FATIGUE RESISTANCE OF THIN MODIFIED BITUMINOUS LAYERS: LITERATURE REVIEW

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EXECUTIVE SUMMARY

Most New Zealand pavements comprise a granular base with a thin bituminous surfacing. When bituminous mixes are used for this surfacing, the predominant failure of the pavement is caused by fatigue cracking. A literature review was undertaken in 1993 to identify those products that could have the potential to be used to improve the fatigue life of thin bituminous mixes for surfacing roading pavements in New Zealand. The emphasis was to search for literature that covered the fatigue life of mixes incorporating modifiers that had been tested under appropriate loading and temperature conditions. This information could be used as inputs into design to give improved performance of typical New Zealand pavement structures.

For flexible pavements with a thin surface layer of bitumen-bound mix, the most appropriate form of laboratory testing is that which includes:

- controlled strain,
- effective rest periods, i.e. greater than 10 times the loading time,
- realistic loading times, i.e. less than 0.1 seconds, and
- more than one temperature at test.

The fatigue resistance of modified bituminous mixes had been investigated and were reported in the literature reviewed, but the modes of testing did not cover the range of conditions that apply to New Zealand pavements. Therefore none of the modifiers tested could be used with confidence in this country, although a number of modifiers appear to have the potential to improve the fatigue life of thin surfacing mixes.

Polymer additives could be successful when used in soft bitumen, but the effect of adding fibres is not clear.

In consequence of these findings, the project did not enter the proposed further phase to compare typical fatigue characteristics of modified mixes with standard mixes in pavement design analysis.

It is suggested that further useful information could be obtained from a programme of fatigue testing using selected additives.

ABSTRACT

Most New Zealand pavements comprise a granular base with a thin bituminous surfacing. When bituminous mixes are used for this surfacing, the predominant failure of the pavement is caused by fatigue cracking. A review of literature was made in 1993 to identify those products that could have the potential to be used to improve the fatigue life of thin bituminous mixes for surfacing roading pavements in New Zealand. The effects of modifiers on the fatigue resistance of thin bituminous mixes are included.

The most appropriate mode of laboratory testing is that which includes:

- controlled strain,
- effective rest periods,
- realistic loading times, and
- more than one temperature at test.

Polymer additives could be successful when used in soft bitumen, but the effect of adding fibres is unclear.

The fatigue resistance of modified bituminous mixes had been investigated and were reported in the literature reviewed, but the modes of testing did not cover the range of conditions that apply to New Zealand pavements. Therefore none of the modifiers tested could be used with confidence in this country, although a number of modifiers appear to have the potential to improve the fatigue life of thin surfacing mixes.

1. INTRODUCTION

The typical form of pavement construction in New Zealand consists of a relatively thin layer bound by bitumen over a granular base. Most of the sealed roading network has chipseal surfacing, but the use of bituminous mix is increasing because it can be used for improving the shape of the pavement, and is also capable of withstanding higher shear stresses than a chipseal.

The most common mode of failure of thin bituminous mix layers is cracking due to fatigue.

Over the last 10-12 years international research has investigated the use of modifiers in bituminous mixes to increase fatigue resistance. Most of the research has concentrated on the fatigue resistance of thick structural layers of mix and has not considered, to the same degree, the properties of thin layers, which are used in New Zealand.

Modifiers that have been studied include a range of polymers and fibres. Some of these materials may have the potential to be used in New Zealand bituminous mixes as a cost-effective method of increasing fatigue resistance.

As part of this research a literature review was undertaken in 1993 to identify those products that could have the potential to be used in New Zealand mixes. The emphasis was to search for literature that covered the fatigue life of mixes incorporating modifiers that had been tested under appropriate loading and temperature conditions. This information could be used as inputs into design of typical New Zealand pavement structures to give improved performance of pavements. Literature published between 1993 and 1996 has not added significantly to this review.

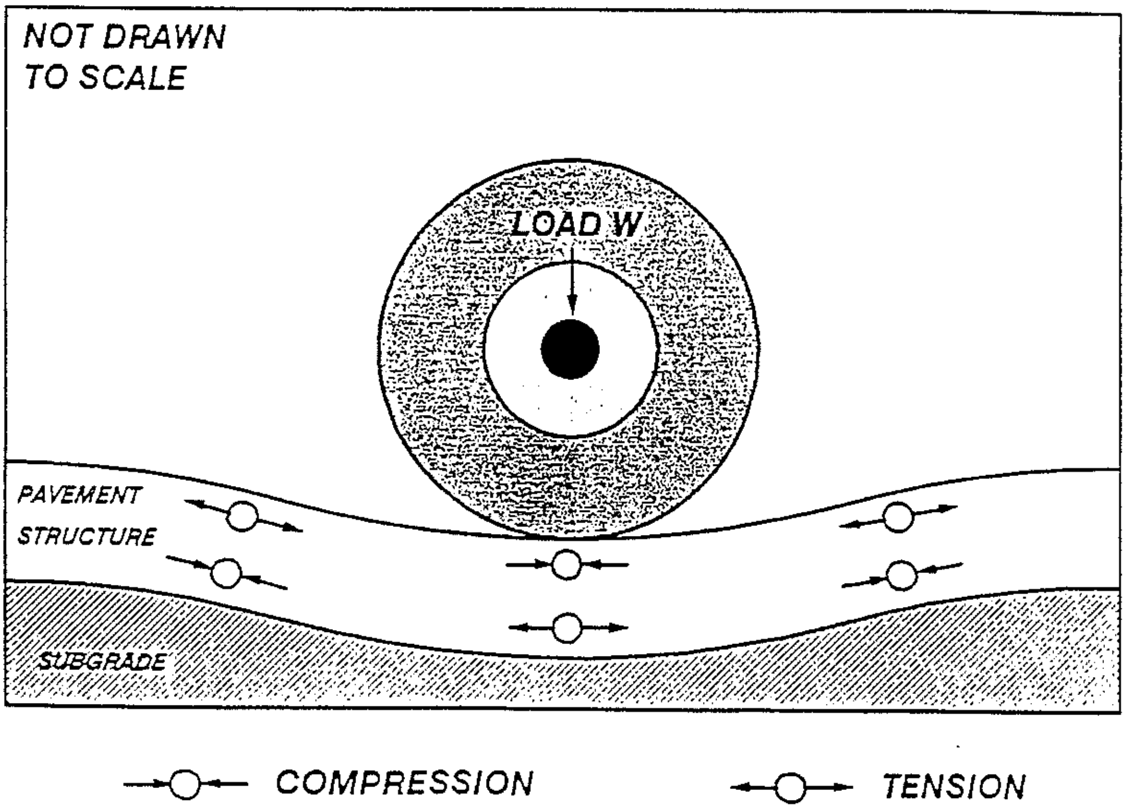
2. FATIGUE AND STRAIN

A material is said to fail by fatigue if it cracks after being subjected to a large number of repetitions of strain at a level which is less than the ultimate strain achievable under a single application of load. As the magnitude of the strain decreases, the number of cycles required to cause failure increases. The number of cycles of strain to reach failure is a measure of the fatigue life of the material at the particular level of strain.

The passage of a vehicle wheel over the surface of a pavement causes the pavement to deform. For a pavement consisting of a bitumen-bound layer over a granular base, with a relatively thin (less than 50 mm) hot mix asphalt surface, the magnitude of the strains induced in the surface layer is primarily dependent on the stiffness of the granular base. A schematic diagram of the deformations and the locations of the areas of principal compressive and tensile strains under the action of a wheel is shown in Figure 1.

For any particular position of the wheel, the maximum tensile strain normally occurs immediately below the centre of the wheel.

Figure 1. Tensile and compressive strains occurring in a bitumen-bound pavement surface layer showing the two ways that cracking could develop when fatigue failure occurs.



3. LABORATORY TESTING

3.1 Simulation

Where the pavement consists of a thin layer of bitumen-bound mix, the deflection of the pavement is not significantly affected by the stiffness of the layer. Under low or high temperatures the same magnitude of tensile strain is developed under the wheel load. Hicks (1965) showed that to model these layers a constant strain fatigue loading mode was appropriate (i.e. the same maximum strain in each cycle). In this form of test, the sample is subjected to repetitive deformations of the same magnitude. As the sample begins to fail, the load level required to deform the specimen decreases. Crack propagation therefore slows and failure can take considerable time before reaching completion. Therefore fatigue life is usually defined in terms of the number of cycles required to reduce the load to half of that initially applied.

As pavements in New Zealand tend to consist predominantly of thin bituminous bound layers, the constant strain mode of testing is considered appropriate for laboratory simulation.

3.2 Rest Periods

Most strain-controlled fatigue testing has been carried out using strains applied either sinusoidally or using a haversine. The testing has not allowed for any rest period between strain cycles to allow self-healing. Therefore, to allow for the rest periods that will occur in practice, shift factors in the order of 100 have been applied to the laboratory fatigue data to compare them with actual performance of pavements when rest periods were used.

Investigations by Bonnaure et al. (1982) concluded that:

(a) the fatigue life seems to reach a maximum when the rest period is 25 times the loading time;

(b) the fatigue life increased with increase of temperature;

(c) the fatigue life increased with decrease in stiffness of the binder;

(d) the effect of level of stress and strain on the shift in the curves was minimal; and

(e) the fatigue life as measured in the constant stress mode is greater than that measured with the constant strain mode.

4. MATHEMATICAL MODEL OF FATIGUE LIFE

A large number of investigations into the fatigue characteristics of bitumen-bound mixes have shown that the fatigue life was often better correlated with tensile strains than tensile stress. The basic failure equation (1) takes the form:

$$W_f = a\left(\frac{1}{\varepsilon_t}\right)^b \qquad (1)$$

where W_f is the fatigue life and is expressed as the number of cycles of failure,
ϵ_t is the tensile strain, and
a and b are constants.

Fatigue life also varies with loading frequency and temperature. In order to allow for these effects, the stiffness of mix at the loading frequency and temperature is added:

$$W_f = a\left(\frac{1}{\varepsilon_t}\right)^b \frac{1}{(S_{mix})^c} \qquad (2)$$

where S_{mix} is the stiffness modulus at a particular temperature and loading frequency, and c is a constant.

For any mix tested under controlled conditions of loading frequency and temperature, the above relationships show that a straight line of log tensile strain versus log load repetitions will result.

Witczak found (in 1976) that a unique strain relationship, as given in equation (1), was reported by researchers using continuous sinusoidal loading. However, those who used pulse loading with rest periods obtained a different tensile strain-fatigue life relationship for each combination of temperature and loading frequency, as given in equation (2) above.

5. GENERAL TRENDS IN THE LITERATURE

From the literature, binder properties and mix properties are shown to have a significant effect on the fatigue life. The effect is different depending on the loading mode (whether constant stress or constant strain). Effects of changing various factors are given in Table 1 (Rao Tangella et al. 1990).

As the objective of this present investigation is concerned with the constant strain mode of testing applicable to thin bitumen-bound layers, factors that reduce the stiffness modulus of the mix, i.e. decreasing bitumen stiffness, increasing bitumen content, open gradings and increasing temperature, are all seen to increase fatigue life. On the other hand, factors that increase the mix stiffness will lead to decreased fatigue life.

Based on this premise, only modifiers that decreased the mix stiffness are regarded as potential additives to increase surfacing life for the majority of New Zealand applications.

Table 1. Factors affecting the stiffness and fatigue life of asphalt paving mixtures[1] (taken from Rao Tangella et al. 1990)

Factor	Change in Factor	Effect of Change in Factor		
		On Stiffness	On Fatigue Life in Controlled Strain Mode of Testing	On Fatigue Life in Controlled Stress Mode of Testing
Asphalt viscosity (stiffness)	Increase	Increase	Decrease	Increase
Asphalt content	Increase	Increase[2]	Increase[3]	Increase[2]
Aggregate gradation	Open to dense	Increase	Decrease[4]	Increase
Air void content	Decrease	Increase	Increase[4]	Increase
Temperature	Decrease	Increase[5]	Decrease	Increase

1 For continuously graded mixtures.
2 Reaches optimum at level above that required for stability.
3 No significant data. Conflicting conditions of increase in stiffness and reduction in asphalt strain make this speculative.
4 No significant data.
5 Approaches limit at below-freezing temperatures.

6. ASSESSMENT OF THE LITERATURE

The literature search has revealed that there is a wide range of types of bitumen testing for fatigue. Different results are obtained depending on:

(a) testing mode - constant stress or strain;

(b) loading type - tensile or flexural;

(c) mix stiffness influenced by loading time and temperature;

(d) mix characteristics - binder type, content, air voids;

(e) rest periods.

Because of the above factors ((a) to (e)), many countries have conducted fatigue tests on mixes used in their area rather than rely on generalised models.

When assessing published research into the use of modifiers, all the above factors need to be taken into account to obtain comparable data. For example, the influence of rest periods has been shown (Bonnaure et al. 1982) to be significant. If modified binders self-heal differently to normal bitumen, comparative fatigue tests performed under sinusoidal loading (without rest periods) may not be valid as an assessment of the performance of the modifier.

Also many tests are performed at only one temperature. Although a unique strain-fatigue relationship has been found with constant stress sinusoidal loading, this relationship is not valid for tests performed with rest periods.

Therefore existing test data are only of very limited value for assessing the fatigue life of modified bitumen mixes in New Zealand.

7. ADDITIVES

A wide range of materials have been added to bituminous mixes to modify their properties. Terrel and Epps (1988) have classified them into 10 types, as shown in Table 2.

Some of the modifiers reduce the mix stiffness and therefore increase the fatigue life. Comments on the modifiers' potential to affect the fatigue life are:

1. **Fillers** in general tend to combine with the bitumen to stiffen the mix. They could tend to decrease the fatigue life of thin layers if used with normal bitumens.

2. **Extenders** are normally used as a replacement for bitumen without fundamentally altering its properties.

3.)
4.) **Polymers**. Refer Section 9.
5.)

6. **Fibres**. Refer Section 10.

7. **Oxidants**, such as manganese salts used in Chemcrete, are used to stiffen the mix. They are not advocated for use for thin layers.

8. **Antioxidants** modify the durability characteristics of the bitumen. As such, they could be regarded as beneficial from a fatigue point of view and could be cost-effective.

9. **Hydrocarbons**, such as rejuvenating oils, if they can be absorbed by the mix, could be used to extend the life of bituminous mixes and could be cost-effective. Transit New Zealand Research Project PR3-0058* is investigating the applicability of rejuvenating agents in friction course.

10. **Anti-strip agents** are used to protect the mix from water damage, and are not regarded as modifiers of the stiffness or fatigue properties.

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* TNZ Research Project PR3-0058: Surfacing regeneration.

Table 2. Generic classification of asphalt modifiers (from Terrel and Epps 1988).

Type		Examples
1. Filler		Mineral filler: - crusher fines - lime - portland cement - fly ash Carbon black Sulphur
2. Extender		Sulphur Lignin
3. Rubber (a) Natural latex (b) Synthetic latex (c) Block copolymer (d) Reclaimed rubber	POLYMERS	Natural rubber Styrene-butadiene (SBR) Styrene-butadiene-styrene (SBS) Recycled tyres
4. Plastic	POLYMERS	Polyethylene Polypropylene Ethyl-vinyl-acetate (EVA) Polyvinyl chloride (PVC)
5. Combination	POLYMERS	Blends of polymers of types 3 and 4
6. Fibre		Natural: - rock wool Man-made: - polypropylene - polyester - fibreglass
7. Oxidant		Manganese salts
8. Antioxidant		Lead compounds Carbon Calcium salts
9. Hydrocarbon		Recycling and rejuvenating oils Hardening and natural asphalts
10. Anti-strip agent		Amines Lime

8. MODIFIED MIXES

Mixes with lower stiffness moduli tend to result in higher fatigue life. As bitumen-bound mixes have their highest modulus at low temperatures, modifiers that can soften the bitumen appear attractive for increasing fatigue life.

For normal penetration grade bitumens, if softer grades were used in the manufacture of mixes, then high temperature stability problems can result. Any additive should therefore either decrease the low temperature stiffness without adversely affecting the high temperature properties of the pavement or it should be added to a soft bitumen to modify the high temperature properties without affecting the lower temperature properties.

The second alternative is often overlooked when assessing the performance of the additives on the traditional grade of bitumen used in an area, without extending the study to other bitumen grades.

Some additives, such as fibres, can allow a mix to be constructed with a higher bitumen content. Although fibres may give a reinforcing effect, increased fatigue resistance may also be gained through the higher binder content. In open graded mixes such as friction course, where use of higher bitumen content is limited by binder run-off, fibres and polymers can allow increased bitumen contents that maintain high temperature performance of pavement without significantly affecting low temperature stiffness. The fatigue resistance increase may be related to the increased bitumen, not specifically to the additive.

9. POLYMERS

Polymers, in the form of natural rubber or styrene butadiene block copolymers (SBS), have been used for a number of years in chipseals in New Zealand. Some limited use has also been made of ethyl-vinyl-acetate (EVA) in both chipseals and some asphaltic concrete.

The main reason for the use of these polymers has been either to resist reflective cracking or to improve the resistance of the surface to high stresses. There are no known New Zealand trials for improving the fatigue resistance of the surface material.

Polymers can be divided into two classes:

1. those that impart elasticity; and
2. those that affect the viscous flow.

As bitumen behaves as a viscoelastic material in the ambient temperature range, it tends to exhibit elastic properties at low temperatures and short loading times, but viscous properties tend to dominate at long loading times and high temperatures.

The rubber materials listed in Table 2 will modify the elastic component of the bitumen, while the plastics will tend to affect the viscous components.

The extent of the modification depends on the polymer and its compatibility with the bitumen. In attempting to measure the effect of the modifier, currently used empirical bitumen tests are inadequate. The response of the binder is affected by test temperature, loading rate and strain rate. A simple test, e.g. penetration, is only measuring one point on a complex curve and it is not duplicating the loading conditions that exist in the field.

There is debate in the literature, e.g. Goodrich (1988), whether rubber polymers result in a softer binder at low temperatures. Depending on the test used, it can be shown that they have either a minimal or a significant effect. The relationship of the measured binder properties to the performance of mix is even more complex.

Empirical relationships between bitumen properties coupled with mix proportions that are currently used to estimate fatigue life (Brown et al. 1982, Shell International Petroleum Company 1978) are known not to be applicable to highly modified binders.

The literature search for this project has not found any data on fatigue testing of mixes using modified binders that have all the following characteristics:

- controlled strain,
- effective rest periods, i.e. greater than 10 times the loading time,
- realistic loading times less than 0.1 second, and
- performed at more than one temperature.

In an effort to obtain a more fundamental understanding of the relationship between binder properties and mix performance, Goodrich (1991) carried out a series of tests using a range of binders with the use of a dynamic analyser. This instrument is capable of measuring the modulus of bitumen from –40°C to +60°C.

The stress-strain relationships developed from the sinusoidal loading pattern are reproduced from Goodrich in Figures 2 and 3. The loss tangent is a measure of the elastic properties of the material. If the loss tangent is 0, the stress and strain responses are in phase, and the behaviour is purely elastic. When the responses are 90° out of phase the behaviour is purely viscous. Goodrich related the loss tangent to the fatigue behaviour of mixes made with straight bitumen (Figures 4 and 6) and the bitumen modified by an ethylene copolymer (Figures 5 and 7). Fatigue tests were performed in the controlled stress mode using a 0.1 second pulse load followed by a 0.5 second rest period. The test temperature was not given.

Goodrich explained the pattern of results by postulating that:

(a) at low strain rates, the elastic structure of the bitumen provides fatigue resistance;

(b) at high strain rates, viscous flow properties of bitumen provide fatigue resistance.

In the fatigue test, with a constant load pulse to generate high strains, the rate of strain must be faster than that required for a low strain. In Figure 6 the loss tangent at low temperatures for asphalts D and F tend to merge; this is reflected in the fatigue lines converging at high strains. In Figure 4, asphalts A and C tend to merge at high temperatures. This is reflected in the fatigue lines at low strains.

These results tend to confirm other investigators in that soft binders perform better in high strain situations.

Goodrich's investigations raise the question whether or not highly elastic binders are better for fatigue resistance. If no rest periods are included in the test then they tend to show an improvement. However, elastic binders may not be as sensitive to the effect of rest periods and, in practice, performance may not be improved. Goodrich also suggests that, at low temperatures less than 10°C, the properties of the bitumen tend to dominate over the polymer (with the polymers and bitumens used for his tests). This tends to support the view that as soft as possible a bitumen should be used for low temperature fatigue improvement.

Both stiffness and elasticity have to be considered in assessing fatigue performance of modified binders. Most research to date has stressed the concept that improvements will be obtained because of the lower mix stiffness. If lower mix stiffness is accompanied by increased elasticity then the expected improvements may not eventuate.

Polymers that affect the viscous component of the bitumen, such as the plastics, also tend to affect its high temperature (greater than 30°C) properties. To effectively increase the low temperature fatigue properties, they could be blended with softer binders which would result in satisfactory high temperature resistance to shear, but remain significantly softer at low temperatures. Research overseas has tended to concentrate on improving the mix's susceptibility to rutting. As such, normal bitumen grades are used and fatigue tests applied to confirm that no adverse effects are occurring (Denning and Carswell 1981).

Figure 2. Stress-strain response under dynamic loading (from Goodrich 1988).

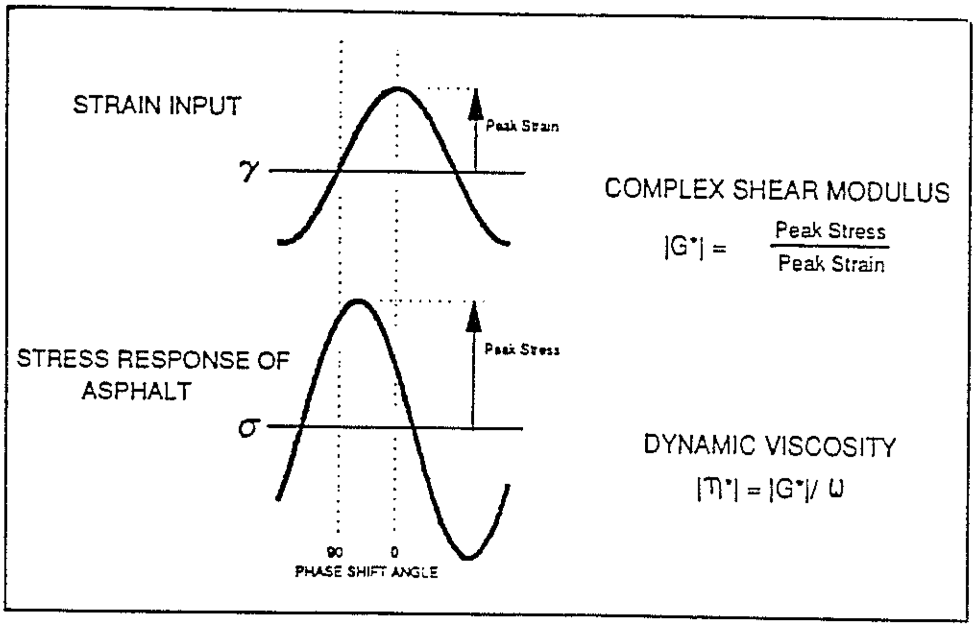


Figure 3. Modulus definitions under dynamic loading (from Goodrich 1988).

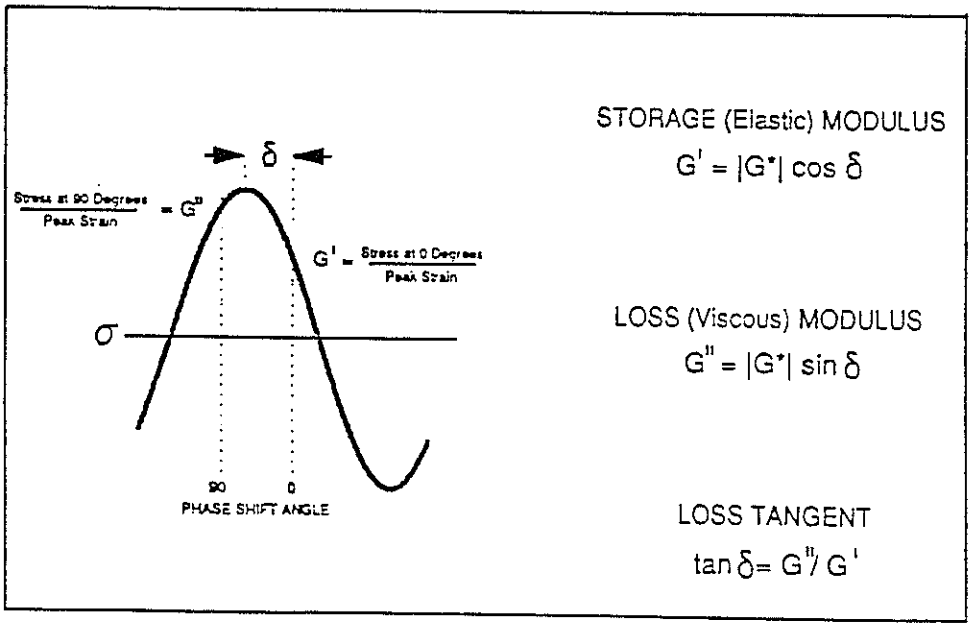


Figure 4. Loss tangent response of three straight bitumens (from Goodrich 1988).

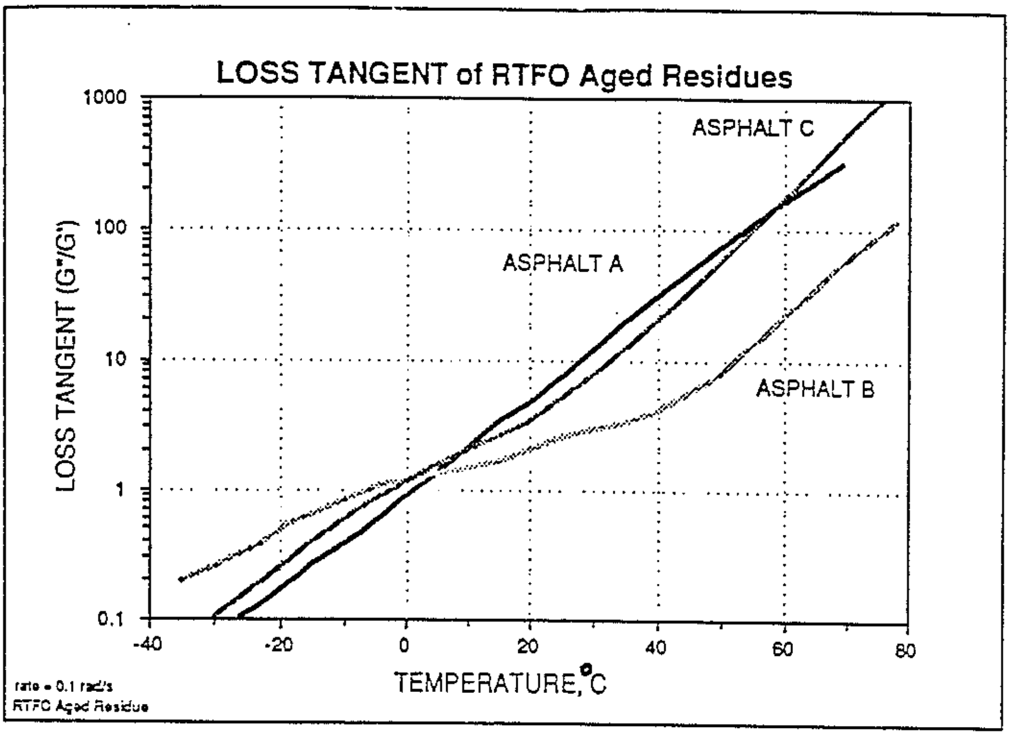
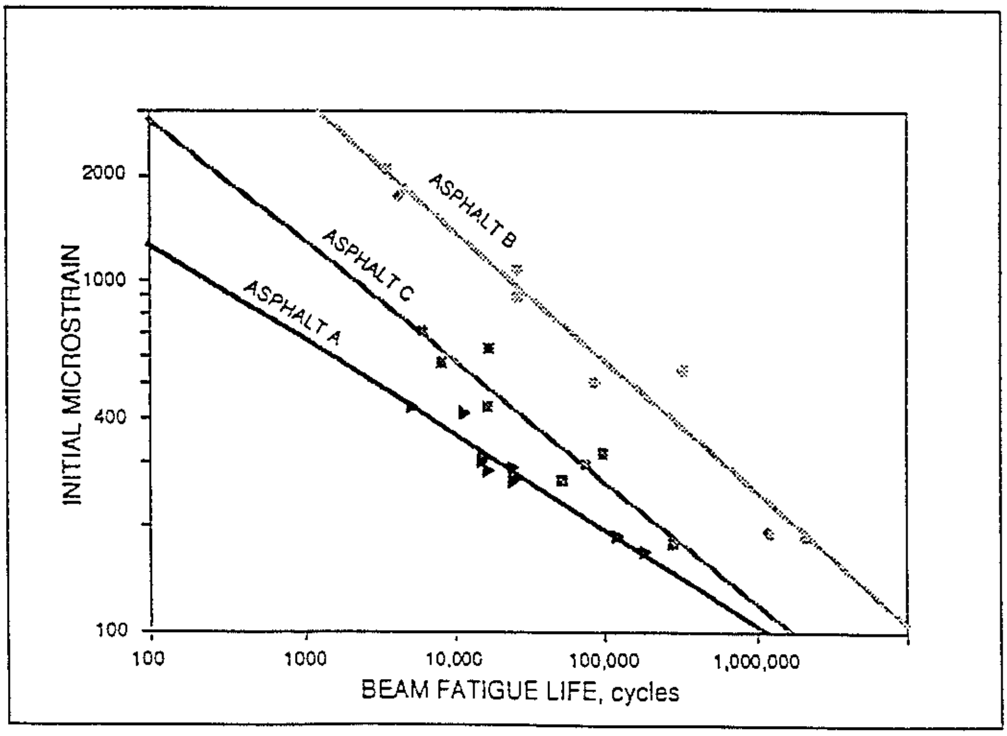


Figure 5. Fatigue response of mixes using three straight bitumens (from Goodrich 1988).



RTFO rolled thin film oven test

Figure 6. Loss tangent response of three bitumens modified by ethylene copolymer (from Goodrich 1988).

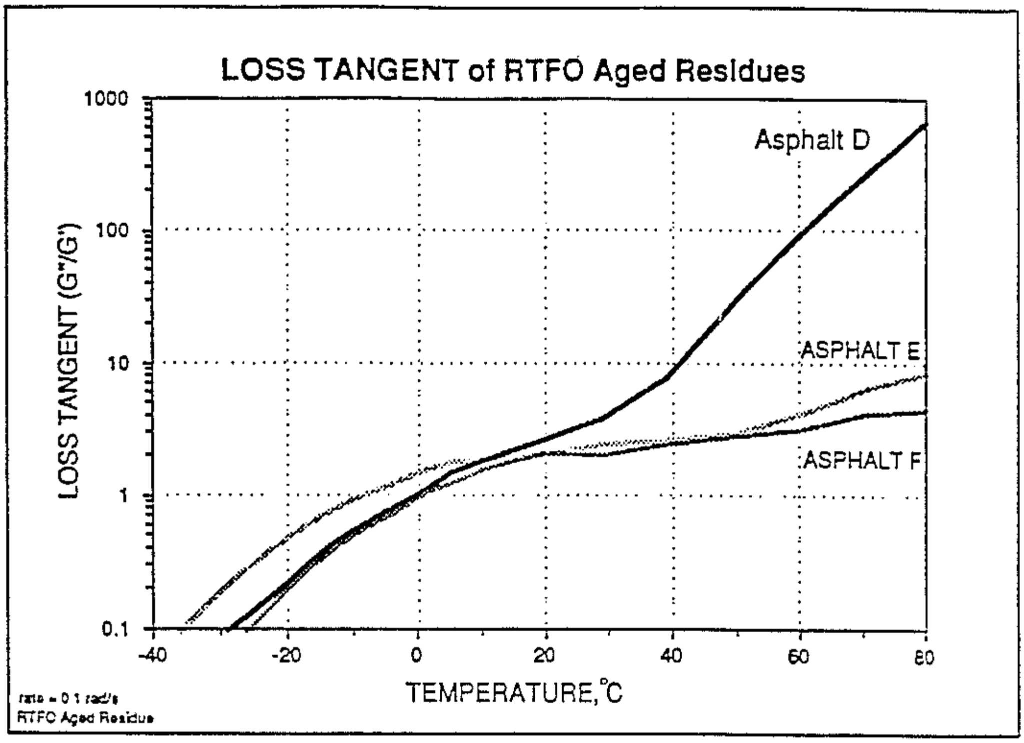
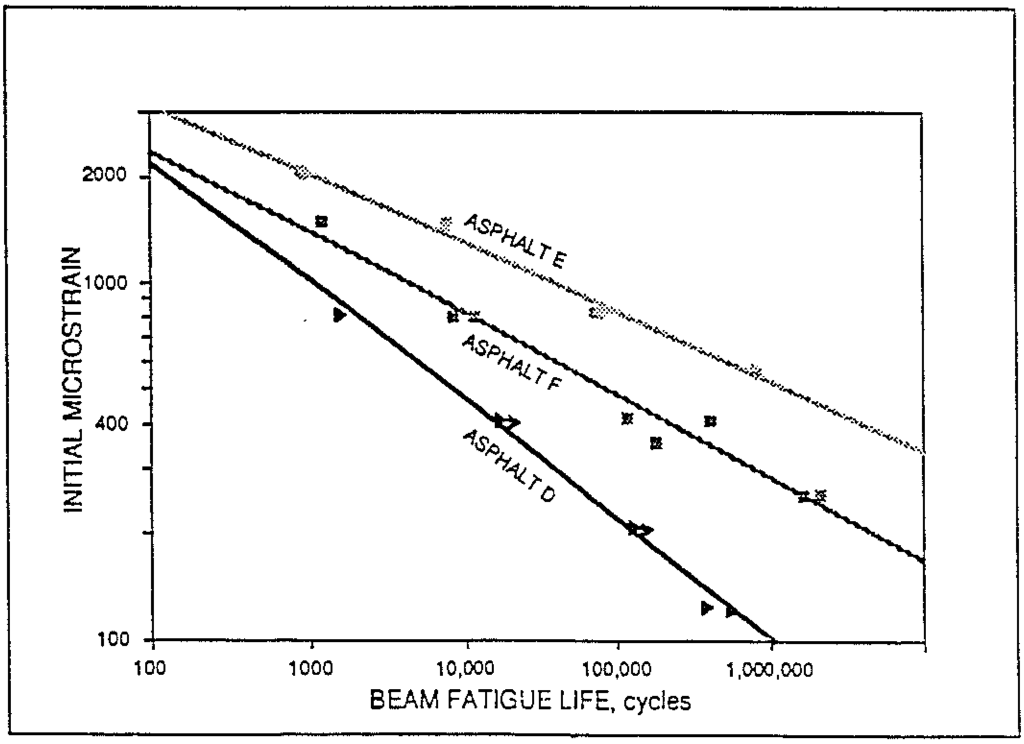


Figure 7. Fatigue response of mixes using three bitumens modified by ethylene copolymer (from Goodrich 1988).



12. RECOMMENDATIONS

In consequence of the findings, the project did not enter the proposed further phase to compare typical fatigue characteristics of modified mixes with standard mixes in pavement design analysis.

It is suggested that further useful information could be obtained from a programme of fatigue testing using selected additives, performed under the test conditions listed in Section 11 of this report.

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