Crumb Rubber
Asphalt Fatigue Study
Phase 2: Asphalt Testing

November 1997

Prepared By:
ARRB Transport Research

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Contract Report

Crumb Rubber Asphalt Fatigue Study
Phase 2: Asphalt Testing

by *John Oliver*

for EcoRecyle Victoria
AUSTROADS
Environment Protection Authority New South Wales

November 1997
CR IC6496C

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Environment Protection Authority New South Wales

	Reviewed
Project Leader	
Quality Manager	

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Executive Summary

Introduction and Aims

The main aims of the study were to obtain data on the properties of crumb rubber binders and on the fatigue properties of crumb rubber asphalts. The data developed would assist in the development of specifications for crumb rubber binders, and help rubber binder manufacturers to produce binders with specific properties.

The overall crumb rubber asphalt fatigue project can be split into two components:

1. characterisation of crumb rubbers and rubber bitumen binders and
2. measurement of the fatigue properties of crumb rubber asphalts.

The first part of the program has been completed and the results published. This report deals with the second phase of the project: measurement of the fatigue properties of asphalt specimens made with crumb rubber binders.

Overview

A work plan was developed to obtain information on the following factors:

- performance of low binder content rubberised asphalts since an initial study using 6% binder content had produced unsatisfactory results,
- the effect of binder type (various rubber crumbs and preblended binders are available commercially) on fatigue,
- the effect of asphalt binder content on fatigue life,
- the effect of addition of oil to the binder,
- the effect of strain level in the fatigue test on fatigue life, and
- dry mixing compared to “wet” binder addition (where the rubber and bitumen are pre-digested before being mixed with the aggregate).

New batches of binders used in the Phase 1 binder study were obtained for the asphalt work and their properties were slightly different. These asphalt binders were therefore tested using a dynamic shear rheometer and an Extensiometer so that binder properties could be correlated with asphalt fatigue resistance.

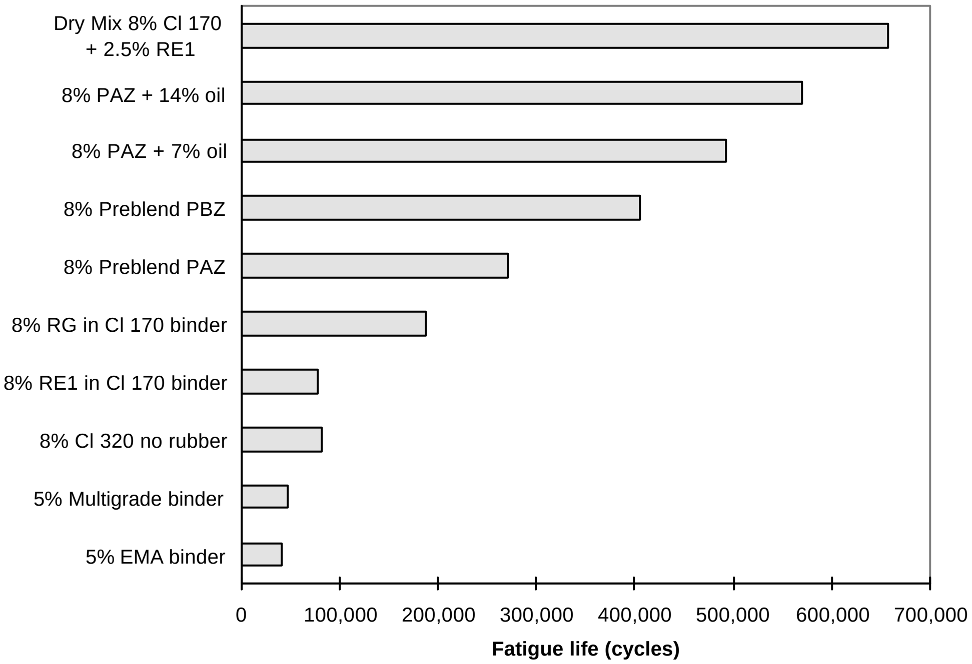
Materials and Testing

Two commercially manufactured preblended rubber binders were used and two binders were manufactured in the ARRB TR laboratory using rubber crumb and Cl 170 bitumen. One of the preblends was modified by the addition of oil.

Most asphalt samples were manufactured with 8% binder and the same aggregate composition. Fatigue testing of triplicate beams cut from each slab was carried out at 20°C and a strain level of $600\mu\varepsilon$.

Results

The fatigue performance of the different binders is summarised in the figure below. The results show that the dry mixed asphalt was superior to the wet mix formulations and that addition of oil resulted in an increase in fatigue life.



A synthetic polymer modified binder (PMB) asphalt (EMA) and a Multigrade binder, tested under identical conditions, are also shown on the graph. They had poorer fatigue performance than the rubberised asphalts probably because of their lower binder contents.

As expected, increase in strain level resulted in reduction in fatigue life for the rubberised asphalt tested. The slope of the strain/fatigue life was determined for this material.

Binder content was also found to have a major effect on fatigue performance, with increase in binder content leading to increase in fatigue life.

Relationships Between Fatigue Life and Binder Parameters

Four binder parameters were studied to determine if they correlated with asphalt fatigue life. The parameters were:

- G*.sin δ measured using a dynamic shear rheometer. This parameter is used in the new U.S Performance Graded (PG) specification to indicate the fatigue resistance of a binder.
- angular recovery using a dynamic shear rheometer. This is the analogue of Elastic Recovery currently used in PMB specifications.
- toughness (the area under the force/deformation curve) measured using an ARRB TR Extensiometer, and
- Peak Force also measured using the Extensiometer.

Both G*.sin δ and Peak Force correlated well with asphalt fatigue resistance. While Toughness at 50 mm deformation appeared to be a good predictor for the rubberised materials, this was not the case for the unmodified Cl 320 bitumen.

Conclusions

It should be noted that the bulk of the fatigue performance data was obtained using wet mixed asphalts. The correlations between binder properties and fatigue performance apply only to binders used in the wet mix process.

1. Low binder content (6% or less) crumb rubber asphalts had short fatigue lives and there was a very high variability between nominally identical samples. This was attributed to excessive "dryness" in the mixes.
2. The dry mixed asphalt (where rubber crumb was added to the aggregate rather than being first digested in bitumen) had a longer fatigue life than any of the wet mixes.
3. Limited data suggested that the fatigue life of crumb rubber asphalts increases by about 70 kcycles for every 1% increase in binder content (for binder contents of 6% or more).
4. Addition of oil resulted in increased fatigue life.
5. Higher strain levels resulted in reduced fatigue life. For the rubberised asphalt tested, the exponent in the fatigue equation was 3.9.
6. The crumbed rubber asphalts (with 8% binder) had considerably longer fatigue lives than an EMA and a Multigrade mix (both with 5% binder) tested under the same conditions. However, a premium grade SBS would be expected to have a much greater fatigue life than the crumb rubber asphalts.
7. $G^*.\sin\delta$ was a good predictor of fatigue life for the rubberised asphalts (R^2 of 0.947) but the (unmodified) Class 320 bitumen did not follow the crumb rubber relationship.
8. There was some evidence that increase in angular recovery correlated with increase in fatigue life but that a different relationship applied if oil was present.
9. Peak Force determined using the Extensiometer correlated well with fatigue life. The relationship for rubberised asphalts also applied to a Cl 320 bitumen (R^2 of 0.954).

Recommendations

1. Dry mixed rubber asphalt should be included in an Accelerated Loading Facility (ALF) fatigue trial, provided the fatigue result obtained in this study is substantiated.
2. Further work should be carried out on dry mixed rubber asphalts to determine the effect of rubber and binder content and rubber particle size, and to ascertain the reason for the increased fatigue life.
3. Initial Peak Force, as measured using the Extensiometer at 4°C, should be used in crumb rubber binder specifications where improved asphalt fatigue resistance is required.
4. Wet mixed crumb rubber asphalts containing 6% or less binder should not be used in situations requiring good fatigue resistance unless laboratory testing of a particular composition indicates otherwise.
5. Where improved fatigue resistance is required, oil addition should be considered, provided it does not prejudice other properties of the mix.

Contents

1. Introduction

1.1 This Report

The work program to investigate the fatigue properties of crumb rubber asphalts can be split into two phases:

1. characterisation of crumb rubbers and rubber bitumen binders, and
2. measurement of the fatigue properties of crumb rubber asphalts.

The first part of the program has been completed and the results published. This report deals with the second phase of the project: measurement of the fatigue properties of asphalt specimens made with crumb rubber binders.

An interim report (Oliver 1997a) was published which covered work performed under the original second phase plan which focused on fatigue testing mixes containing 6% binder. Such mixes were found to have poor fatigue performance, and a revised work plan was developed which concentrated on mixes with a higher percentage of binder. This report describes the work done under the revised plan, and briefly summarises the earlier study and the binder investigation.

1.2 Summary of Findings from Phase 1

The first phase of the project (Oliver 1997b) looked at commercially available preblends of crumb rubber and bitumen, and blends of rubber with bitumen manufactured in the ARRB TR laboratory. The properties of the blends were examined using a dynamic shear rheometer and an Extensiometer.

It was considered that good fatigue resistance in asphalt would be indicated by binders which had:

- a low value of G*.sin delta (a parameter determined using dynamic shear rheometry),
- a high value of angular recovery (determined using the dynamic shear rheometer),
- a high value of toughness (as measured on the Extensiometer), and
- small change in modulus (and phase angle) with temperature (low temperature susceptibility as determined using the dynamic shear rheometer).

Using these indicators, a number of binders were selected which were considered to cover the range of poor to good fatigue resistance. The strategy, of including binders with a wide range of performance in the Phase 2 asphalt work, was adopted to assist in developing correlations between binder properties and asphalt fatigue resistance.

1.3 Summary of Original Work Plan Findings

Asphalt slabs were manufactured with scrap rubber binders at a concentration of 6% binder by mass of the mix. Although a number of samples were tested (Oliver 1997a), the key findings are best illustrated by considering the following three binders which had been identified as promising in the Phase 1 study (note “Z” indicates a new batch of binder with similar but possibly not identical properties to the corresponding batch tested in the binder study):

- PAZ - a new batch of the commercially manufactured preblend PA
- RE1Z - a 15% blend of rubber RE1 manufactured in bulk in the ARRB TR laboratory, and

- RGZ - a 15% blend of rubber RG manufactured in bulk in the ARRB TR laboratory

The results are compared in Fig. 1 with a mix containing 5% of unmodified Cl 320 bitumen. Such a mix would be expected to have poorer fatigue properties than modified binder mixes with 6% binder.

In a pavement, fatigue life will depend on the amount of deflection (strain level) of the asphalt layer under traffic. It is useful, therefore, to plot fatigue results on a graph which shows how life is affected by strain level. This graph is shown in Fig. 1 and uses logarithmic scales on both axes.

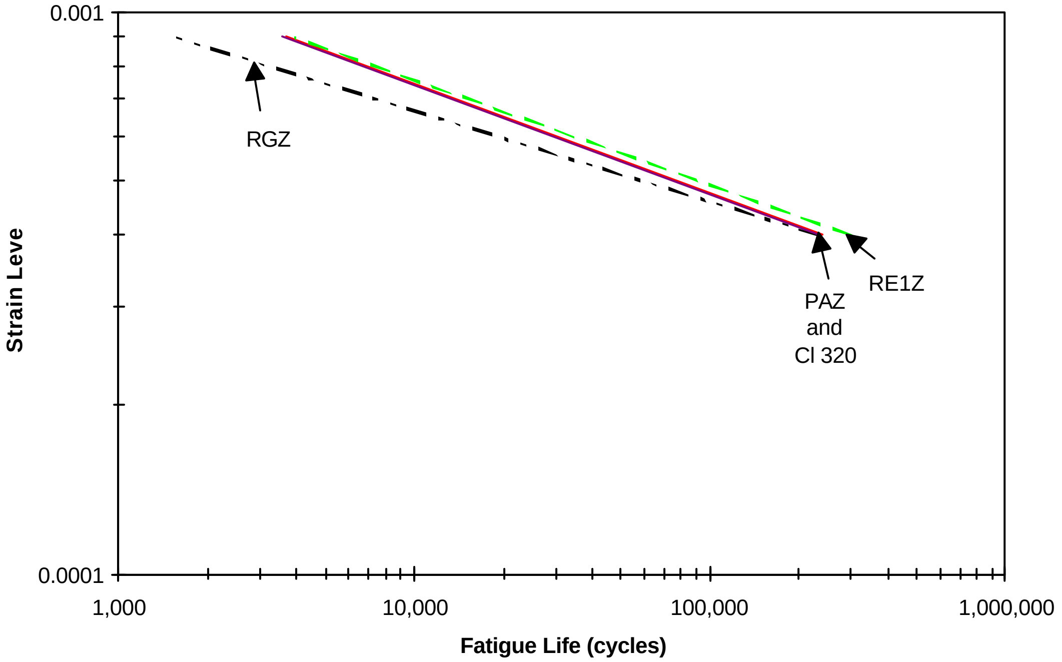


Fig. 1 Initial peak to peak strain versus number of cycles to fatigue failure for crumb rubber mixes with 6% binder and a Cl 320 mix with 5% bitumen

The plots indicate that the scrap rubber mixes had a fatigue performance similar to that of the unmodified Cl 320 bitumen. This was unexpected since the binder testing program (Oliver 1997b) and field experience suggested that rubber modification of the binders should improve the fatigue life of asphalt mixes.

Analysis of the results indicated that, for slabs made with the rubber modified binders, the variation in fatigue life between triplicate beams from the one slab was much greater than expected. Fatigue results for asphalt samples made with the PAZ binder are compared with those for a Class 320 bitumen in Table I.

Table I

Fatigue Results for Mixes with a Rubber Modified and a Bitumen Binder

Strain Level (me)	Fatigue Life (cycles)	
	PAZ Asphalt	Cl 320 Asphalt
800	9,690	10,000
	3,390	6,900
	19,170	5,305
600	19,730	15,060
	71,260	23,490
	5,730	31,630
400	353,700	196,640
	82,060	289,090
	799,210	173,430

The variation between triplicates can be expressed numerically by calculating the coefficient of variation. The coefficient of variation is the standard deviation of a group of samples divided by their mean and expressed as a percentage. A comparison between the class 320 bitumen asphalt and the asphalt made with binder PAZ is shown in Table II.

Table II

Coefficient of Variation of Fatigue Lives of Triplicates

Strain Level (me)	PAZ Asphalt (%)	Class 320 Asphalt (%)
800	74	32
600	87	35
400	108	27

The coefficient of variation of the crumb rubber samples was much larger than the Class 320 bitumen samples. The variation in Class 320 results is considered typical of both straight bitumen and PMB modified asphalts. It is clear, therefore, that the variation between nominally identical triplicate beams made with binder PAZ is unusually high.

The asphalt beams made with binder PAZ were examined to determine a possible cause for the high variation between results, and it was observed that the asphalt appeared drier than normal. It was also noted that the PAZ rubber asphalt samples had tended to crumble or ravel at the edges during cutting, indicating either a lack of binder in the mix or insufficient cohesion in the binder.

The observed “dryness” could be due to a number of factors:

- insufficient binder in the mix (although the binder content was high at 6.0%, this was equivalent to only 4.7% bitumen),

- absorption by the rubber particles of oil from the bitumen,
- poor coating of aggregate particles and/or inhomogeneity in the mix due to the high viscosity of the binder during the aggregate/binder mixing process, and
- the presence of rubber particles requiring binder to coat them, thus reducing the binder available to coat aggregate particles.

The “dryness” or low binder content might also be responsible for the poorer than expected fatigue results for the rubber modified binders. It was decided, therefore, to carry out a further program of work concentrating on asphalt samples with a higher binder content.

2. Revised Work Plan Overview

The revised work plan required the bulk of the samples to be tested at a single strain level (600 με) and one binder content (8%). Mixes were to include samples made with the following binders (see Table III for a description of the binders):

To indicate the effect of binder type on fatigue resistance

- Binder PAZ
- Binder PBZ
- Rubber RE1 digested in Cl 170 bitumen
- Rubber RG digested in Cl 170 bitumen

To determine the effect of oil addition on fatigue

- Binder PAZ modified with 7% aromatic oil
- Binder PAZ modified with 14% aromatic oil

To indicate the change in fatigue properties with use of rubberised binders

- Control sample - Cl 320 bitumen with the same aggregate composition as the above mixes

To determine the effect of strain level on fatigue life

- Binder PAZ at 400 με
- Binder PAZ at 800 με (in addition to PAZ at 600 με tested under point 1 above)

To determine the effect of asphalt binder content on fatigue

- Binder PAZ at a concentration of 10% binder
- Binder RE1Z at a concentration of 10% binder (in addition to samples at 8% and 6% binder already tested)

To determine the effect of Dry Mixing

- Mix manufactured with 8% Cl 170 bitumen and 2.5% (by mass of binder) of dry rubber RE1. This mix would be similar in composition to dry rubber mixes laid in successful road trials in New South Wales and Victoria.

3. Materials

3.1 Binders

Two types of rubberised binders were used. The first of these were preblends supplied by commercial manufacturers. Since much larger quantities were required for asphalt testing than for binder testing in the Phase 1 study, new batches were obtained from the manufacturers. These had similar but not identical properties to the Phase 1 binders (Oliver 1997b) and the binder tests were repeated on these new batches. In order to distinguish the Phase 1 and Phase 2 batches, the latter are distinguished by a Z in the binder code.

The second group of binders was those mixed from constituent materials in the ARRB TR laboratory. To make the larger quantities of binder required in Phase 2, the following procedure was used.

A 20 L drum of Class 170 bitumen was heated overnight at 190°C. The drum was then placed in a special oven set at a temperature of 185°C. This oven had been modified to permit a stirrer to be inserted into the drum of bitumen. Stirring was commenced, and the selected rubber crumb added slowly over about a 15 minute period. Where oil was to be included in the blend, this was added prior to addition of the rubber crumb. The stirring speed was adjusted to achieve good mixing and the digestion was monitored every half hour. The stirring speed was adjusted as necessary to obtain good dispersion.

After 3.5 h, mixing was stopped, the drum removed from the oven and the contents decanted into 2 L containers for use in asphalt manufacture.

Table III

Binders Used in the Study

Description	Code
Preblend PAZ	PAZ
Preblend PBZ	PBZ
15% Rubber RE1 digested in Cl 170 bitumen	RE1Z
15% Rubber RG digested in Cl 170 bitumen	RGZ
Preblend PA with 7% oil	PAZ7
Preblend PA with 14 % oil	PAZ14
Class 320 bitumen	Cl 320

3.2 Asphalt Grading

To obtain a mix which could accommodate 6% binder, a series of mixes of different aggregate composition was manufactured using a gyratory compactor. Class 320 binder was used to make the specimens according to the procedure described in the Australian Provisional Mix Design Guide (APRG 1997).

The grading given in Table IV, which produced approximately 5% air voids at 120 gyratory cycles (the compaction level used for heavy and very heavy traffic), was selected.

Table IV

Mix Grading for 6% Binder Mixes

Sieve Size (mm)	Per Cent Passing
19	100
13.2	97
9.5	76
6.7	60
4.75	44
2.36	29
1.2	23
0.6	19
0.3	15
0.15	8
0.075	5.7

The proportions of the different aggregate fractions used are given in Table V.

Table V

Mix Composition for 6% Binder Mixes

Aggregate Fraction	Per Cent by Mass of Total Aggregate
14 mm Montrose	29.6
10 mm Montrose	10.0
7 mm Montrose	33.0
5 mm minus Montrose	12.5
Fine natural sand	10.2
Filler ARC CWFD	4.7
Binder (% by mass of total mix)	6.0

In the case of the dry mix, and the 8% and 10% binder wet mixes, the composition was changed to that given in Table VI. The intention was that the 10% binder content wet mix and the 8% bitumen with 2.5% rubber dry mix could be directly compared since their aggregate composition was the same.

Table VI

Mix Grading for 8 and 10% Binder Mixes

Sieve Size (mm)	Per Cent Passing
19	100
13.2	97
9.5	71
6.7	43
4.75	29
2.36	19
1.2	14
0.6	11
0.3	8
0.15	4
0.075	2.7

The proportions of the different aggregate fractions used for the dry mix and the 8 and 10% binder content wet mixes are given in Table VII.

Table VII

Mix Composition for 8 and 10% Binder Mixes

Aggregate Fraction	Per Cent by Mass of Total Aggregate
14 mm Montrose	35.0
10 mm Montrose	27.4
7 mm Montrose	19.3
5 mm minus Montrose	12.1
Fine natural sand	5.2
Filler (Lime)	1.0
Binder (% by mass of total mix)	8 or 10

3.3 Asphalt Manufacture and Testing

Slabs of asphalt 75 mm thick were manufactured according to the procedure described in the Australian Provisional Mix Design Guide (APRG 1997). Compaction was carried out in a heated mould using a footpath roller. Difficulties were experienced in obtaining the design air void content and there was a suspicion that the samples were dilating (expanding) after compaction and while still at an elevated temperature. Slabs manufactured at a later stage in the program were surcharged immediately after compaction and then removed from the mould when they had cooled.

In the case of the dry rubber mix, a similar procedure was followed except that the dry rubber crumb was added to the dry aggregate in the mixer and mixing carried out for 15 s before the Cl 170 binder was added. The material was then mixed for 3 minutes before being conditioned and compacted using the normal procedure.

The asphalt slabs were sawn into beams 400 x 50 x 63.5 mm in size. The beams were tested in a MATTA fatigue device at 20°C using continuous haversine loading at 10 Hz under controlled strain conditions. Samples were tested in triplicate. Failure was determined as the number of cycles for the flexural stiffness to fall to 50% of its initial level.

4. Results

4.1 Binder Testing

New batches of the binders tested during Phase 1 of the study were obtained for the manufacture of asphalt samples, and these binders might have different properties to the originals. The new materials were, therefore, tested and the results are given in Table VIII.

Table VIII

Binder Properties

Code	G*.sind (kPa)	T 250 (Nm)	T 50 (Nm)	Peak Force (N)	Displace. at PF (mm)	Angular Recovery (%)
PAZ	2430	11.93	3.14	77.17	4.06	56.9
PBZ	1423	6.02	2.55	59.53	7.4	33.6
RE1Z	2870	9.7	3.6	91.2	4.1	43.4
RGZ	2766	11.1	3.1	79.9	3.9	51.9
PAZ7	1373	9.3	1.9	44.1	5.3	43.0
PAZ14	723	6.7	1.1	23.4	7.6	58.4
Cl 320	5297	0.3	0.3	101.5	1.8	-

G*.sin δ is identified in the dissipated energy approach to fatigue as a likely indicator of fatigue resistance (G* is the modulus of the binder under the test conditions and δ is the phase angle). This parameter has been adopted for use in the U.S. Performance Graded (PG) binder specification. Since laboratory fatigue testing of asphalt is commonly performed in Australia at 20°C and a loading rate of 10 Hz, G*.sin delta was calculated under these conditions.

T 250 and T 50 refer to Toughness at 50 mm and 250 mm displacement in the Extensiometer. In the Extensiometer, specimens with a square cross section of 9 x 9 mm and a length of 25 mm are subjected to an elongation of 250 mm at a strain rate of 0.7 mm/s at 4°C, during which the force exerted on the specimen and its elongation are continually measured.

An example of an Extensiometer trace is shown in Fig. 2. A number of parameters were calculated from the test data, such as the initial peak force (PF), the displacement at which this occurs (displacement at PF) and the areas under the force/displacement curve (Toughness) to a displacement of 50 mm (T 50) and 250 mm (T 250).

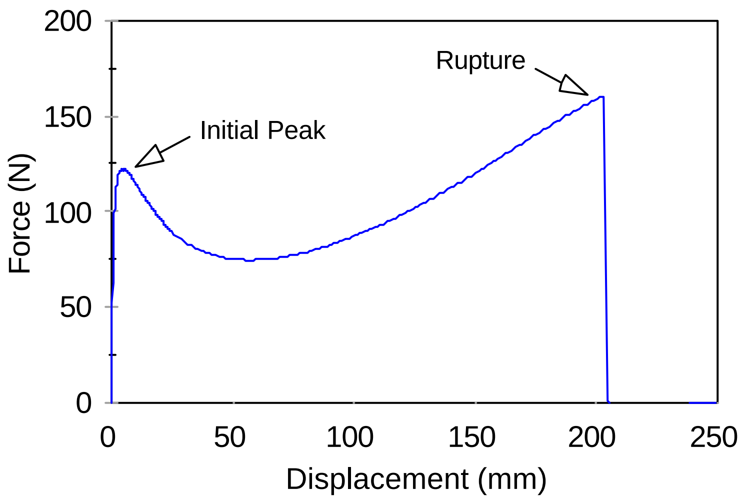


Fig. 2 Typical Extensiometer test result

Angular Recovery was obtained from dynamic shear rheometer data. The sample was displaced 0.2 radians at 60°C over a period of 10 s and the percentage recovery which occurred over the following 100 s determined. Fuller information on binder testing is given in the Phase 1 report (Oliver 1997b).

4.2 Asphalt Fatigue Resistance

The results of testing the asphalt samples are given in Table IX. The air voids, initial flexural stiffness and fatigue life results are the mean of tests on triplicate beams manufactured from the same slab of asphalt. The final column gives the coefficient of variation of fatigue life of each set of triplicates.

Table IX

Asphalt Fatigue Results

Asphalt Sample (binder code)	Strain (με)	Binder Content (%by mass)	Air Voids (%)	Init. Flexural Stiffness (MPa)	Fatigue Life (cycles)	Coeff of Variation (%)
PAZ	600	8	5.5	2,098	271,400	38
PAZ	600	10	6.2	1,780	293,057	24
PAZ	400	8	6.7	2,310	819,067	14
PAZ	800	8	6.3	1,709	52,800	22
PBZ	600	8	5.2	2,154	404,967	20
RE1Z	600	8	6.3	1,986	77,650	9
RE1Z	600	10	4.7	1,968	218,740	25
RGZ	600	8	6.6	1,598	186,667	57
PAZ7	600	8	5.9	1,437	492,700	19
PAZ14	600	8	6.7	972	569,600	33
Cl 320	600	8	6.3	2,070	81,967	57
Dry Mix 8% Cl 170 + 2.5% RE1	600	-	4.3	1,525	657,200	28

5. Discussion on the Fatigue Life of Crumb Rubber Asphalts

5.1 Laboratory Fatigue Testing

The fatigue lives quoted in this report are those obtained using laboratory testing. While laboratory testing does not simulate exactly the loading and environmental conditions in the road, it is the best approach currently available to obtain rapid and reliable results.

Fatigue lives on the road are generally greater than those in the laboratory and one reason for this is believed to be "rest periods" between vehicles which are not simulated in the laboratory test. During these rest periods it is possible that healing of microcracks occurs. Healing may, therefore, be an important binder property but at present there is no simple means of measuring it. It is possible that the high binder content crumb rubber mixes may have better healing properties than the lower binder content synthetic polymer modified binders.

5.2 Performance of Low Binder Content Mixes

The fatigue lives and coefficients of variation given in Table IX are in line with expectations for rubber modified mixes. This suggests that the excessive variation between triplicates observed in the 6% binder mixes (Oliver 1997a) may have been due to the observed "dryness". Binder contents of 6% or lower may be unsuitable for binders containing medium to high proportions of crumb rubber (15 to 25% rubber by mass of binder).

5.3 Fatigue Life Comparison

An overall comparison of fatigue lives is given in Fig. 3 for those samples containing 8% binder which were tested at 600 με.

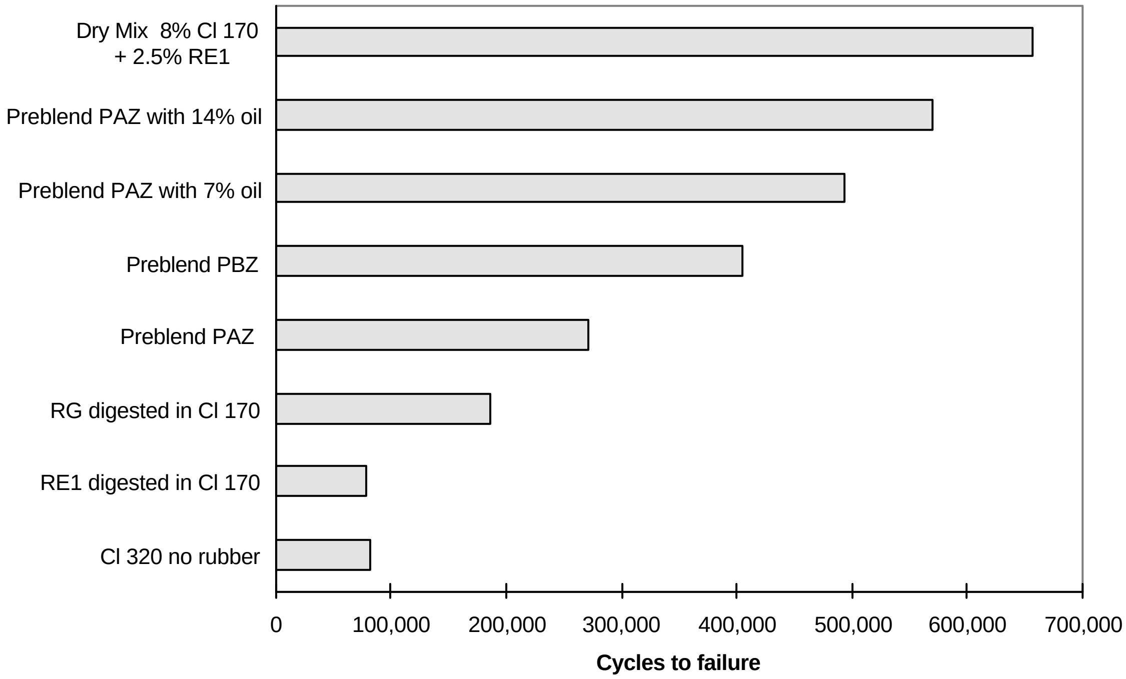


Fig. 3. Fatigue lives of 8% binder content samples tested at 600 me

The results indicate that the dry mix gave the longest fatigue life. This is discussed in more detail in the Section 5.4.

The preblended binders generally had longer fatigue lives than those manufactured in the ARRB TR laboratory. This may be because the preblends contained a higher concentration of rubber than the ARRB TR digestions and because they may have been further modified through oil addition. The effect of oil is considered in Section 5.7.

Compared to a Cl 320 binder, the digestion of rubber RE1 in Cl 170 bitumen did not produce a fatigue life increase. However, use of the other rubberised binders (RG in Cl 170, PAZ and PBZ) resulted in asphalt fatigue lives ranging from two to more than five times the life of the Cl 320 bitumen asphalt.

5.4 Performance of the Dry Mix

The dry mix was manufactured using 8% Cl 170 binder and 2.5% rubber RE1 and the same aggregate composition as the wet 10% mixes. The dry mix could be considered as either (a) a mix with 8% Cl 170 binder with dry rubber, in which case it would be directly comparable to the 8% wet mix or (b) as a mix with 10.5% binder (8% bitumen + 2.5%) rubber in which case it would be comparable to the 10% wet mix. The dry mix is compared with both the 8% and the 10% wet mixes in Fig. 4, and the Cl 320 control is also included.

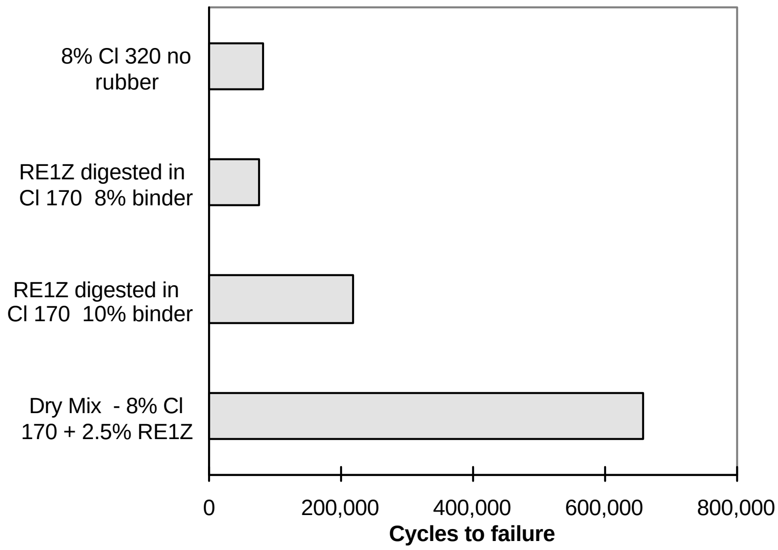


Fig. 4. Fatigue lives of dry and wet mixes compared

The results show that the dry mix has a fatigue life approximately three times that of the 10% wet mix, and eight times that of the 8% wet mix and Cl 320 control. It appears that dry rubber mixed with bitumen has a greater effect on fatigue life than the same rubber bitumen combination which is first digested before being mixed with aggregate. The reason for this difference should be investigated further to determine whether further increases in fatigue life are possible.

5.5 Effect of Binder Content

Asphalt mixes were manufactured with 8% and 10% of binder PAZ and the fatigue lives determined. Testing of a 6% PAZ mix had been carried out earlier (Oliver 1997a) and, although the low binder content results were less reliable, they have been included in Fig. 5. Also included in Fig. 5 are test results for mixes made with binder RE1Z at 8 and 10% binder contents and for mixes made with binder RGZ at 6 and 8% binder contents.

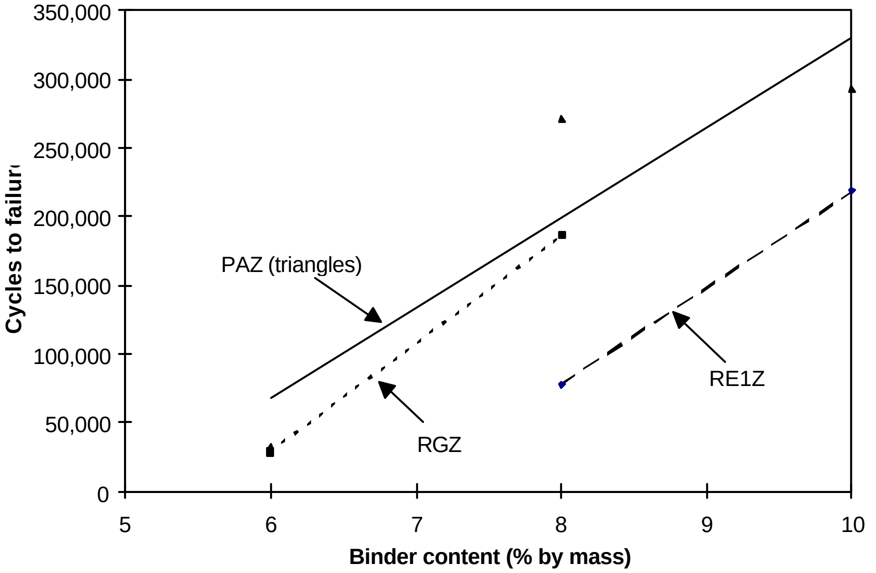


Fig. 5. The effect of binder content on fatigue life

Although there is considerable scatter in the PAZ data, the lines for the three rubberised asphalts are fairly parallel. The data suggests that the fatigue life of crumb rubber asphalts increases by about 70 kcycles with every 1% increase in binder content (for binder contents of 6% or more).

5.6 Effect of Strain Level

Binder PAZ was used to manufacture three asphalt slabs with a binder content of 8% and these were sawn to produce beams which were tested in triplicate at strain levels of 800 $\mu\varepsilon$, 600 $\mu\varepsilon$ and 400 $\mu\varepsilon$. The results are shown in Fig. 6.

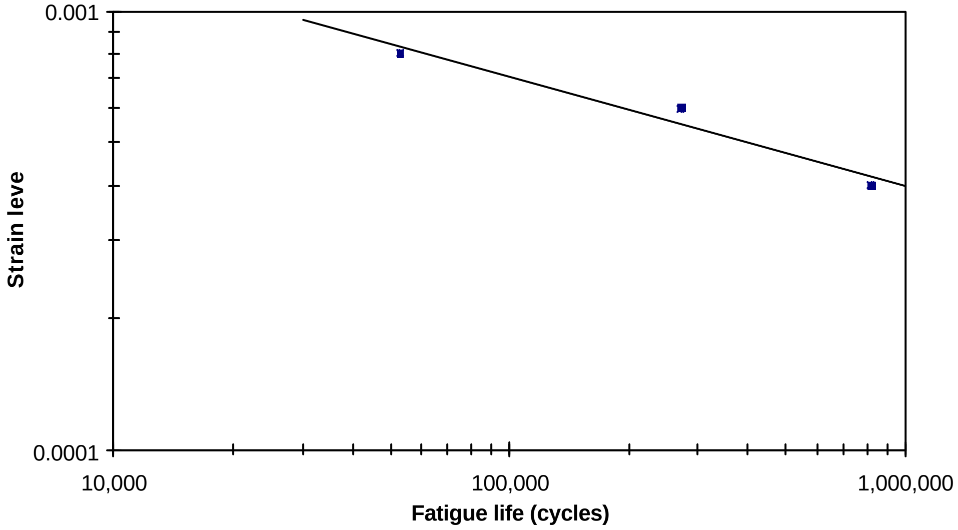


Fig. 6 The effect of strain level on fatigue life

Laboratory fatigue results are commonly interpreted in terms of a relationship between the fatigue life, N_F, and the initial peak strain amplitude ε_0. The relationship is given by the following equation:

$$N_F = K(\varepsilon_0)^{-n}$$

where K and n are a mix dependant constant and exponent respectively. Generally the exponent n has values ranging from 2.5 to 7. For the data shown in Fig. 6, the exponent is 3.9.

5.7 Effect of Oil Addition

The effect of adding an aromatic oil to a binder was determined by blending 7% and 14% of Mobilsol 40 to preblend PAZ. The results of testing asphalts made with the three binders are shown in Fig. 7.

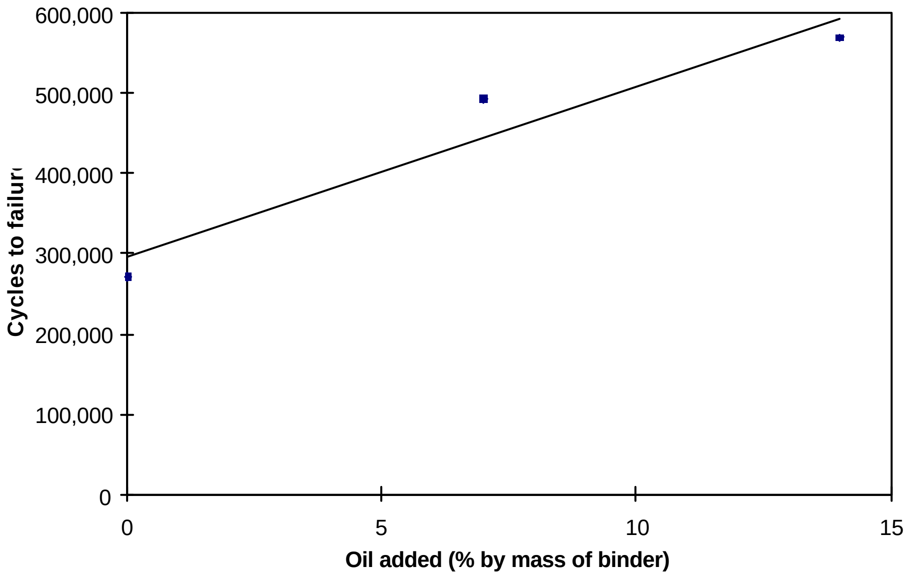


Fig . 7 The effect of oil addition on fatigue life

The addition of oil resulted in a substantial increase in fatigue life and made the binders extremely sticky. While this improved their adhesion to aggregate, it also made them difficult to handle.

Using the limited data in Fig. 7 it may be estimated that there is a 20 kcycle increase in fatigue life for every 1% addition of oil. This figure applies over the range of oil addition 0 to 14% but the data is insufficient to determine whether the increase is linear over the range.

5.8 Comparison with PMBs

A small number of PMB asphalts have been fatigue tested in the ARRB TR laboratory (Babaramani and Hogan 1997a, 1997b; Baburamani 1997). For conditions comparable to the crumb rubber testing (600 με and 20°C), only data for two PMB asphalts (an EMAand a PBD) and an asphalt made with a Multigrade binder was available (Baburamani and Hogan 1997a, 1997b). The binder content of the EMA, PBD and Multigrade mixes was 5%, as against 8% for the crumb rubber. The results are compared in Fig. 8 with those for crumb rubber asphalts.

It can be seen that the higher binder content, crumb rubber mixes have longer fatigue lives than the EMA and Multigrade mixes. The PBD had a fatigue life comparable to that of one of the preblends. However, other PMBs may provide improved performance. A premium grade SBS mix, tested at higher strain levels (800 μεand 900 με) gave excellent results (Baburamani 1997), and it is estimated that this mix would have a fatigue life of around 4 million cycles at 600 με.

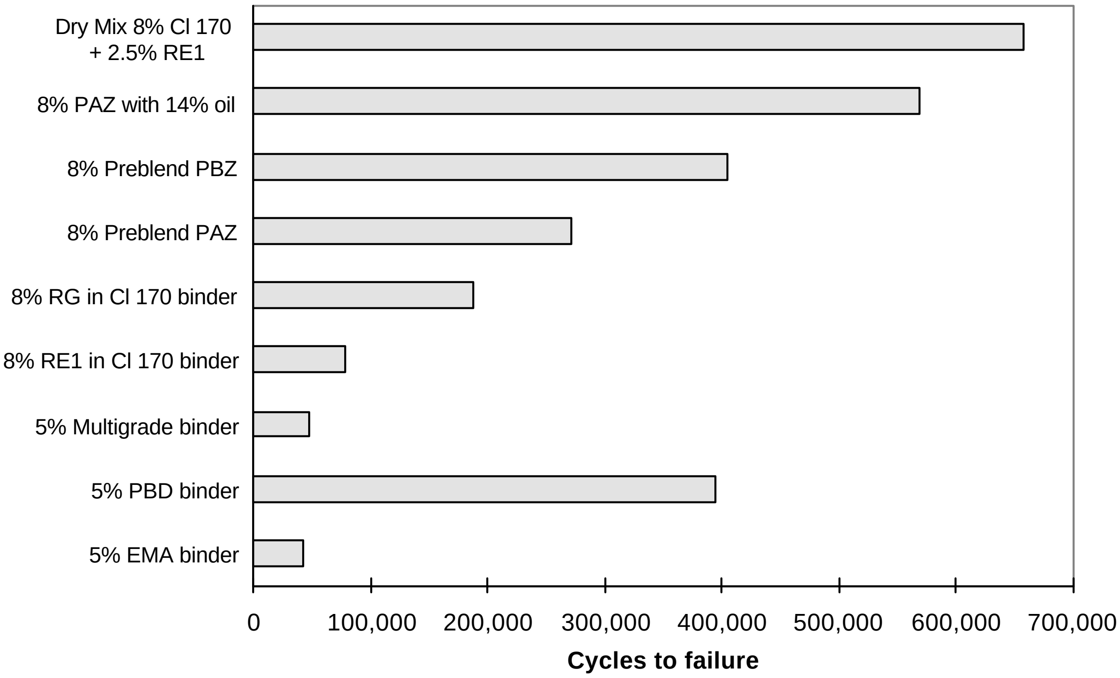


Fig. 8 Fatigue life of asphalts made with crumb rubber, EMA, PBD and Multigrade binders tested at 600 με

6 Relationships Between Fatigue Life and Binder Parameters

6.1 G*.sin δ

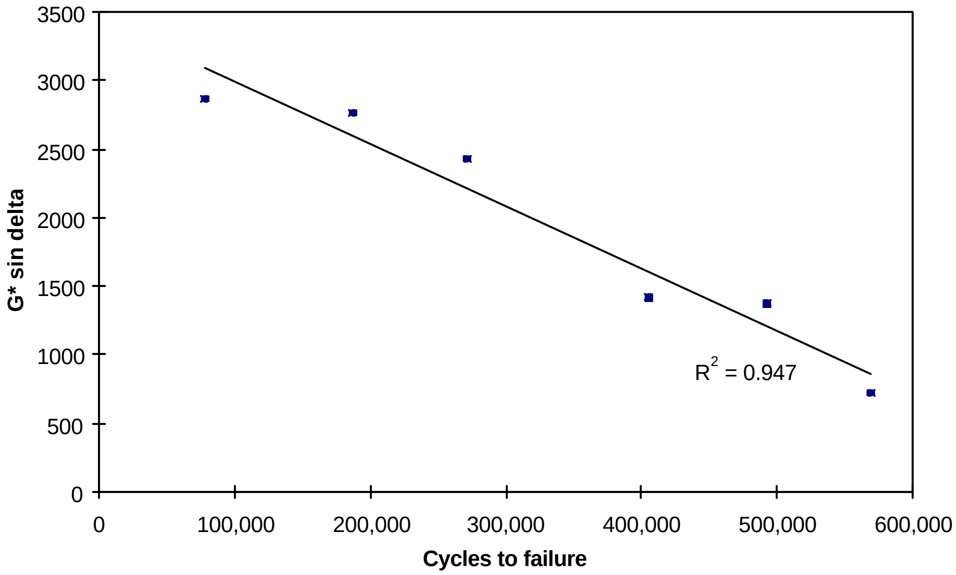


Fig. 9 Correlation between G*.sin δ and fatigue life of crumb rubber asphalts

As indicated earlier, G*.sin δ is used in the U.S Performance Graded (PG) specification to indicate the fatigue resistance of a binder. The fatigue lives of six crumb rubber asphalts are shown in Fig. 9 plotted against the G*.sin δ value of the binder (measured at 20°C and 10 Hz). These asphalts all had the same composition but were manufactured with different binders.

The correlation is good ($R^2 = 0.947$) suggesting that G*.sin δ is a good indicator of fatigue life. However, if the Cl 320 bitumen is included, the correlation coefficient ($R^{2)}$ drops to 0.746 and it is clear that the bitumen asphalt does not conform to the relationship for the crumb rubber asphalts (see Fig. 10).

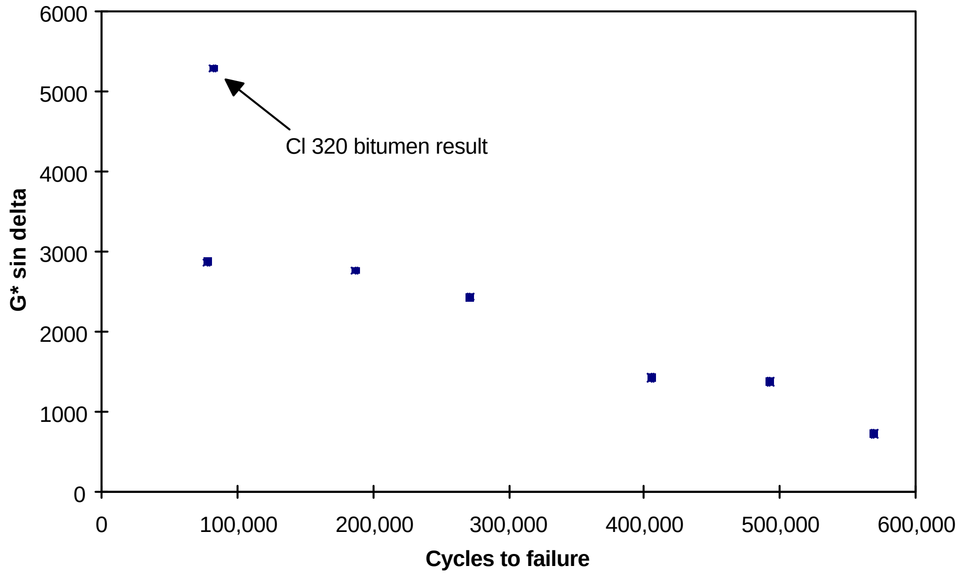


Fig. 10 Correlation between G*.sin d and fatigue life of crumb rubber asphalts with Cl 320 bitumen included

6.2 Angular Recovery

Angular Recovery, measured on a dynamic shear rheometer, is analogous to Elastic Recovery measured on an Elastometer. It was considered likely that materials which exhibit a high degree of elasticity will have longer fatigue lives than those materials with low elasticity.

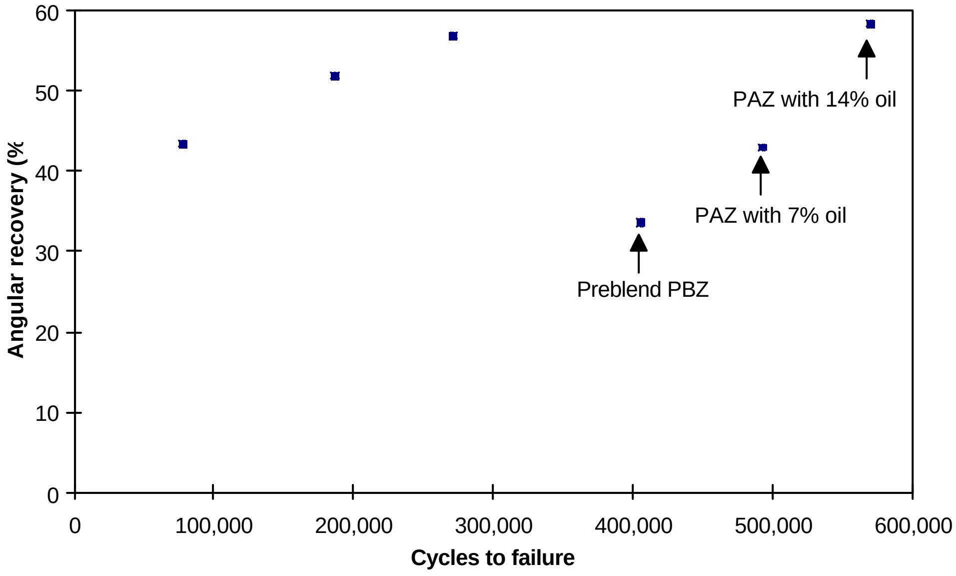


Fig. 11 Correlation between angular recovery and fatigue life of crumb rubber asphalts

A plot of angular recovery against fatigue life is shown in Fig. 11. The data appears to split into two separate groups. The high fatigue life group comprises the two oil modified binders and preblend PBZ. Although no data on the composition of PBZ was supplied by the manufacturer it is considered likely that this blend contains added oil. Within each group fatigue life appears to increase linearly with Angular Recovery.

6.3 Toughness

The Extensiometer has only recently been developed and work still has to be done on interpretation of results. However, it might be expected that the area under the force displacement curve (see Fig. 2), called "toughness", will act as an indicator of the fatigue resistance of a binder.

The toughness parameter most likely to correlate with fatigue life was considered to be T 250. However, the correlation was relatively poor as can be seen in Fig. 12. Furthermore, the line slopes in the opposite direction to that expected. Increased fatigue life would normally be expected to be correlated with increased toughness. The data appears to have split into the same two groups as for angular recovery.

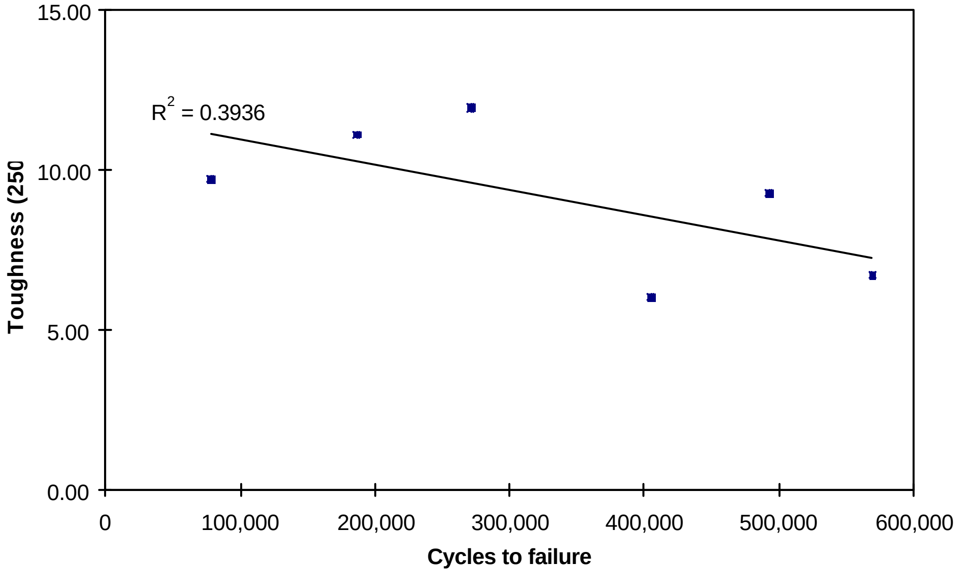


Fig. 12 Correlation between Toughness 250 and fatigue life for crumb rubber asphalts

The toughness correlation improved as the displacement was reduced and the correlation for the initial toughness (T 50) was quite acceptable (R^2 of 0.915) as shown in Fig. 13. An examination of the Extensiometer data suggested that, rather than the area under the force displacement curve being the variable which correlated with fatigue life, it was the level of peak force. This parameter is discussed in Section 6.4.

Inclusion of the result for Cl 320 bitumen in the data set dropped the correlation coefficient to 0.04, clearly indicating that the rubberised binder relationship for initial toughness does not apply to unmodified bitumen.

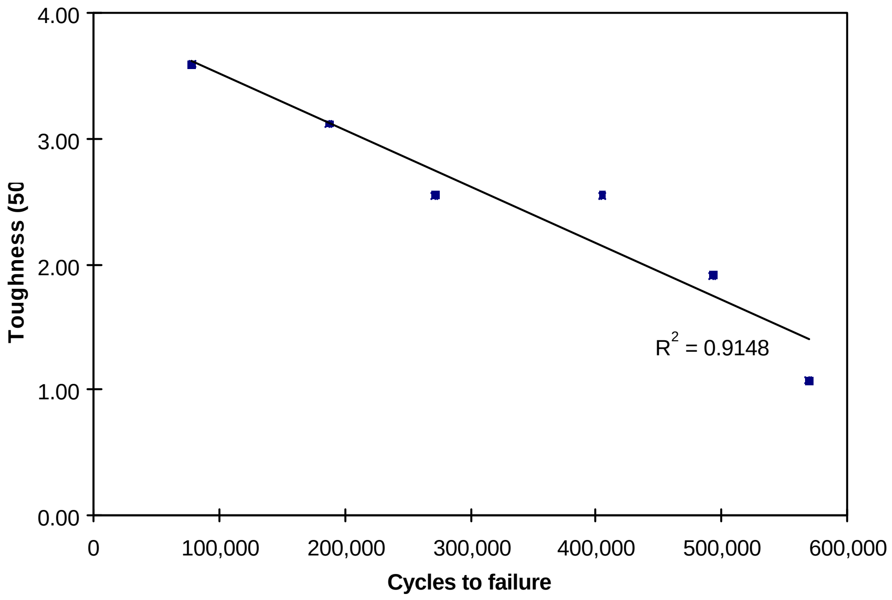


Fig. 13 Correlation between Toughness 50 and fatigue life for crumb rubber asphalts

6.4 Peak Force

The Peak Force reported by the Extensiometer software is the force associated with the initial peak (see Fig. 2). Peak Force is plotted against fatigue life in Fig. 14 for crumb rubber asphalt samples. There appears to be reasonably high degree of correlation between the two variables.

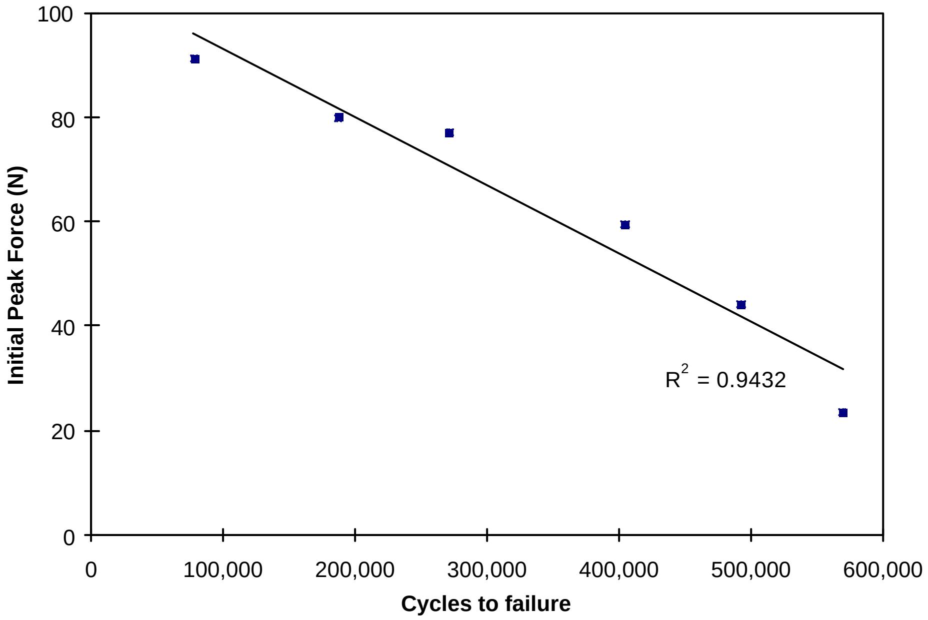


Fig. 14 Correlation between Initial Peak Force and fatigue life for crumb rubber asphalts

Inclusion of the Cl 320 bitumen in the data set improves the correlation as shown in Fig. 15, suggesting that initial Peak Force relationship may also apply to binders with rubber concentrations lower than those tested (the Class 320 bitumen could be regarded as the extreme case of a low content rubber binder, being a rubberised binder with 0% rubber).

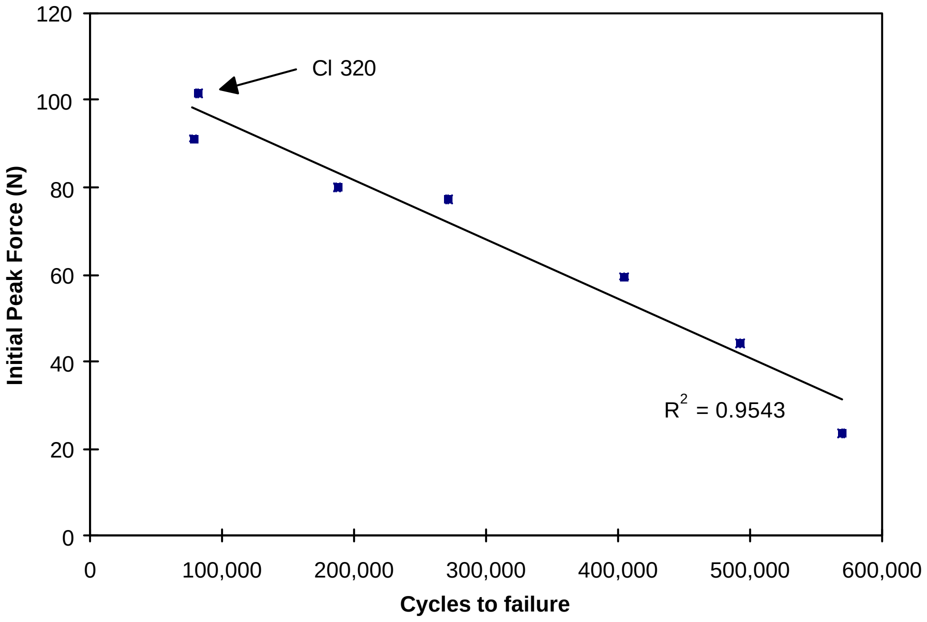


Fig. 15 Correlation between Initial Peak Force and fatigue life for crumb rubber asphalts and Cl 320 bitumen

7. Conclusions

The following conclusions are based on a limited number of materials and there may be risks in generalising them beyond the scope of the data. Where the application of a finding might have important consequences, it is recommended that further testing be carried out with the actual materials to be used.

It should be noted that the bulk of the fatigue performance data was obtained using wet mixed asphalts. The correlations between binder property and fatigue performance apply only to binders used in the wet mix process.

1. Low binder content (6% or less) crumb rubber asphalts had short fatigue lives and there was a very high variability between nominally identical samples. This was attributed to excessive "dryness" in the mixes. Binder contents of 6% or less may be unsuitable where the binder contains medium to high proportions of crumb rubber (15 to 25% rubber by mass of binder).
2. The dry mixed asphalt (where rubber crumb was added to the aggregate rather than being first digested in bitumen) had a longer fatigue life than any of the wet mixes. Its fatigue life was considerably greater than wet mixes made with identical constituents.
3. Limited data suggests that the fatigue life of wet mixed crumb rubber asphalts increases by about 70 kcycles for every 1% increase in binder content (for binder contents of 6% or more).
4. The addition of oil a binder resulted in increased asphalts fatigue life. There was estimated to be a 20 kcycle increase in fatigue life for every 1% (by mass of the binder) addition of oil.

5. Higher strain levels resulted in reduced fatigue life for wet mixed asphalts. For the rubberised asphalt tested, the exponent in the fatigue equation was 3.9.
6. The commercially manufactured, preblended binders generally had longer fatigue lives than those prepared in the ARRB TR laboratory. This may be because the preblends contained a higher concentration of rubber than the ARRB TR digestions and because they may have been modified through oil addition.
7. The crumb rubber asphalts (with 8% binder) had considerably longer fatigue lives than an EMA and a Multigrade mix (both with 5% binder) tested under the same conditions. However, a premium grade SBS with 5% binder would be expected to have a much greater fatigue life than the crumb rubber asphalts.
8. G*.sin δ was a good predictor of fatigue life for the rubberised asphalts ($R^2 = 0.947$) but the (unmodified) Class 320 bitumen did not follow the crumb rubber relationship.
9. There was some evidence that increase in angular recovery correlated with increase in fatigue life but that a different relationship applied if oil was present.
10. Toughness (the area under the force/deformation curve) did not correlate well with fatigue life for 250 mm deformation. For 50 mm deformation there was an acceptable correlation but the correlation did not apply to asphalt made with Cl 320 bitumen.
11. Peak Force determined using the Extensiometer correlated well with fatigue life. The relationship for rubberised asphalts also applied to a Cl 320 bitumen ($R^2 = 0.954$).

8. Recommendations

1. Dry mixed, rubber asphalt should be included in an Accelerated Loading Facility (ALF) fatigue trial, provided the fatigue result obtained in this study is substantiated.
2. Further work should be carried out on dry mixed rubber asphalts to determine the effect of rubber and binder content and rubber particle size, and to ascertain the reason for the increased fatigue life.
3. Initial Peak Force, as measured using the Extensiometer at 4°C, should be used in crumb rubber binder specifications where improved asphalt fatigue resistance is required.
4. Wet mixed crumb rubber asphalts containing 6% or less binder should not be used in situations requiring good fatigue resistance unless laboratory testing of a particular composition indicates otherwise.
5. Where improved fatigue resistance is required, oil addition should be considered, provided it does not prejudice other properties of the mix.

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