dressings, with particular reference to the early stages when the dressing is most vulnerable.

Keywords: Pavement maintenance, surface dressing, Binder rheology, Mechanical Properties

INTRODUCTION

Surface dressing is one of the most economically viable means of maintenance for the rehabilitation of skid resistance of otherwise structurally sound roads. Its simple make-up of a layer of binder, usually a bitumen cutback or emulsion and rolled-in aggregate chippings, makes it an invaluable option to pavement maintenance engineers world-wide. Whilst it is recognised that a proper and comprehensive design of the surface dressing system is paramount for long-term service, the success of the dressing operation depends to a large extent on the type of binder used. This is particularly so during the early stages of the dressing's

life when little or no embedment of the chippings into the road substrate has taken place. The onus is on the binder to maintain the dressing's integrity under the fretting action of traffic which could lead to the dislodgement of the chippings and thus to premature failure. It is, therefore, imperative to select a binder that will perform adequately under the anticipated service conditions. To this end, there is considerable emphasis on the specification criteria adopted to aid in the selection of the right binder.

Specifications expressed in fundamental engineering properties and related to end-product performance are gradually being adopted in the UK for the selection of binders. This practice has been prompted, in

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part, by the emergence in the early 1990s of the US Strategic Highway Research Program (SHRP) binder rheological specification criteria and is exemplified by the complex shear modulus, G^* , and the phase angle, δ . Interest in the use of rheological criteria has been increasing as a result of the adoption by surface dressing suppliers of a multitude of binders incorporating various types of modifying agents, with particular emphasis on copolymers.

Binder rheological properties, e.g. G^* and δ , are usually determined in the Dynamic Shear Rheometer (DSR) under the temperatures and loadings relevant to conditions in service. G^* and δ are measured in the oscillatory mode of testing which the DSR is capable of applying, in addition to creep and viscometry modes. Whilst the DSR is a very versatile piece of laboratory equipment, testing and interpretation of results are complex and time consuming. Furthermore, the equipment is very expensive (circa US\$65k) and thus may not be affordable by all those involved with surface dressing, such as designers, suppliers and users. For the above reasons, some surface dressing specifications¹ now include parameters obtainable from a suite of simpler and more economic laboratory test procedures, such as the Vialit Pendulum², viscosity, penetration and softening point. In the Vialit Pendulum Test the amount of energy required to break a 1 mm film of a binder sandwiched between two platens under the impact action of a pendulum is evaluated.

Besides the Vialit Pendulum Test, there are other mechanical tests used to discriminate between different binders and to predict the dressings' performances under conditions similar to those in service. The Mini Fretting Test (MFT) is one such method³. It causes the dislodgement of chippings from a surface dressing sample as a result of the movement of a cylindrical piece of rubber under specified load, duration and temperature conditions. The movement of the rubber represents the action of a vehicle tyre. Apart from its realistic mode of application, the test is simple and quick to carry out, affordable on tight R&D budgets, and the results are presented in a performance-related format as the percentage of chippings retained by the surface dressing.

This paper attempts to validate the MFT results by correlating them with fundamental engineering properties measured in the DSR for three cutback binders and their surface dressing systems. The behaviour of the materials during the early stages of curing is given particular emphasis due to its significant impact on the overall performance of the dressings.

RHEOLOGY TESTING

The DSR⁴, shown schematically in Figure 1, can be operated in three different modes, namely oscillatory, creep and viscometry. The oscillatory mode was used in this study as it closely simulates the nature of the repeated vehicular loading applied to the surface dressing in-situ. In this mode, a sinusoidal shear stress is applied to a bitumen sample of less than 1 g in weight. The sample is sandwiched between two parallel circular plates, one of which is fixed. The plates are separated by a constant gap of 1000 μm which is adopted to suit the test geometry and the temperature and frequency conditions used. The resulting displacement and phase lag (δ) between stress and strain are measured.

The testing was conducted on three cutback binders: a conventional 100sec cutback, as measured in a Standard Tar Viscometer at 40°C⁵ and two polymer modified cutback binders having the same 200pen base binder. The same solvent applied in the same concentration was used with each. One of the modified binders contained natural rubber incorporated using a proprietary chemical technique (for which details are not available) and the other contained a linear Styrene Butadiene Styrene co-polymer. The sample preparation involved heating the binders to their equi-viscous spraying temperatures, which ranged from 135 to 145 °C, pouring a fixed mass onto aluminium plates and spreading the binders at a rate of 1.1 litre/m² to a film of even thickness. This spread rate is typical for surface dressings with cutback binders and 6 mm size chippings laid over a hard to very hard substrate⁶ and has been used in preparing the surface dressing samples for the subsequent MFT experiments. The binders were then placed in a fanas-

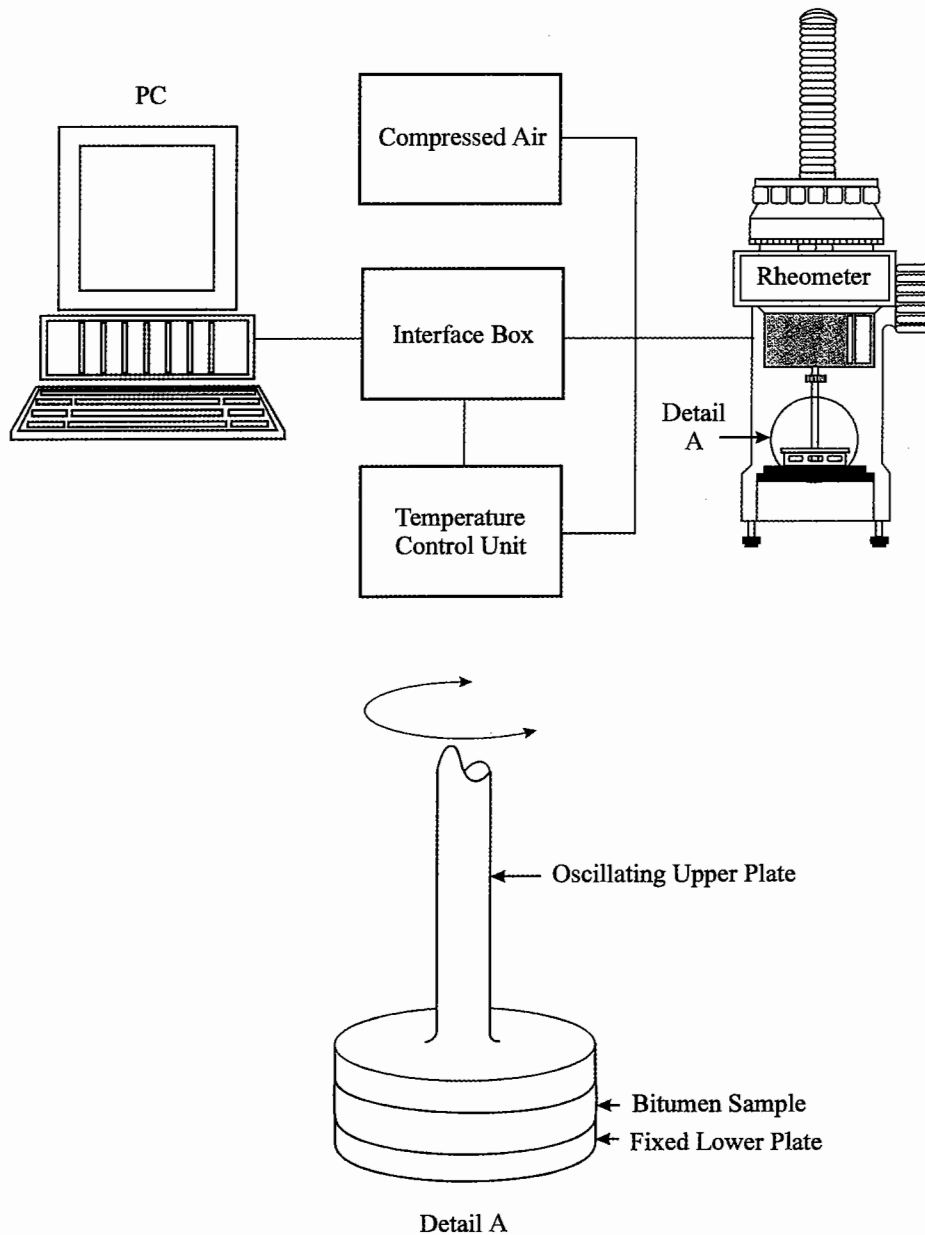


FIGURE 1 The dynamic shear rheometer assembly

sisted, constant temperature chamber over a temperature range of 10 – 40°C for periods ranging from 1 to 24 hours. At the end of the conditioning period, a small amount of less than 1 g of the binder was removed and introduced to the DSR ready for testing.

The starting point for the examination of each binder was to determine its linear viscoelastic region (LVER) at the extremes of temperature and frequency ranges expected immediately after placing to cover those used in the actual testing programme. To this

end, amplitude sweeps were conducted at 0.1 and 30Hz frequency at both 10 and 40°C. It was noticed that although the values of G^* and δ were affected by the frequency of oscillation, they were not affected by the level of the resulting strains, which ranged from 1×10^{-4} to 1.8×10^{-3} , and hence a linear viscoelastic response was evident. Jamieson et al⁷ defined the limit of the LVER as the point beyond which the measured value of G^* decreased to 95% of its original value. The final strain level chosen for testing all the binders in this project was 0.001 (0.1%) which was comfortably within the LVERs that were determined at each test temperature. Confirmation that such a strain level was representative of site conditions was provided by Christensen and Anderson⁸ who noted that strains in a pavement rarely exceed 1% under traffic loading.

Testing was carried out in the oscillatory mode at a frequency of 10Hz over a temperature range of 10 – 40°C. The 10Hz frequency is consistent with a medium traffic speed of approximately 60kph (40mph)⁹ and the temperature range chosen is representative of one within which surface dressing works are normally carried out in the UK.

The early stages after laydown are the most critical for the survival of a surface dressing. This is due primarily to the fact that the remaining flux oils in the binders tend to evaporate at a higher rate leading to the build-up of the dressing's strength in this early stage. Therefore, knowledge of the changes in rheological properties of the binders during this critical stage is essential to understanding the behaviour of surface dressing. To this end, Figure 2 shows the influence of temperature and conditioning period on the rheological parameters, G^* and δ , for the three binders. The conditioning durations of 1, 3 and 5 hours represent the early stages during which the changes in properties can be observed and compared to those achieved after 24 hours. No further significant change in properties occurred as monitoring continued up to 48 hours and, thus, 24-hour conditioning was assumed to represent quasi-full strength development.

The general increase in the complex modulus and decrease in the phase angle values with conditioning

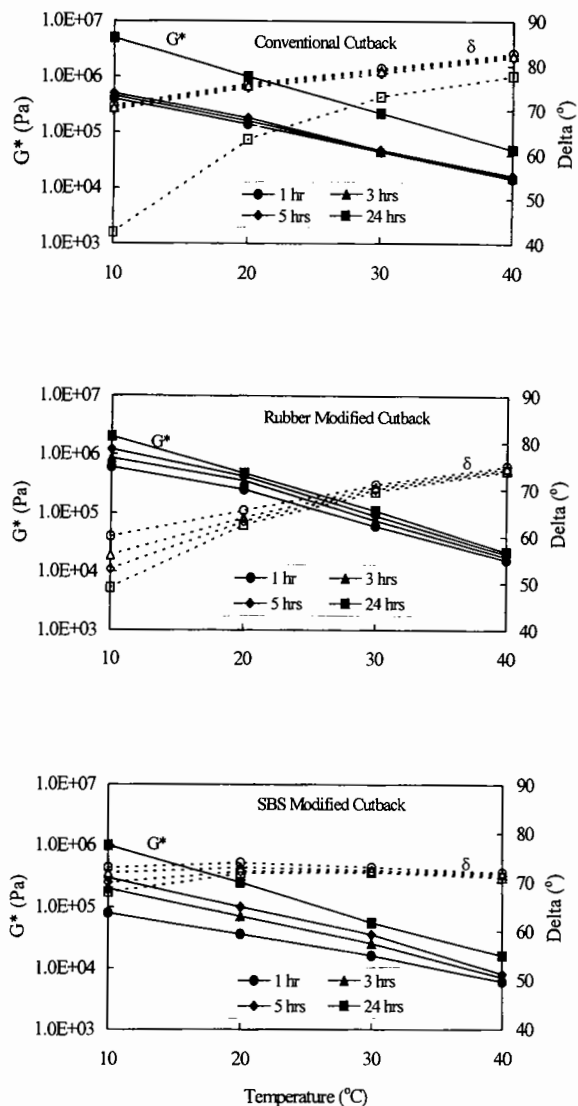


FIGURE 2 Rheological properties of the three cutbacks as a function of temperature and conditioning period determined at 10Hz

period is exhibited by all the binders. This is due to continuing losses in the flux oils within the binders, together with ageing as a result of oxidation. However, at 24 hours, the conventional cutback is seen to achieve the highest G^* and lowest δ values at 10°C which is an indication of its tendency for brittle behaviour at low temperatures. At 40°C, even though this binder achieved the highest G^* value, its δ is also

the highest, which indicates a tendency to undergo viscous deformation under the applied load. The polymer modified binders, on the other hand, exhibit a less temperature susceptible behaviour for both G^* and δ over the temperature range used. Hence there is a benefit in polymer modification.

The phase angle, δ , is indicative of how elastic or viscous the behaviour of the binder is, the closer its value to 0 or 90° respectively. Also referred to as the loss angle, δ gives a relative measure of the amount of energy per cycle dissipated by the binder under oscillatory loading conditions⁹. The continuing increase in δ with temperature for the conventional cutback is indicative of gradual weakening evidenced by its increased viscous flow under pressure. At the low temperature end (10°C), the conventional binder exhibits brittle behaviour as it achieves the lowest δ and highest G^* values. The SBS modified cutback, on the other hand, has δ almost independent of temperature, within the range used in this study, whilst G^* exhibits least temperature susceptibility of the three binders. Thus ranking the binders in descending order of performance in terms of G^* and δ , the SBS modified cutback comes first, followed by the rubber modified cutback and then the conventional binder.

THE MINI FRETTING TEST

The Mini Fretting Test (MFT) is one of the most realistic simulations of the fretting action of traffic on a surface dressing^{10,11}. It was originally developed by Tausk et al¹² as a modification of the Wet Track Abrasion Test devised by McCoy and Coyne¹³. Further development was carried out on the test procedure¹⁴ to bring it to its present status, shown in Plate 1. More details of the test procedure, together with repeatability data can be found elsewhere¹⁴. Some cross-laboratory experiments were conducted in the UK under the aegis of the Institute of Petroleum to establish reproducibility values for the MFT, but the results which were not published, were inconclusive. However, the test remains as a useful, in-house R&D tool to discriminate between surface dressing binders.



PLATE 1 The Mini Fretting Test set-up (See Color Plate I at back of this issue)

The MFT involves the preparation of 190 mm diameter samples of surface dressing which are then subjected to surface shear by a piece of cylindrical rubber of a specified hardness mounted on the adjustable head of a planetary mixer. The planetary movement of the rubber causes the dislodgement of the chippings from the surface dressing sample. The percentage of chippings retained on the test plaque after fretting is a measure of the dressing's ability to resist chipping loss, i.e. the strength of the bond developed between binder and aggregate, and hence is also a measure of the binder's performance. On the road, the resistance to chipping loss is provided not only by the binder (except in the early stages) but also by the interlocking forces due to chipping embedment into the road substrate. In the MFT, however, the resistance is provided entirely by the binder. This makes the test conditions somewhat more severe than those on the road. So, if a binder performs well in the test, it would be unlikely that it would fail under similar conditions on the road.

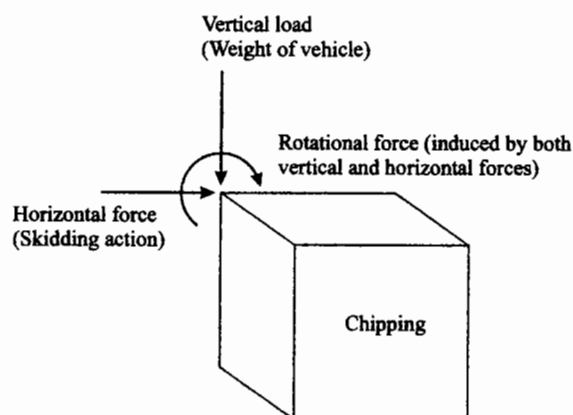


FIGURE 3 The forces exerted on a single chipping in the Mini Fretting Test

Figure 3 shows a diagram of the forces exerted in the MFT on a single chipping. It can be seen that the test exerts a vertical load representing the vehicle weight and a horizontal force representing the friction at the interface. It also applies a twisting or rotational force which depends on the point of contact between the tyre and the chipping. This rotational force may result in dislodgement of adjacent chippings which are not directly affected by the tyre. The ability of the test to simulate these forces renders it ideal for assessing surface dressing binders prior to use and also for studying the factors affecting the dressing's performance in the early stages in which little or no embedment of the chippings has taken place.

Figure 4 shows the MFT results for the three cutback dressings determined at the same conditioning and test temperatures and for the same conditioning periods as those in the rheological testing. Samples were conditioned and tested at the same temperatures as this was found to closely represent site conditions in the early stages of the life of the dressing. The chippings used were 6 – 3 mm graded crushed granite aggregates from the Criggion Green quarry commonly used in surface dressing works in the UK. The use of 6 – 3 mm graded chippings was found to improve the repeatability of the test¹⁰ which led to its adoption as a draft standard by the Institute of Petroleum³. The figure shows that the ability of the

dressings to retain chippings is greatly affected by temperature as it causes the binder stiffness to decrease, thereby reducing the binder's cohesive strength. However, the rate of decrease in chipping retention with temperature is seen to be dependent on the binder type. The highest rate is for the conventional cutback and the lowest for the SBS modified binder. At 10°C, the latter binder retained its resilience and was less brittle than the other two binders. At 40°C, the SBS modified cutback exhibited elastic recoil characteristics which enabled it to retain the chippings even if they were moved by the action of the rubber, thus preventing their dislodgement. It is evident from Figure 4 that the higher aggregate retention capability of the modified systems is contributed by the binder's stiffness as well as its energy absorbing capability. Both parameters act concurrently to mitigate the impact of the fretting action imparted during the test. The MFT ranks the surface dressing systems as the SBS binder giving best performance, followed by the rubber modified binder and last is the conventional cutback dressing, as with the rheology ranking.

CORRELATIONS

Clearly, the binder has a significant role in preserving the integrity of the surface dressing, especially during the early stages in service. As the load is applied to the binder through the vehicle tyres, the binder is worked and thus loses energy. In the context of rheology, it has been shown^{9,15} that the parameter $G^*/\sin\delta$ is inversely proportional to the amount of energy dissipated by the binder as a result of stress application. This parameter combines the necessary fundamental properties to reflect the contribution of the binder to the resistance to chipping loss in surface dressing systems. This is because G^* is the modulus which, for a viscoelastic material, gives the total resistance to viscous flow under oscillatory loading, whereas $\sin\delta$ gives the relative amount of dissipated energy by the binder per loading cycle. Thus a higher G^* will result in lower total deformation and a lower $\sin\delta$ will result in less energy dissipated.

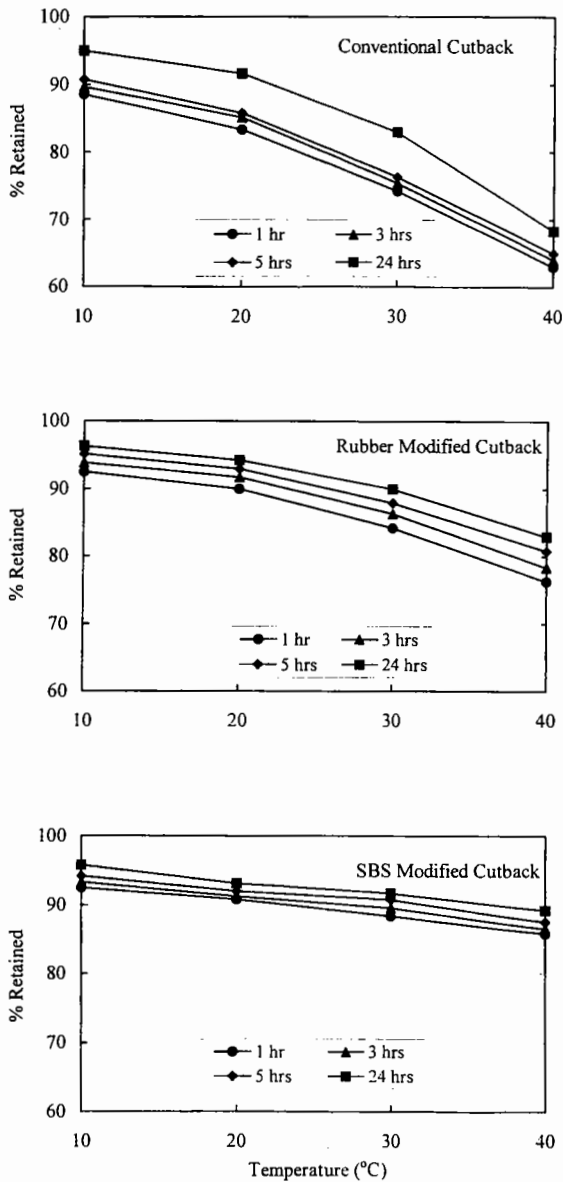


FIGURE 4 The Mini Fretting Test Results for the three cutback binders

The MFT results can be considered in terms of the ability of the surface dressing to maintain its integrity during the fretting action by absorbing the energy intent on dislodging the chippings. The important role of the binder in this process, especially during the dressing's early stages, is apparent and so correlations

with rheological properties were inevitably sought. The author believes that $G^*/\sin\delta$ can be considered as a measure of the binder's ability to dissipate load-induced strains through viscoelastic response. It can thus be conceptualised that if a binder exhibits such a behaviour, then it would be capable of mitigating the fretting action in the MFT, leading to low chipping loss. However, if the binder were to exhibit too brittle or too viscous a behaviour, then it would not have the mechanism to dissipate the strains induced by the fretting action and the chipping loss in the MFT would increase.

The relationship between $G^*/\sin\delta$ and the percentage chippings retained in the MFT, shown in Figure 5, has been found to be best depicted in the form of equation (1), whose corresponding coefficients are presented in Table I. R^2 is the coefficient of determination which indicates the strength of the correlation between the two variables.

$$Y = ax^b \tag{1}$$

TABLE I Coefficients for equation (1)

Description	a	b	R ²
Conventional Cutback	8×10^{-18}	11.7	0.88
Rubber Modified Cutback	3×10^{-38}	22.0	0.91
SBS Modified Cutback	5×10^{-87}	46.5	0.95

It is customary to specify a minimum value for the percentage of chippings retained in the MFT at a given temperature and conditioning period to safeguard against premature failure of the surface dressing. This requirement will affect the type as well as the quantity of the binder chosen for the dressing. It follows that, in setting performance-related binder specifications for surface dressings, the developed relationship will facilitate the setting of a corresponding minimum $G^*/\sin\delta$ value for specified temperature, frequency and conditioning period.

In the light of the move in recent years to more performance-based binder specifications expressed in fundamental engineering properties, it has become incumbent upon highway engineers to fully assimilate and implement the new criteria. This paper provides a

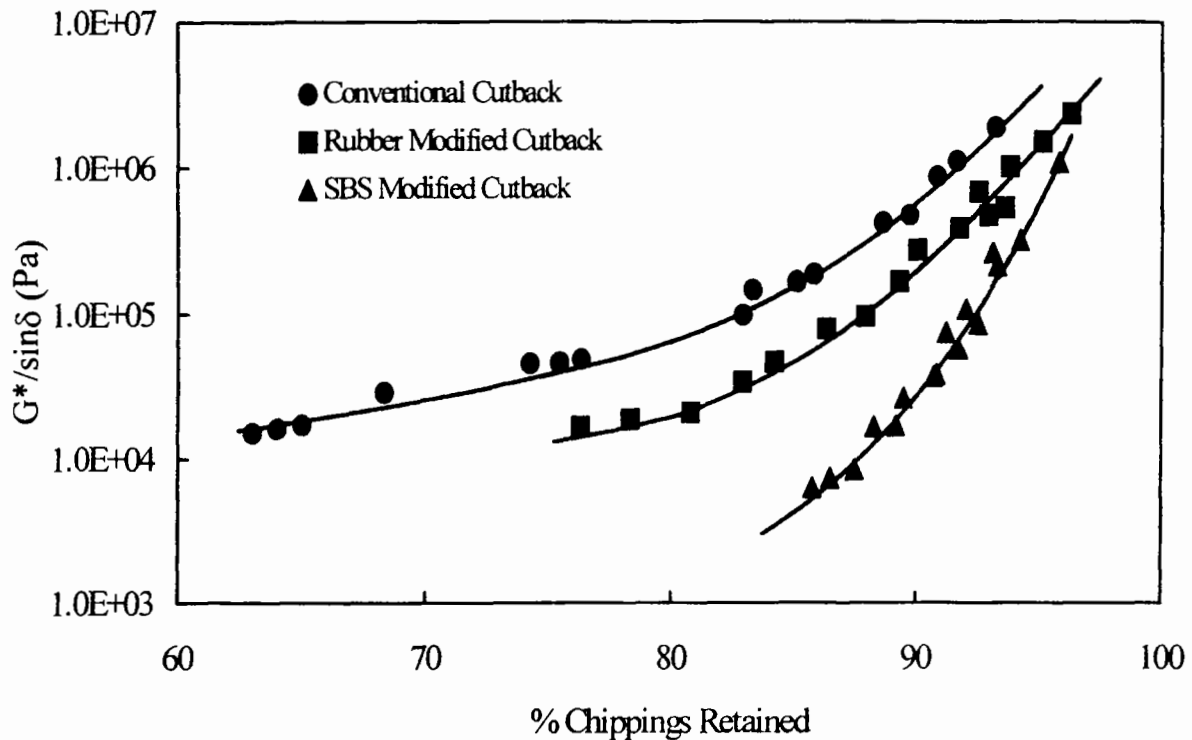


FIGURE 5 Correlations between the rheological properties of the three cutback binders and the Mini Fretting Test results of their surface dressings

means of relating simple, yet very useful binder selection criteria for surface dressings based on the Mini Fretting Test with fundamental characterisation techniques using rheology.

CONCLUSIONS

The main conclusions from this study can be summarised as follows.

(a) All the three cutback binders generally underwent an increase in G^* and a decrease in δ with conditioning period. There was a steady increase in G^* for the polymer modified cutbacks during the early stages, whereas the conventional cutback showed only a very slow increase initially. δ for the SBS modified cutback was least dependent on

conditioning period, whereas that of the conventional cutback showed the largest decrease.

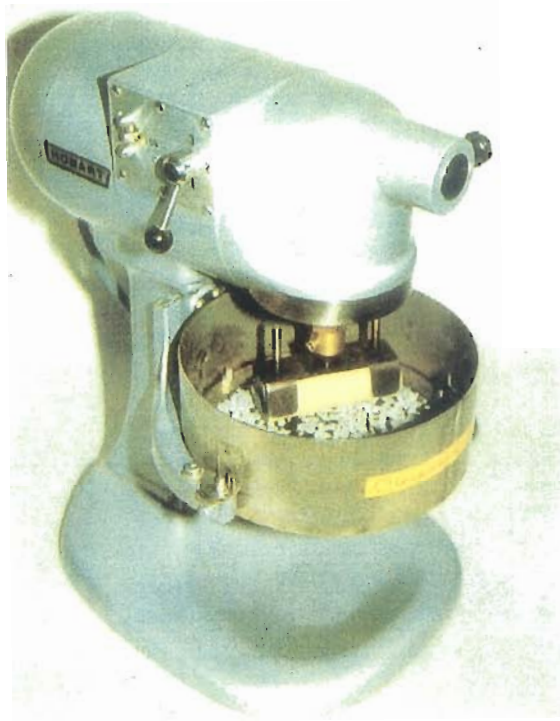
(b) G^* for the SBS modified cutback was the least sensitive to changes in temperature over the range 10 – 40°C. The conventional cutback exhibited the highest sensitivity to temperature over that range. The phase angle, δ , for the conventional and rubber modified cutbacks continued to increase with temperature, whereas that of the SBS modified cutback was almost independent of temperature.

(c) The Mini Fretting Test is a useful means of discriminating between different types of surface dressing binders. It shows the build-up of a surface dressing's strength during its early life, thus enabling the prediction of its performance in service.

(d) A useful correlation has been established between the fundamental parameter $G^*/\sin\delta$ and the percentage of chippings retained in the Mini Fretting Test for the three cutback binders and their surface dressing systems. This correlation will aid in setting performance-based specification criteria for surface dressing binders in terms of fundamental engineering properties.

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Color Plate I (See page 197, Plate I) The Mini Fretting Test set-up