ASSESSMENT OF TORSIONAL BRAID ANALYSIS TECHNIQUE FOR POLYMER-MODIFIED BITUMENS

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AN IMPORTANT NOTE FOR THE READER

CONTENTS

EXECUTIVE SUMMARY

1. Introduction

Although conventional bituminous materials provide perfectly adequate service in most conditions on New Zealand roads, there are locations where polymer-modified bituminous materials in the road surfacing layer can be used to advantage. Such locations are on roads that are subject to high stress, such as on heavily trafficked sections, sharp bends, and bridge decks, or roads subject to wide variations in temperature. Addition of polymer to bitumen improves the visco-elastic properties by increasing the resistance to permanent deformation at high temperatures and stresses.

2. Torsional Braid Analysis Technique

To encourage more accurate road surfacing design in New Zealand, accurate reproducible measurements of the mechanical properties of both unmodified and polymer-modified bitumens are needed. Conventionally these data are obtained by testing in high priced rheometers or by other expensive test methods. A low cost analysis technique, torsional braid analysis, has potential to be used for both quality control and performance specification in testing laboratories.

The technique consists of two elements: the torsional pendulum, of which the periodic and angular displacements are measured while the inertial disk of the pendulum rotates in a horizontal plane; and a fibre braid which, as the torsion bar, is used to suspend the inertial disc and is impregnated with the (modified or unmodified) bitumen sample. The fibre braid has negligible effect on the rotational mechanical properties of the pendulum because of its fibrous nature, but the visco-elastic properties of the bitumen sample impart different mechanical properties to the torsional pendulum. Measurements of displacement of the disc thus allow estimates to be made of the mechanical properties of the sample.

An investigation to test the torsional braid analysis technique was commenced in 1991 using samples of unmodified and polymer-modified bitumens that are used on New Zealand roads. The samples were tested in the temperature range of 5–60°C and in the frequency range 0.1–0.01 Hz. It also attempted to extend the frequency range to the higher frequencies (e.g. 1–16 Hz) that are typical of the vibrations caused by traffic using asphaltic road surfaces.

3. Analysis of Results Obtained by the Technique

Mathematical analysis of results obtained by the technique shows that, by measuring the periodic and angular displacements of the inertial disc suspended by the bitumen-impregnated braid of the pendulum, estimates may be deduced of the elastic storage modulus, G', the loss modulus, G'', the complex shear modulus, G^*, and the loss tangent, $\tan \delta$. These quantities define the visco-elastic properties of the substance under examination.

The elastic storage modulus G' measures the elastic properties, and the loss modulus G" measures the viscous properties (i.e. how much energy is lost due to deformation).

The other two quantities may be derived from the first two as follows: the complex shear modulus G* combines the two moduli into a single number, and loss tangent, tan δ, gives the phase angle between applied stress and resultant deformation of the sample on the pendulum.

The loss tangent, tan δ, is used to give a direct indication of the damping provided by a sample. A high tan δ means the material has heavy damping characteristics and removes a relatively high amount of energy during motion. The converse applies to materials of low tan δ.

The mathematical analysis has been restricted to linear visco-elastic materials. This is a justifiable assumption for polymer-modified bitumens over short loading times and in the ambient temperature range.

4. Technical Problems

In practice, the torsional braid analysis technique worked quite well except for some technical difficulties. They included quite large variations in the period of oscillation of the pendulum disc, with irregular variations in successive angular displacements.

These large variations suggest that the assumptions made for the mathematical analysis need to be more fully examined in future work. The results showed too that, although the technique works reasonably well, the quantitative results for the shear moduli of the bitumens tested were difficult both to interpret and to compare with other results because of the high experimental error, especially in these low frequencies (0.1–0.01 Hz) and in this temperature range (5–60 °C) These errors could be reduced with further work. Exploratory tests at frequencies greater than 1 Hz were not successful.

The results of the investigation did show that the technique may be suitable as an indicative test. However, the expected changes in complex shear modulus of at least two orders of magnitude were not observed with the materials tested over the temperature range used.

5. Conclusion

The torsional braid analysis technique does work but the technical improvements that are needed would reduce the cost advantages of the technique over conventional rheometry. The major technical improvement required is automated data collection. However, because the costs of such automation would be substantial, such development is considered inappropriate.

ABSTRACT

Modified bituminous materials can be used to advantage on roads that are subject to high stress, such as on heavily trafficked sections, sharp bends, and bridge decks, or to wide variations of temperatures. Addition of polymer to bitumen improves the visco-elastic properties by increasing the resistance to permanent deformation at high stresses and temperatures. To encourage more accurate road surfacing design in New Zealand, accurate reproducible measurements of the mechanical properties of both unmodified and polymer-modified bitumens are needed.

Test methods to obtain these data are generally expensive. A low cost analysis technique that has potential for both quality control and performance specification in testing laboratories is torsional braid analysis.

An investigation to test the torsional braid analysis technique was commenced in 1991 using samples of unmodified and polymer-modified bitumens that are used on New Zealand roads. The technique was tested in the frequency range 0.1–0.01 Hz, and in the temperature range 5–60 °C. However, the quantitative results for the shear moduli of the bitumens tested were difficult both to interpret and to compare with other results because of the high experimental error, especially in these low frequencies and in this temperature range.

The method without refinements, such as automated data collection, was not entirely satisfactory for the intended application of characterising polymer-modified materials to be used in high temperature and high stress sections of New Zealand roads.

1. INTRODUCTION

Conventional bituminous materials provide an adequate surface in most conditions on New Zealand roads. However, on sections of roads that are subject to high stress, such as sharp bends, bridge decks, and heavy trafficking, or of roads subject to wide temperature variations, some use has been made of polymer-modified bitumens. The polymers in the bitumen modify the visco-elastic properties of the bitumen by increasing its resistance to permanent deformation at high temperatures and cracking at low temperatures.

To encourage more accurate road surface design in New Zealand, accurate reproducible measurements of the mechanical properties of both unmodified and modified bitumens are needed. These measurements are often made by expensive rheometers. However, the torsional braid analysis technique, used by Koortschot and Woodhams (1984) to characterise bitumen–rubber blends at low temperatures, appears to have the potential to provide a low cost alternative to the expensive rheometers.

The torsional braid analysis technique involves measuring the periodic and successive angular displacements of a freely oscillating torsional pendulum disk. The disc rotates in the horizontal plane and is suspended by a fibre braid, which is the torsion bar. The fibre braid is coated and impregnated with the bitumen sample because the bitumen used on its own as the torsion bar cannot support the inertial disk.

An uncoated untwisted fibre has negligible effect on the rotational mechanical properties of the pendulum and should not return to its original position when given a small angular displacement. A fibre coated and impregnated with a bitumen sample however will have different mechanical properties imparted by the visco-elastic properties of the bitumen sample. Measurements of displacement of the disc thus allow estimates to be made of the mechanical properties of the sample.

The aim of the work was to assess the potential of the torsional braid analysis technique as a method to specify and control the stiffness properties of unmodified, and polymer-modified, bitumens. Specifically the objectives of using this analysis were:

- to measure the properties of:
  unmodified 180/200[1] bitumen;
  5% SBS[2] polymer-modified 180/200 bitumen; and
  1.5% natural rubber (NR) polymer-modified 180/200 bitumen
- to determine whether these measurements produced results that showed potential for use as a specification test.

The torsional braid analysis technique has been applied to bitumen in only one other known instance, by Koortschot and Woodhams (1984) who showed that the technique was viable at low temperatures (less than 10°C) and at frequencies less than 1 Hz.

The present investigation records first the usefulness of the technique to provide accurate results at low frequencies (<1 Hz, particularly at 0.1–0.01 Hz), and at temperatures (e.g. 5°, 15°, 25°, 40°, and 60°C) that are typical of New Zealand conditions. It then records attempts to extend the frequency range to the higher frequencies (e.g. 1–16 Hz) that are typical of the vibrations caused by traffic using asphaltic road surfaces.

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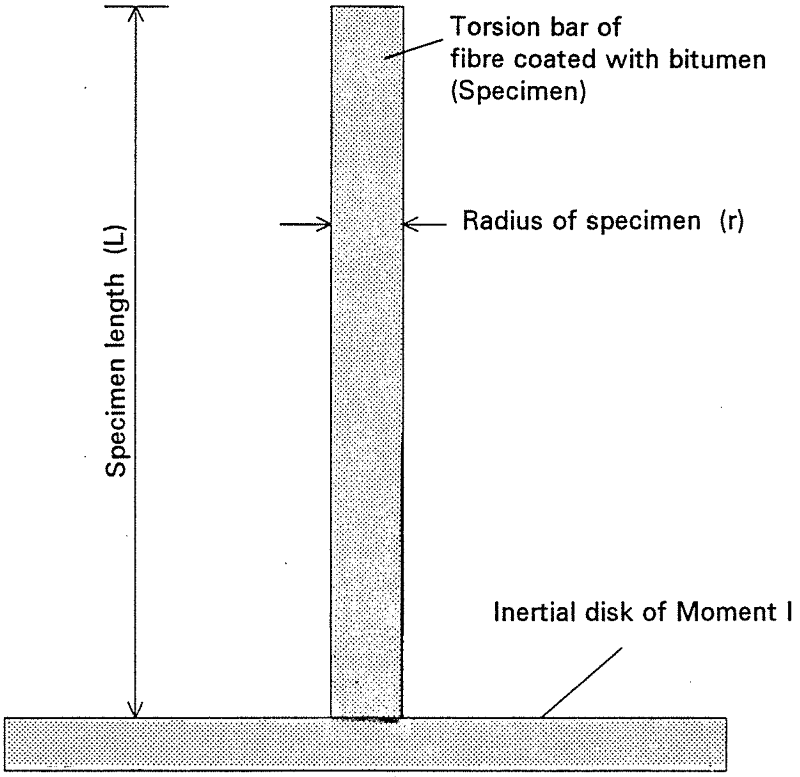
[1] 180/200 penetration grade of bitumen.

[2] SBS Styrene butadiene styrene block polymer

2. BACKGROUND

The torsional braid analysis technique employs a torsional pendulum (Figure 2.1) which allows damped simple harmonic rotational motion of a torsional specimen (composed of braid and sample) in a horizontal plane.

Figure 2.1 Diagram of a torsional pendulum.



A disk having moment of inertia (I) is supported by a rod-shaped specimen (in this case a kevlar braid coated and impregnated with the bitumen to be tested) whose shear modulus, G (Pa), may be determined from:

$$G = \frac{8 \pi L I}{r^4 p^2}$$

where L = length of specimen (m)
I = moment of inertia (kg/m^2)
r = radius of specimen (m)
p = period of oscillation (s)

This equation applies to both lossless and damped torsional simple harmonic motion. In the case of a damped torsional motion, the shear modulus becomes the complex shear modulus, G*, which is a function of the elastic storage modulus, G', and loss modulus, G", thus:

$$G^{*2} = G'^2 + G''^2$$

with $G' = G^* \cos \delta$

$G'' = G^* \tan \delta$

and $G''/G' = \tan \delta$

G' and G" measure energy stored and dissipated respectively by mechanical deformation.

The phase angle δ measures the phase difference between the applied stress and the resultant deformation (strain).

The elastic storage modulus G' is still given by:

$$G' = \frac{8 \pi L I}{r^4 p^2}$$

with the loss modulus given by G" = G' tan δ. The motion is described by an exponentially decaying sinusoidal angular displacement.

The natural logarithm of the ratio of successive amplitudes is the logarithmic decrement Δ; from this the loss tangent tan δ may be calculated, viz:

$$\Delta = \ln \frac{A_i}{A_{i+1}}$$, where A_i is the i'th angular displacement

and $$\tan \delta = \frac{\Delta}{\pi}$$

The equations are applicable to linear visco-elastic materials. Although not strictly true, the unmodified bitumens can be assumed to be linearly visco-elastic over short loading times and the ambient temperature range. In this study no allowance for non-linearity in any of the samples has been made.

The above equations can be applied to composite materials. For torsional braid analysis, as described in this report, a rod-shaped composite specimen is made of a multi-filamentary type of braid (the substrate) coated and impregnated with the material to be tested (such as a bitumen or uncured resins) which on its own cannot be used as the torsion bar as it cannot support the inertial disk of the pendulum. Such a fibre braid should have negligible effect on the rotational mechanical properties of the pendulum disc and thus contribute least to the torsional characteristics of the composite specimen. Therefore measuring the shear modulus of the composite specimen will provide information about the mechanical properties of the binding agent itself.

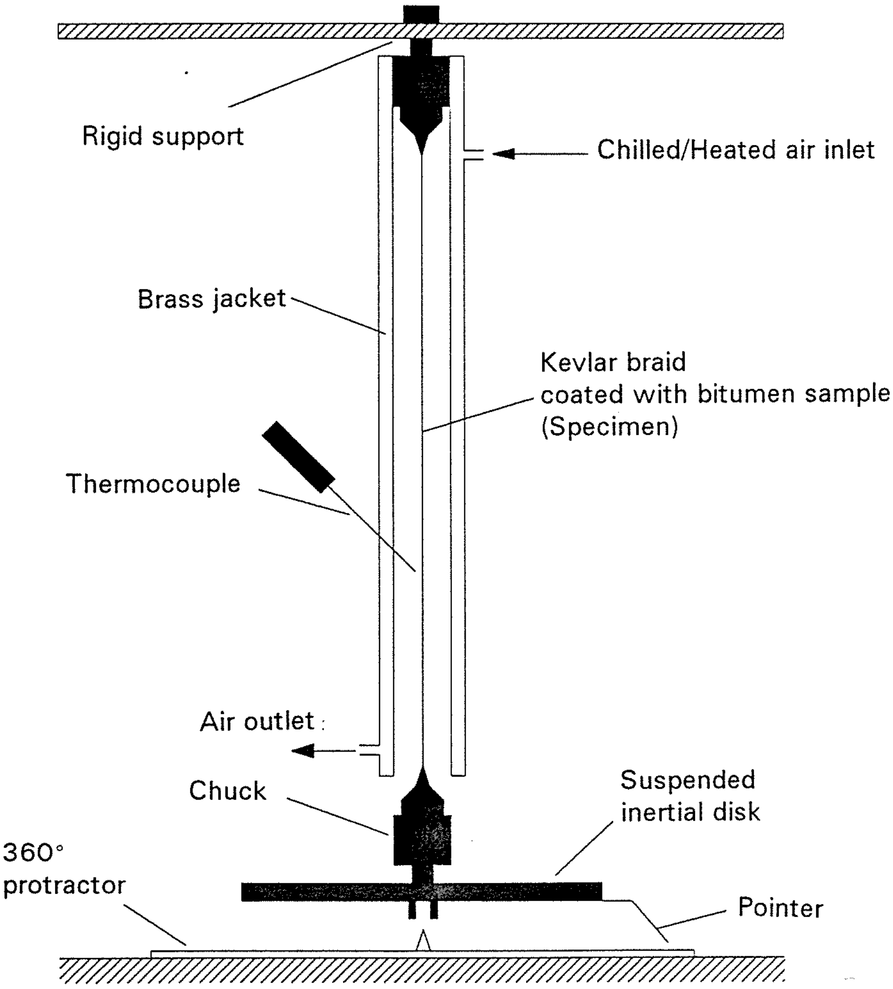
3. METHOD

The method used in this investigation closely follows that of Koortschot and Woodhams (1984) who used an adaptation of the torsional braid technique developed by Gillham (1974, 1979) and Lewis and Gillham (1962). The Koortschot and Woodhams paper deals with a system which operates at temperatures below 10°C and at frequencies generally less than 1 Hz.

The test used in this investigation followed Koortschot and Woodhams technique, and so a piece of Kevlar fibre braid was laid on a dish containing the bitumen sample. To impregnate the braid the bitumen was heated just past its melting point but below 120°C so that oxidation of the bitumen or polymers did not occur. The Kevlar fibre was thoroughly coated and impregnated with this heated sample. A 1.1 mm diameter specimen was obtained by drawing the coated fibre through a 1.1 mm hole in a metal drawplate.

The composite specimen of bitumen-coated fibre was gently pulled while the bitumen cooled to ambient temperature to remove kinks from the finished composite specimens. Sections 5 mm long of 3 mm-diameter stainless steel tube were crimped onto the specimens at either end to provide mounting points. An outline of the apparatus used for the technique is shown in Figure 3.1.

Figure 3.1 The apparatus used for torsional braid technique.



Each specimen was clamped at the upper end of a rigid support frame enclosed in a brass isothermal jacket, and an inertial disk of moment $9.12\ 10^{-4}$ kg/m^2 was attached at the lower end by means of a small chuck. A shield was set up to keep draughts off the inertial disk. The temperature of the composite specimen was controlled to ±1 °C using either chilled or heated air passed through the isothermal jacket, and the temperature was monitored using a type-K thermocouple glued to the inside of the jacket.

The inertial disk of the pendulum was first allowed to come to rest. Its initial position was marked on a protractor centred beneath the inertial disk. The inertial disk was then given an initial angular displacement of about 180°. Its subsequent motion was followed, using a stopwatch to record the period of the displacement and making marks on the protractor to record the successive amplitudes of the displacements. In all cases the initial angle of torsion, measured as the initial displacement multiplied by the ratio of sample radius to length, was less than 0.02 radians.

The volume of space available in the braid that the sample could fill was estimated to be 35–45%. According to Nielsen (1974), this amount of bitumen sample in the braid should increase the measured shear modulus relative to the modulus of the bitumen by no more than a factor of 2.

4. RESULTS

The results obtained for the present work are given in Table 4.1. Points of interest to note are low resonant frequencies (0.006 – 0.014 Hz) and the high experimental errors, especially in the loss tangents and loss moduli. The experimental errors represent one standard deviation. These errors must be borne in mind when considering the results, although no doubt with more development of the technique these errors could be reduced markedly.

The low frequencies were recorded using apparatus and specimens similar to those used by Koortschot and Woodhams (1984), and occurred just below the lower limit of their stated frequency range of 1 to 0.04 Hz.

Table 4.1 Summary of results for all samples of the three bitumens tested.

Sample	**Temp-erature (°C)**	**Frequency (Hz)**	**Loss Tan δ**	**Elastic storage modulus G' (MPa)**	**Loss modulus G'' (MPa)**	**Complex shear modulus G* (MPa)**
180/200 bitumen	5	0.014	0.146 ±0.033	4.30 ±0.62	0.63 ±0.23	4.35 ±0.65
	15	0.011	0.084 ±0.033	2.76 ±0.38	0.23 ±0.12	2.77 ±0.39
	25	0.011	0.122 ±0.050	2.65 ±0.36	0.32 ±0.17	2.67 ±0.38
	40	0.011	0.110 ±0.062	2.71 ±0.37	0.30 ±0.18	2.73 ±0.39
	60	0.008	0.091 ±0.062	1.65 ±0.22	0.15 ±0.12	1.66 ±0.23
5% SBS-modified 180/200 bitumen	5	0.011	0.096 ±0.042	2.27 ±0.30	0.22 ±0.12	2.28 ±0.31
	15	0.009	0.094 ±0.043	1.79 ±0.23	0.17 ±0.10	1.80 ±0.24
	25	0.009	0.110 ±0.340	1.71 ±0.22	0.13 ±0.06	1.71 ±0.22
	40	0.009	0.093 ±0.028	1.71 ±0.22	0.16 ±0.07	1.72 ±0.23
	60	0.009	0.091 ±0.053	1.70 ±0.22	0.16 ±0.11	1.71 ±0.23
1.5% natural rubber (NR)-modified 180/200 bitumen	5	0.010	0.125 ±0.044	2.28 ±0.30	0.29 ±0.14	2.30 ±0.32
	15	0.010	0.075 ±0.032	2.30 ±0.30	0.17 ±0.10	2.31 ±0.31
	25	0.006	0.094 ±0.069	1.00 ±0.13	0.06 ±0.05	0.95 ±0.13
	40	0.009	0.107 ±0.083	1.83 ±0.24	0.02 ±0.02	1.83 ±0.24
	60	0.009	0.180 ±0.171	1.84 ±0.24	0.03 ±0.03	1.84 ±0.24

The results shown in Table 4.1 are also shown in graph form in Figures 4.1 to 4.4. For the sake of clarity, error bars have been omitted on these graphs. Errors are quite large in some cases, and range from about 10% to 90%.

Figure 4.1 Variation of complex shear modulus (G*) recorded at the five temperatures at which the three bitumen samples[2] were tested.

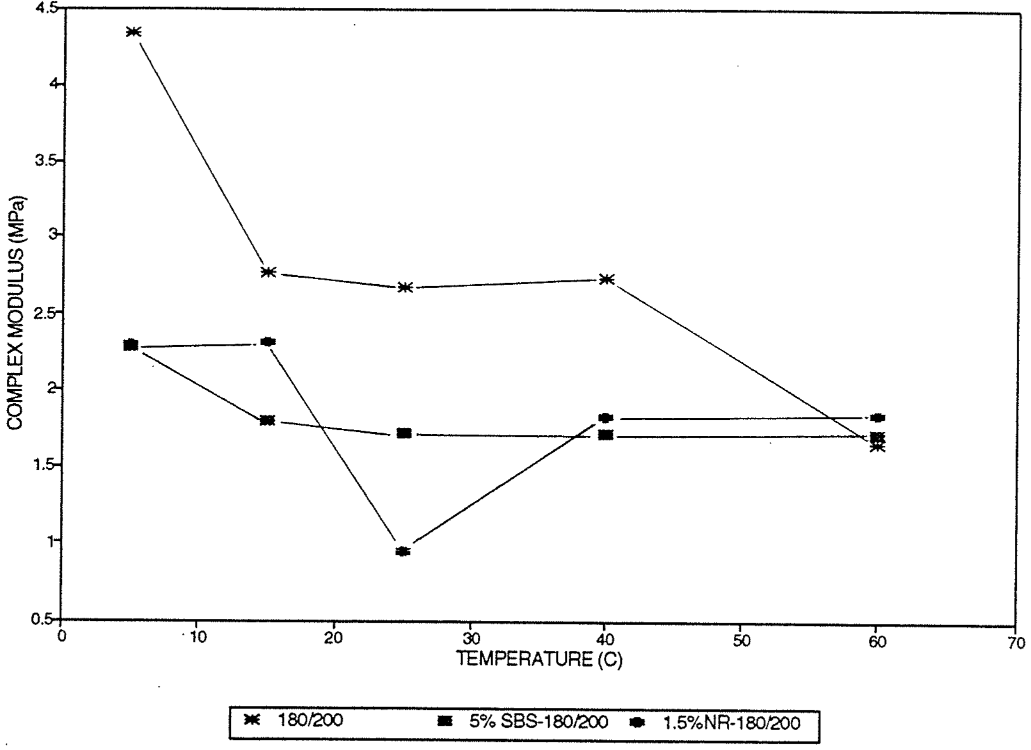
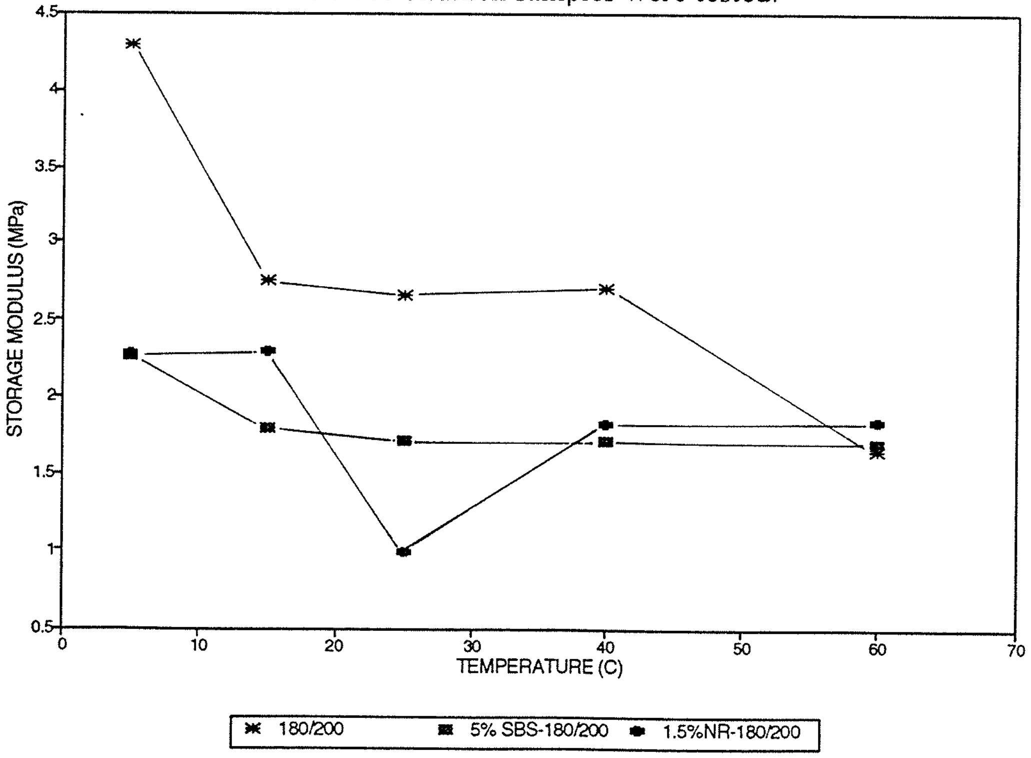


Figure 4.2 Variation of elastic storage modulus (G') recorded at the five temperatures at which the three bitumen samples were tested.



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[2] 180/200 penetration grade of bitumen
SBS styrene butadiene styrene block polymer
NR natural rubber

Figure 4.3 Variation of the loss modulus (G") recorded at the five temperatures at which the three bitumen samples were tested.

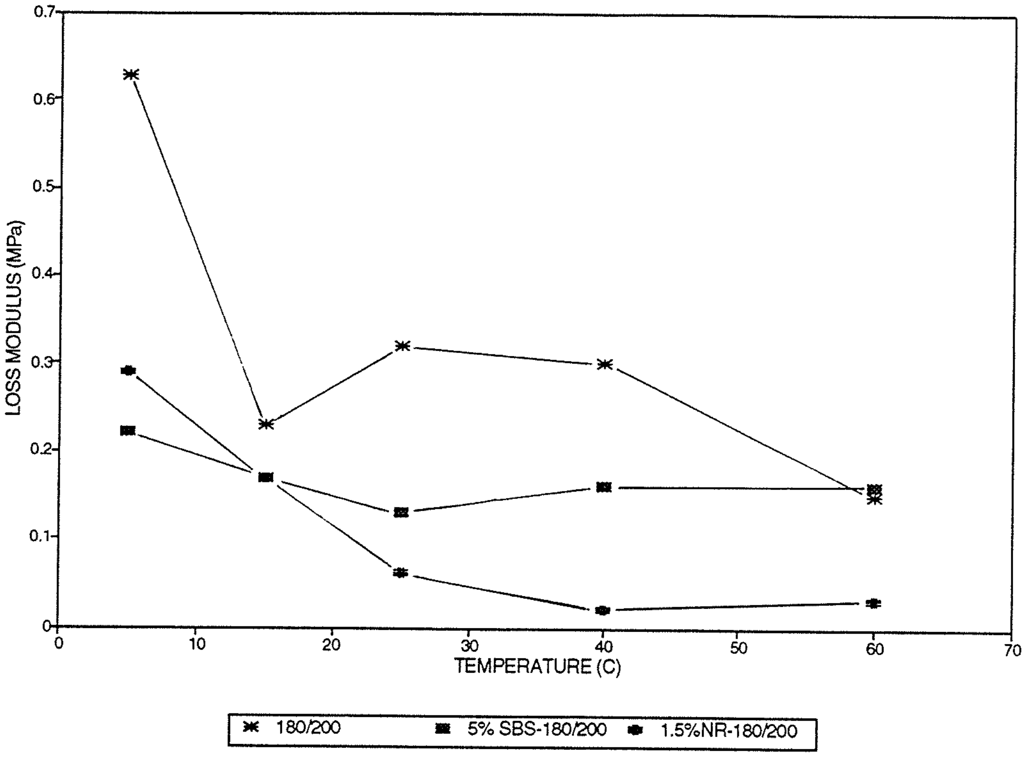
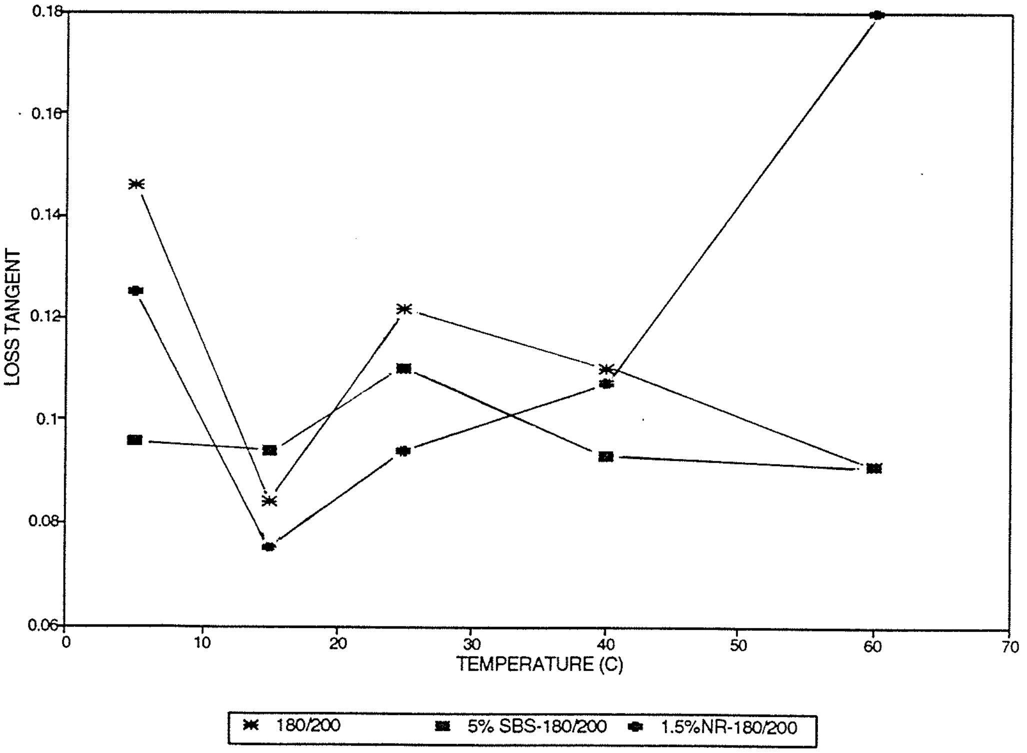


Figure 4.4 Variation of the loss tangent (tan δ) recorded at the five temperatures at which the three bitumen samples were tested.



5. DISCUSSION

The results from this investigation show some similarities to those that Koortschot and Woodhams (1984) obtained from their use of the torsional braid analysis technique. The high frequencies and larger moduli that they measured appear to be related to the range of lower temperatures (less than 5 °C) that they used. They do not show data for higher temperatures.

The results also demonstrate expected differences in the materials at the lower end of the temperature range and suggest, apart from some anomalous points, that the materials are becoming less viscous with increasing temperature (i.e. the elastic shear modulus decreases, see Table 4.1). At the lower temperatures, about 5 °C, shear modulus values are approximately at the expected level. Unfortunately, the change in modulus with temperature was not recorded during the investigation, but it is considered that it would be about 2 orders of magnitude (Dickinson 1984).

Loss tangent values of 0.075–0.180 measured in the present investigation appear too low compared with the values recorded in the published data (Koortschot and Williams 1984, Dickinson 1984). The torsional properties may be dominated by the fibre at the higher temperatures of 40°– 60 °C at which viscous flow is expected to increase.

In service, bituminous binders are subject to stresses over low frequencies (long loading times) in the order of 0.001 Hz associated with contraction of the surface through temperature changes, and high frequencies (very short loading times) in the order of 20 Hz that are associated with traffic loading. Temperature–induced stresses are normally associated with low temperatures (less than 0 °C), while traffic–induced stresses occur throughout the ambient temperature range.

The low frequencies (Table 4.1) obtained with the apparatus and the shape of the sample used in this investigation is appropriate for characterising binders for the temperature–induced stresses, but frequencies greater than 10 Hz would be required in order to model the behaviour of the bitumen under traffic–induced stress.

At these low frequencies (as recorded in Table 4.1) the response of the binder is dominated by the loss modulus, and higher frequencies are required so that the effect of the polymer (which would be expected to significantly affect the elastic modulus) could be measured.

Exploratory tests were made to increase the loading frequency above 1 Hz. One test used a composite specimen with diameter greater than 1.1 mm but this increased diameter greatly increased the damping of the pendulum, and the motion following the initial displacement was difficult to follow. The problem was not investigated further but a combination of adjustments to specimen diameter, inertial moment and specimen length would eventually provide a solution.

The experimental errors recorded for the elastic moduli (Table 4.1) were acceptable but those for the loss tangents and loss moduli were not acceptable. These errors of loss tangents and moduli were related to variations in the period of oscillation and in the successive angular displacement measurements. It is likely that hysteresis in the properties of the modified bitumen (seen as delay in response) is influencing the reaction of the bitumen under test. In consequence an improvement in measuring technique may reduce these variations.

6. CONCLUSIONS

The torsional braid analysis technique used in this investigation is capable of measuring bitumen properties over part, at least, of the tested temperature range of 5–60°C but not in the full frequency range of 0.001–16 Hz. In consequence, the technique in its present form is not useful as a general laboratory test. However the results of the present investigation show that, further development and modifications are needed before it would be more useful as a routine laboratory measure of the elastic properties of bitumens. Such development will inevitably raise the level of technical complexity, increasing both costs and the technical skills required to perform the test.

Further development would involve:
- improving the sample preparation method;
- enclosing the entire apparatus in a chamber to more closely control the temperatures of samples;
- verifying whether the test is worth performing at temperatures greater than about 10°C, which is the upper limit used by Koortschot and Woodhams (1984);
- decreasing the loading time of the apparatus by adjusting the parameters in the governing equation:

$$G' = \frac{8 \pi L I}{r^4 p^2}$$

For instance, the period of oscillation or loading time p(s) may be reduced by increasing the specimen radius r, or decreasing the specimen length L, or decreasing the moment of inertia I for a given modulus.

However, exploratory tests have shown that, while all these modifications work and increasing radius r gives the greatest reduction in loading time, increasing the specimen radius by more than 0.55 mm greatly increases the damping and makes the technique difficult to use.

The effects of reduced period (greater frequency) and increased damping means that, for the technique to operate at frequencies of ~1 Hz, an automated data collection system would have to be installed. Because the damping is so great, the oscillation decays after very few oscillations, i.e. in a very short time, and with big amplitude changes which could be followed only with accurate sensing equipment but not with the simple stopwatch and protractor system.

The low frequencies measured in this investigation were a major drawback which may be very difficult to overcome without the expenditure of considerable effort. In fact, it may be more sensible to move from a freely oscillating system to a forced system such as the Rheovibron, where samples are forced to vibrate at an adjustable driving frequency (Koo 1974).

7. RECOMMENDATION

The torsional braid technique does not provide a relatively low cost test for measuring the modulus and elastic properties of modified bitumen. This investigation demonstrates that substantial development would be needed to obtain measurements at the loading frequencies associated with traffic–induced stresses, and that an automatic data recording system would be needed to obtain accurate results.

The recommendation is that no further investigation of the technique is carried out.

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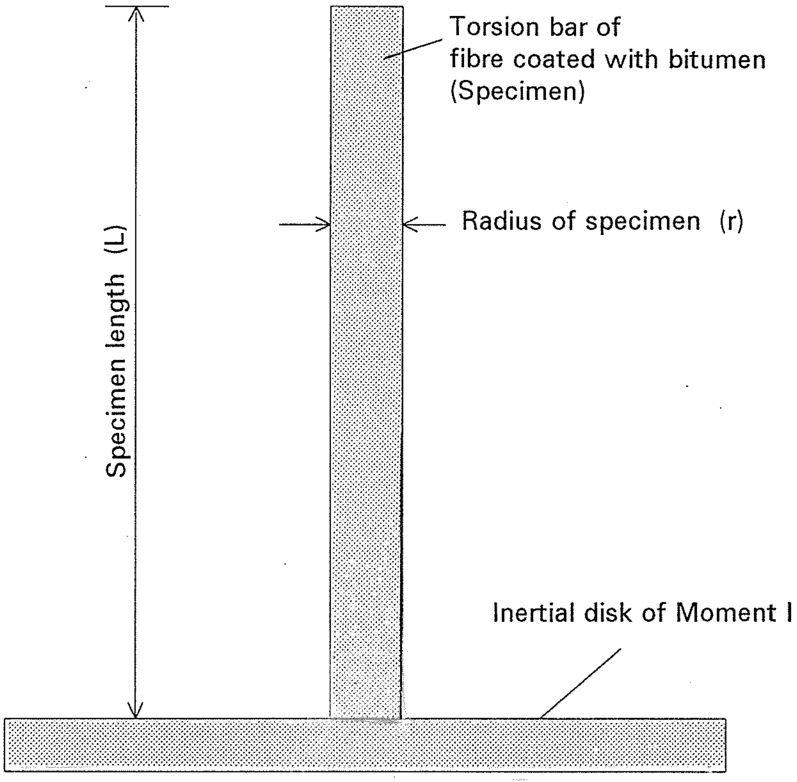
2. BACKGROUND

The torsional braid analysis technique employs a torsional pendulum (Figure 2.1) which allows damped simple harmonic rotational motion of a torsional specimen (composed of braid and sample) in a horizontal plane.

Figure 2.1 Diagram of a torsional pendulum.



A disk having moment of inertia (I) is supported by a rod-shaped specimen (in this case a kevlar braid coated and impregnated with the bitumen to be tested) whose shear modulus, G (Pa), may be determined from:

$$G = \frac{8 \pi L I}{r^4 p^2}$$

where L = length of specimen (m)
I = moment of inertia (kg/m^2)
r = radius of specimen (m)
p = period of oscillation (s)

This equation applies to both lossless and damped torsional simple harmonic motion. In the case of a damped torsional motion, the shear modulus becomes the complex shear modulus, G*, which is a function of the elastic storage modulus, G', and loss modulus, G", thus:

Figure 4.1 Variation of complex shear modulus (G*) recorded at the five temperatures at which the three bitumen samples[2] were tested.

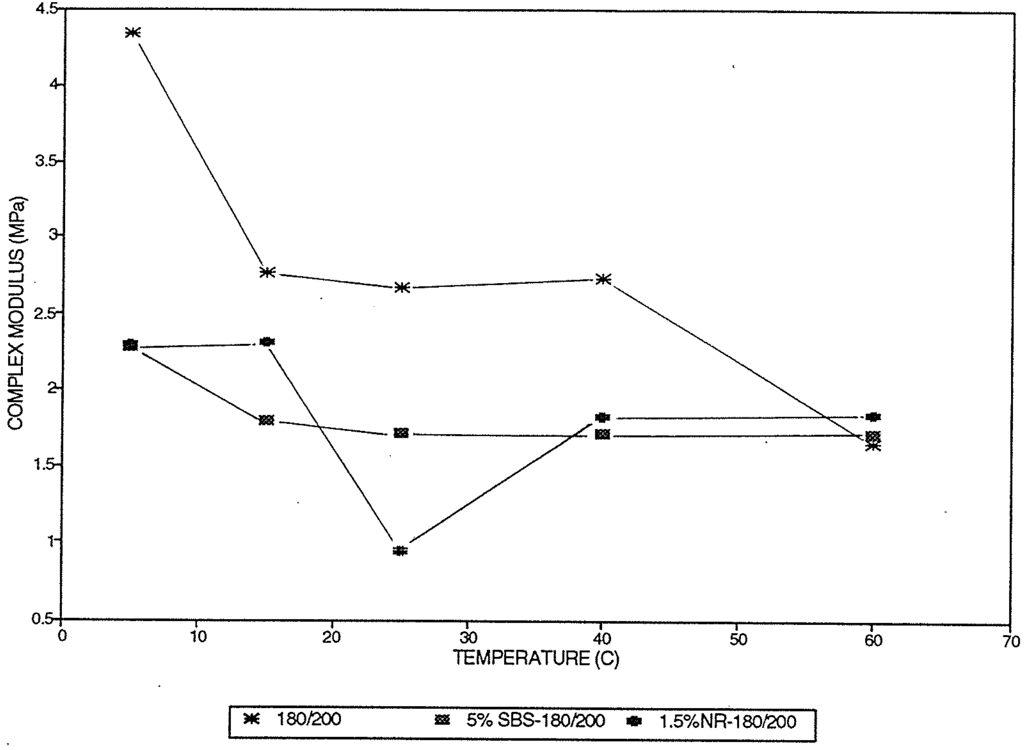
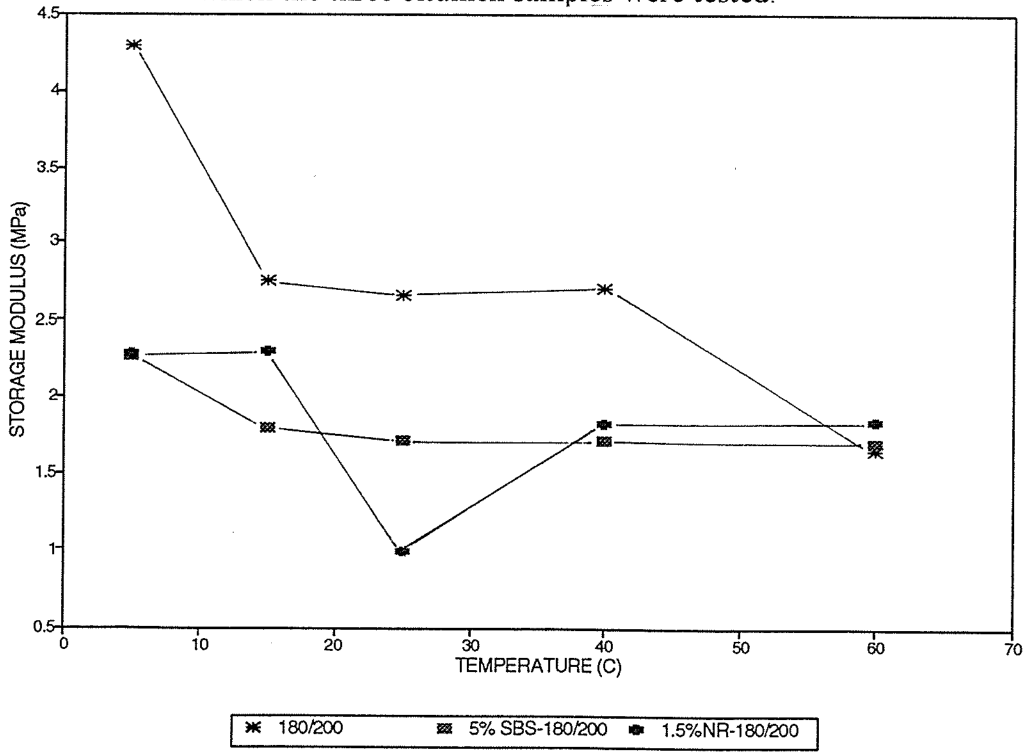


Figure 4.2 Variation of elastic storage modulus (G') recorded at the five temperatures at which the three bitumen samples were tested.



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[2]

180/200	penetration grade of bitumen
SBS	styrene butadiene styrene block polymer
NR	natural rubber

Figure 4.3 Variation of the loss modulus (G") recorded at the five temperatures at which the three bitumen samples were tested.

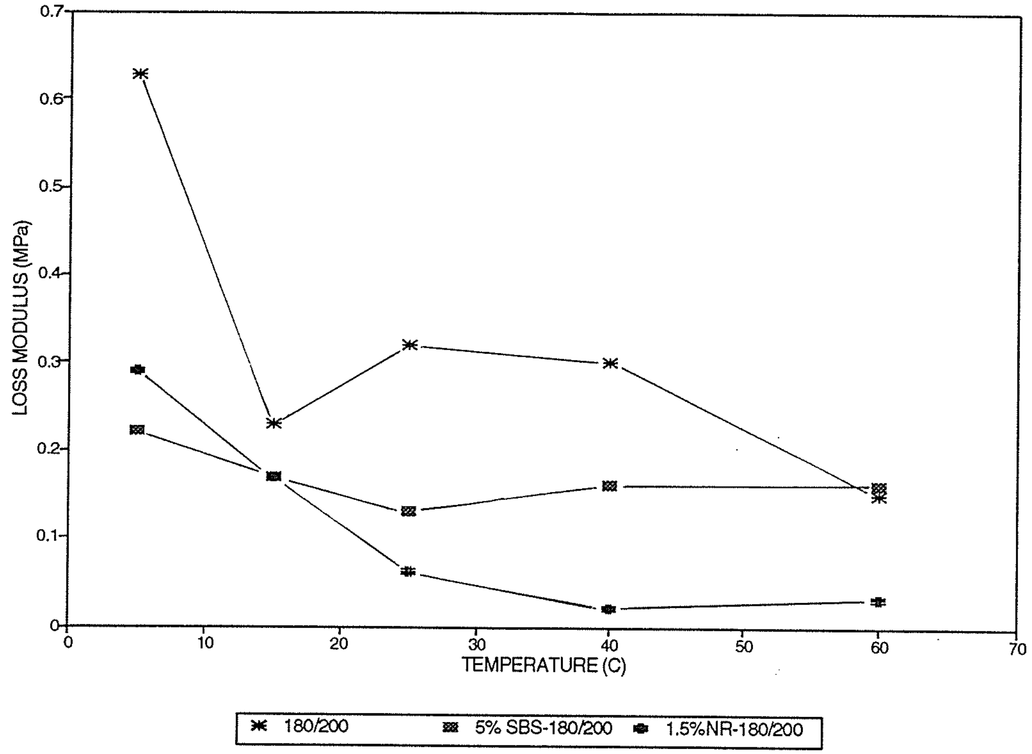

Figure 4.4 Variation of the loss tangent (tan δ) recorded at the five temperatures at which the three bitumen samples were tested.