TOWARDS PERFORMANCE-RELATED DESIGN CRITERIA AND SPECIFICATIONS FOR MODIFIED BINDERS

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INTRODUCTION

The reflection of primary cracks through overlays and seals on roads is recognized as a serious problem. The ingress of rain-water through these cracks can cause pumping which leads to forms of distress such as potholing and/or deformation. This can, in turn, lead to the premature failure of an otherwise sound pavement.

Asphalt overlays and bituminous seals are often used to rehabilitate both flexible and rigid pavements. However, the reflection of cracks through these treatments will cause a recurrence of the same problems, thus invalidating the expenditure involved. Special or innovative materials such as bitumen-rubber, geofabrics and low-vicosity asphalt have been used in attempts to solve this problem with varying degrees of success (*1*,*2*).

There is currently a lack of performance-related design criteria and specifications for the use of bitumen-rubbers and especially homogeneous modified binders. This is true for surface treatments as well as premix. There was therefore an urgent need to investigate the factors controlling the field performance of these materials and to enhance optimum and most economic use.

Cracks in a pavement can reflect because of thermal as well as wheel load effects or combinations of the two. Extensive investigations have been done regarding crack reflection due to thermal effects on concrete pavements. However, there are relatively few concrete pavements in southern Africa and past problems with strongly cemented bases led to the use of weaker cemented materials. In these materials crack movement due to thermal changes is relatively less severe and consequently this research effort was concentrated on load-associated crack movement.

Research into the crack reflection problem carried out at the Division for Roads and Transport Technology involved:

- the measurement of crack movement in the field;
- fatigue testing of various materials under simulated crack movement, and
- the monitoring of trial sections to determine the field performance of surface treatments with these materials under normal traffic.

The Crack-activity Meter (CAM) (*3*,*4*), was developed to investigate and measure load-associated crack movement in the field. The CAM has been used extensively with the Heavy Vehicle Simulator (HVS) during the accelerated

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The oral presentation was made by Professor Hugo.

testing of various types of pavements (*4*). The measurement and analysis of crack movement and changes in crack movement with pavement deterioration has led to the identification of four typical mechanisms of crack and joint movement under heavy wheel loads (*4*). This information has laid the foundation for more meaningful research into the problems of and possible solutions to crack reflection.

Furthermore, trial sections have been constructed (*5*) in conjunction with the Department of Transport, a consultant and the binder manufacturing industry on a national route (the N3) with relatively heavy traffic (approximately 1200 standard axles per day). Nine different modified binders were applied in surface treatments at varying spray rates. In parallel, a testing program has been started to determine the fatigue characteristics of the above modified binders under simulated crack movement in the laboratory. Initial results from the above work are discussed in this paper.

MEASUREMENT OF LOAD-ASSOCIATED CRACK MOVEMENT

The Crack-activity Meter (CAM), shown in Figure 1, can measure both relative vertical and horizontal crack movement simultaneously. The CAM is used to measure crack movement caused by moving wheel loads. A mobile data acquisition system for the CAM has also been developed and can be used to measure crack movement on any road. Data are recorded continuously as a 40 kN dual wheel load approaches the point of measurement and passes over it. A plot of crack movement versus the distance of the wheel from the measuring point is therefore the influence line of crack movement (*3*).

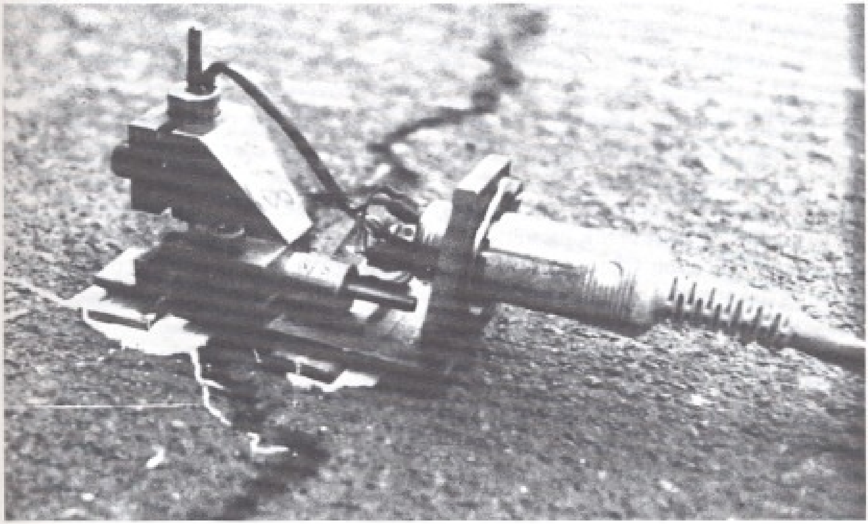

Figure 1. The crack-activity meter

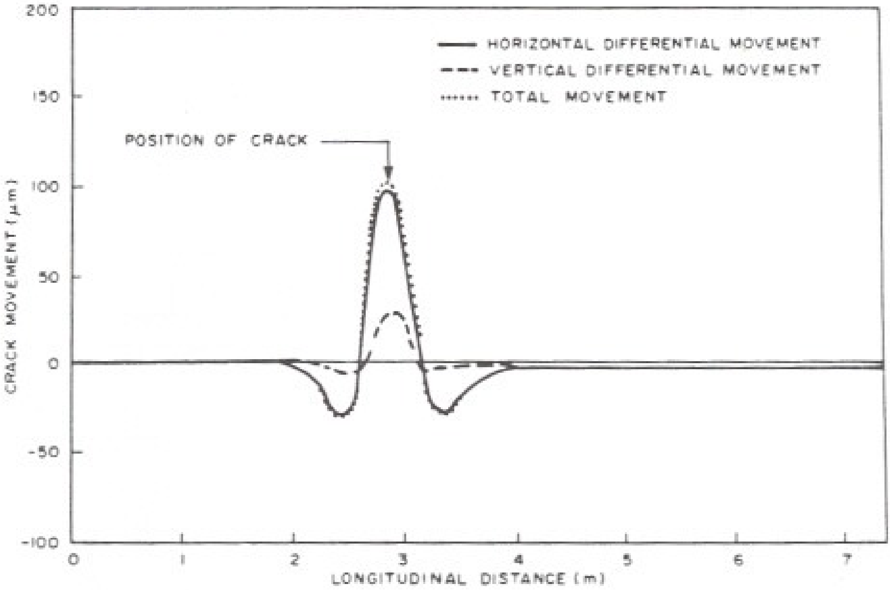

Figure 2. Typical influence of crack movement obtained on the MR27

The CAM can be used to measure crack movements on a pavement at different stages during its structural life. Typical influence lines of crack movement recorded on a cemented base pavement are shown in Figure 2. It is important to note that the horizontal crack movement caused by a moving wheel load was much higher than the vertical crack movement. This phenomenon was found on the majority of sites where crack movement had been measured over the last five years. This high horizontal movement takes place in a part of a second if the wheel moves at normal traffic speed and should be clearly distinguished from the slow horizontal movement due to thermal changes in a 24-hour cycle.

Naturally, the crack movements can change if the factors influencing them change. Changes in crack movement are for example brought about artificially during HVS testing when accelerated trafficking causes changes in parameters such as the shape of the deflection basin or the size of the blocks defined by the cracks. The peak crack movements recorded at various stages of an HVS test can be plotted against trafficking to produce a crack movement behavior curve (Figure 3). The CAM can thus be used in conjunction with the HVS to determine how the crack movement will change as a pavement deteriorates.

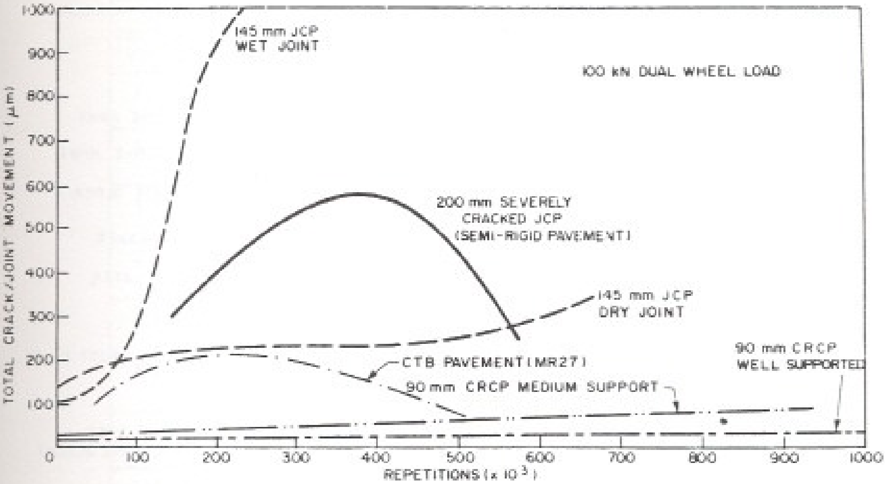

Figure 3. Crack movement behavior curves obtained during HVS testing

FIELD EXPERIMENTS AND FIELD PERFORMANCE

The N3 Trial Sections

The purpose of trial sections mentioned above was to:

- determine the ability of the materials to withstand crack movement in the field under normal traffic, and
- to determine the general relative performance of the materials with respect to factors such as bleeding, loss of chips and durability.

In order to simulate crack movement, 32 concrete blocks (see Figure 4) were built into the road. These blocks were placed on rubber layers of 8 mm and 16 mm thickness to simulate varying degrees of crack movement on each section. In addition the design of the block allowed for a solid concrete toe on the one side to allow only horizontal crack movement. On the other side both horizontal and vertical crack movements were designed to occur. The movement of the joints or "cracks" on each block were measured with the aid of the CAM. The blocks were then covered with an asphalt levelling layer (approximately 25 mm thick) which was designed to be relatively stiff in order to allow the "cracks" to reflect reasonably quickly.

Nine different modified binders were then applied in surface treatments on 14 of the sections (2 blocks per section). One section was left uncovered to determine the rate of crack reflection through the levelling layer, and one section was covered with a conventional binder. Table 1 gives a summary of the material and spray rate used in each section. Table 2 gives the relative crack movements measured (vertically and horizontally). It was intended that the two

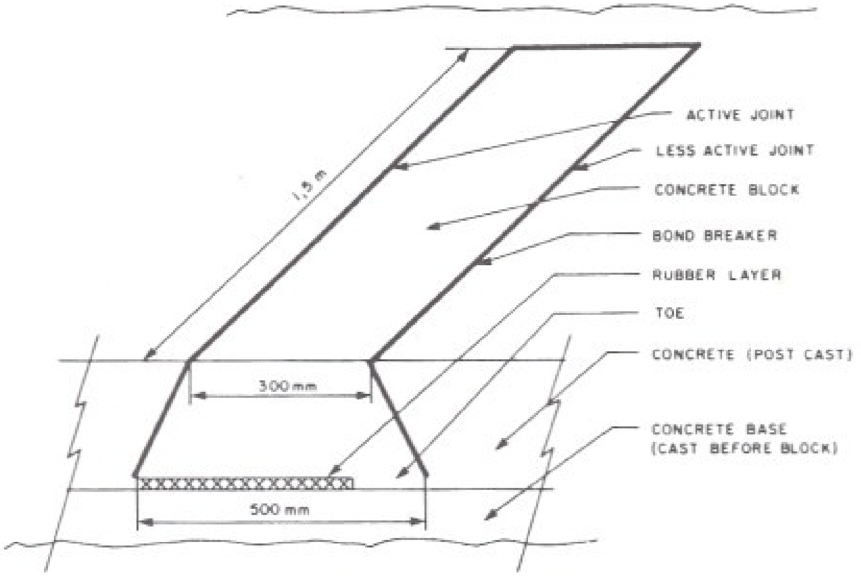

Figure 4. Concrete blocks used in N3 trials

types of blocks used should result in similar crack movements on each section i.e. that block one should have similar crack movements to block three and block two similar crack movements to block four. The results in Table 2 show that some variation occurred during construction. However, the crack movements were measured accurately with the CAM and the variation will be taken into account during the final analysis of the data when the relative performance of the materials is assessed.

Current State of the N3 Experiment

Observations of the N3 experiment have shown that on the section with the uncovered blocks the cracks have reflected through the levelling layer at block 32 (high crack movement) after about six months. After approximately one year the cracks have also reflected through one of the sections which was treated with a PVC tar (block 6 in Tables 1 and 2). However, it should be noted from Table 2 that this section had the highest crack movement. Rational assessment of the relative performance of these materials will only be possible when more results become available, and the relative crack movements on each section will then be taken into account. The other sections are still intact after 2.5 years.

Field Performance of Surface Treatments

The performance of a bitumen-rubber surface treatment under normal traffic was also monitored on a road with a cement-treated base located near Cape

SEC-TION	BLOCK NO.	PRODUCT	APPLICATION RATE (ℓ/m^2)			TEMPERATURE
			ACTUAL	MEAN	TARGET	°C
1	1 2	BR-1	1,64 2,15	1,90	1,8	180
2	3 6		2,39 2,37	2,38	2,4	
3	5 6	MOD1	1,20 1,30	1,25	1,8	110
4	7 8	BR-2	2,24 2,37	2,30	2,7	200
5	9 10		1,89 1,95	1,92	2,1	
6	11 12	MOD4	1,08 1,07	1,08	1,75	175
7	13 14	80/100 pen bitumen	1,14 1,03	1,08		
8	15 16	BR-3	1,80 1,86	1,83	2,2	175
9	17 18		2,49 2,42	2,46		
10	19 20	MOD2	1,20 1,06	1,13	1,8	160
11	21 22	Tar/bitumen/rubber	2,19 1,98	2,08	2,7	194
12	23 24		1,57 1,72	1,64	2,1	
13	25 26	MOD3	1,15 1,14	1,14	1,8	175
14	27 28	Tar-rubber	2,14 2,05	2,10	1,8	195
15	29 30	Uncovered				
16	31 32					

Table 1. Binder application rates - N3 Trials

Town. Typical single cracks where the crack movement was in the order of 170 μm had not reflected through the surface treatment after approximately two years of traffic. However, where the crack movements were in the order of 200 μm to 390 μm the cracks had reflected through (*4*). Other trial sections have been laid but unfortunately the crack movements prior to sealing had not been measured on many of them.

SEC No	BLOCK No	JOINT 1 (ACTIVE)		JOINT 2 (LESS ACTIVE)	
		VERT.	HOR.	VERT.	HOR.
1	1	191.9	128.2	0.8	102.1
	2	376.1	190.2	72.3	152.3
2	3	190.8	191.1	6.0	88.3
	4	817.0	390.5	24.0	370.5
3	5	534.5	260.5	99.0	240.5
	6	946.0	584.5	42.5	445.5
4	7	421.5	248.6	67.0	184.5
	8	837.0	411.0	48.5	395.0
5	9	392.0	209.0	55.0	164.5
	10	271.5	130.5	9.5	133.5
6	11	153.5	95.0	17.0	63.5
	12	465.5	251.0	43.0	214.0
7	13	166.5	107.5	16.5	78.0
	14	374.0	119.0	8.5	186.5
8	15	192.0	117.5	13.0	101.0
	16	482.0	262.5	25.5	237.5
9	17	121.0	54.0	52.0	60.0
	18	343.5	178.0	33.0	165.0
10	19	191.0	106.0	35.5	95.0
	20	471.5	267.5	29.0	222.0
11	21	180.0	107.0	18.0	87.0
	22	332.0	160.5	16.5	150.0
12	23	193.5	96.5	39.0	89.0
	24	284.0	140.5	33.5	129.5
13	25	182.0	104.5	12.0	73.5
	26	290.5	133.0	25.0	121.0
14	27	222.0	124.5	30.0	101.5
	28	244.5	108.0	11.0	106.5
15	29	144.0	78.5	37.5	58.0
	30	213.5	134.5	43.5	103.5
16	31	175.5	95.0	43.5	76.0
	32	323.5	184.5	67.0	147.5

Table 2. Crack movements measured - N3 Trials (μm)

LABORATORY FATIGUE TESTING

The Crack Movement Simulator

The Crack Movement Simulator (CMS) (*4*) was developed to investigate the fatigue characteristics of thin layers of conventional and modified binders under simulated crack movement and controlled conditions in the laboratory. This apparatus consists of a frame onto which the sample is fixed, a cabinet for con-

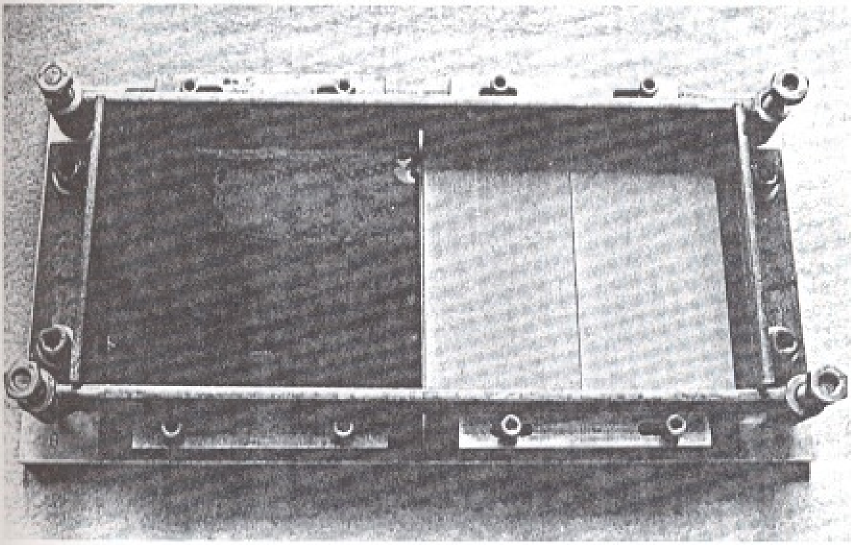

Figure 5. Bitumen-rubber sample prepared in rig

trolling the testing temperature and an LVDT which measures the actual movement applied to the sample. The apparatus is used in conjunction with the INSTRON testing facility which controls the movement and applies the load. The CMS can be used in two configurations to simulate horizontal and vertical crack movement respectively. The samples are prepared by heating the binder to a specified temperature and then spreading it evenly over two plates set up in a rig such as is shown in Figure 5. The two plates are separated by a metal sheet of known thickness to control the simulated crack width. Two bars are fixed onto the two plates to prevent damage to the sample prior to the test. These bars and the metal sheet are removed when the sample is fixed in the CMS.

Figure 6 shows the configuration of the CMS for horizontal crack movement. The plates on which the samples are cast are fixed with epoxy onto two similar, vertically positioned plates. The top plate is kept stationary while the bottom plate is moved repetitively by the ram of the INSTRON facility.

The factors influencing the fatigue life of the sample that were varied in this work were:

- the testing temperature (usually 5 C and 12.5 C but lower temperatures were also used in some cases);
- the magnitude of crack movement, and
- the material tested.

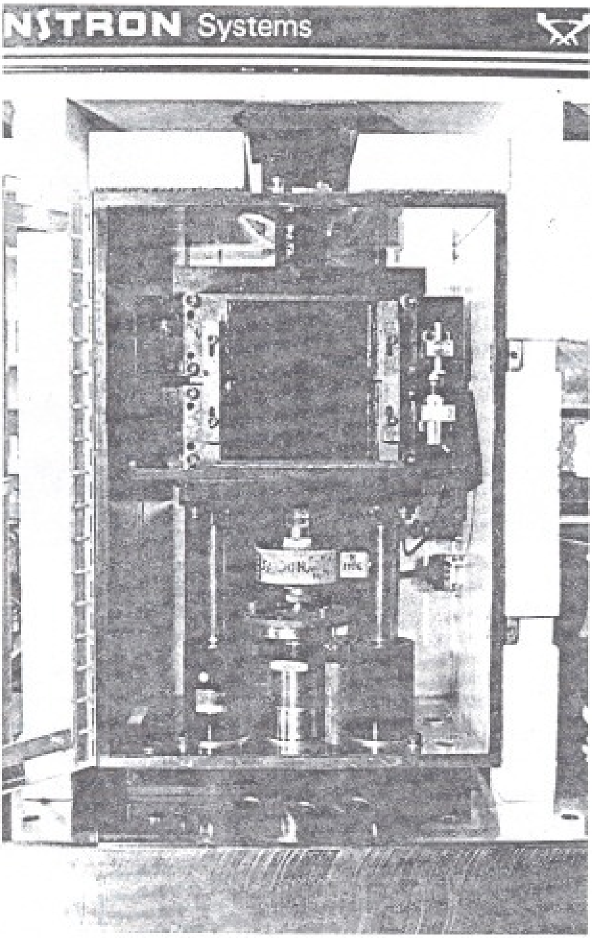

Figure 6. The crack movement simulator – configuration for simulated horizontal movement

Future work will incorporate other variables such as the wave shape of the loading cycle, frequency of loading, thickness of the material etc.

To date eight of the materials used in the N3 trials have been tested in the Crack Movement Simulator. These were a conventional binder, four homogeneous modified binders and three bitumen-rubbers. The samples were subjected to simulated horizontal crack movement with a sine-wave function simulating compression and tension in one cycle at a frequency of 5 Hz. The frequency of 5 Hz was derived from assuming heavy traffic moving at 75 km/h and assuming that the influence sphere of crack movement has a diameter of 4m. Although the diameter of the influence sphere can vary considerably, CAM measurements have shown that diameters of 4 m are not atypical.

During testing of the conventional and modified binders the layer thickness was kept between 2.5 mm and 3.0 mm. However, when the bitumen-rubbers were tested it was found that the material could not be spread in even layers: the thickness generally varied between 2 mm and 3.5 mm. A special technique to monitor the fatigue life of the bitumen-rubber samples at the various thicknesses was developed. Regression analyses were then conducted to determine the equivalent fatigue lives at a 2.5-mm thickness in order for the results to be comparable to those of the other materials tested.

The estimated fatigue life, or repetitions to failure (y) can be represented as below (the constants were determined by multiple non-linear regression analyses):

$$y = (\text{temp})^{n1} \times \text{X1-coefficient} + (\text{movement})^{n2} \times \text{X2-coefficient} + (\text{thickness})^{n3} \times \text{X3-coefficient} + \text{constant}$$

where n1, n2, and n3 represent the powers to which the respective parameters must be raised before it is multiplied by the relevant X-coefficient.

Fatigue of a Conventional Binder and Three Bitumen-Rubbers

The three bitumen-rubbers used in the N3 trials were subjected to fatigue testing in the CMS. For the purpose of this report these materials will be referred to as BR-1, BR-2 and BR-3. The conventional binder was a 80/100 Pen bitumen. Table 3 shows the results of the regression analyses of these materials. It can be noted that the coefficients for the models of the four materials in this table differ significantly. The correlation coefficients (R^2) are very high; generally in the order of 0,99. This is due to the fact that the variation in the test results were already eliminated during the first series of regression analyses to determine the equivalent lives of the materials at a thickness of 2.5 mm. As such these values therefore do not give a representation of the true variation.

Figure 7 shows fatigue curves of the bitumen-rubbers at temperatures of 5 C and 12.5 C. One of the bitumen-rubbers (BR-2) was also tested at 1 C and 3 C. The effect of temperature on the fatigue life of bitumen-rubber is marked. It can also be seen that there is no marked difference between two of the three bitumen-rubbers at 5 C (BR-1 and BR-2), while the third is markedly different. The fatigue curve for a conventional asphalt is also shown. This indicates that modification of bitumen by adding a high percentage of rubber (such as in bitumen-rubber) can result in a marked improvement in the fatigue characteristics of the binder.

It should be noted that these results still need to be correlated with the field performance of the materials in the N3 trials before final conclusions can be made. Furthermore, it should be kept in mind that the selection of a surface treatment should be done on the basis of the activity of the cracks. Consequently, the selection of materials with less ability to stop crack reflection could be the optimum solution (their costs also being taken into account) to specific problems where extreme crack movements do not occur.

TYPE	TEMP	MOV	LIFE	MOV^n	TEMP^n	REGRESSION PARAMETERS
MOD 3	12.5	600	5000	0.5275	12.5	X1 : 404530.90
	12.5	400	9000	0.5493	12.5	X2 : 2273.16
	12.5	300	13500	0.5653	12.5	C : -238391.38
	12.5	200	35000	0.5887	12.5	RSQD : 0.8707
	5	300	5000	0.5653	5	STD DEV : 5085.76
	5	200	9500	0.5887	5	n 1 : -0.10
	5	100	26500	0.6310	5	n 2 : 1.00
MOD 4	20	500	6000	500.0000	20	X1 : -4.50
	12.5	300	4000	300.0000	12.5	X2 : 486.67
	5	100	500	100.0000	5	C : -1233.33
	5	200	300	200.0000	5	RSQD : 0.9838
						STD DEV : 612.37
						n 1 : 1.00
						n 2 : 1.00
MOD 2	12.5	300	67500	169.5935	12.5	X1 : -513.23
	12.5	400	40000	219.7121	12.5	X2 : 12502.17
	5	100	30000	63.0957	5	C : -2626.45
	5	150	6500	90.8829	5	RSQD : 0.9741
	5	200	3700	117.7408	5	STD DEV : 5969.32
						n 1 : 0.90
						n 2 : 1.00
MOD 1	5	600	27300	0.0408	5	X1 : 1875016.90
	5	800	16500	0.0354	5	X2 : 10889.88
	0	200	28500	0.0707	5	C : -103968.93
	0	300	4400	0.0577	5	RSQD : 0.9995
						STD DEV : 417.91
						n 1 : -0.50
						n 2 : 1.00

Table 3. Regression models for modified binders

Fatigue of Four Modified Binders

Four of the homogenous modified binders used in the N3 trials were also subjected to fatigue testing in the CMS. These were rubber-modified bitumens with 2 and 5 percent modifier, PVC-tar and a polymer-modified bitumen. For

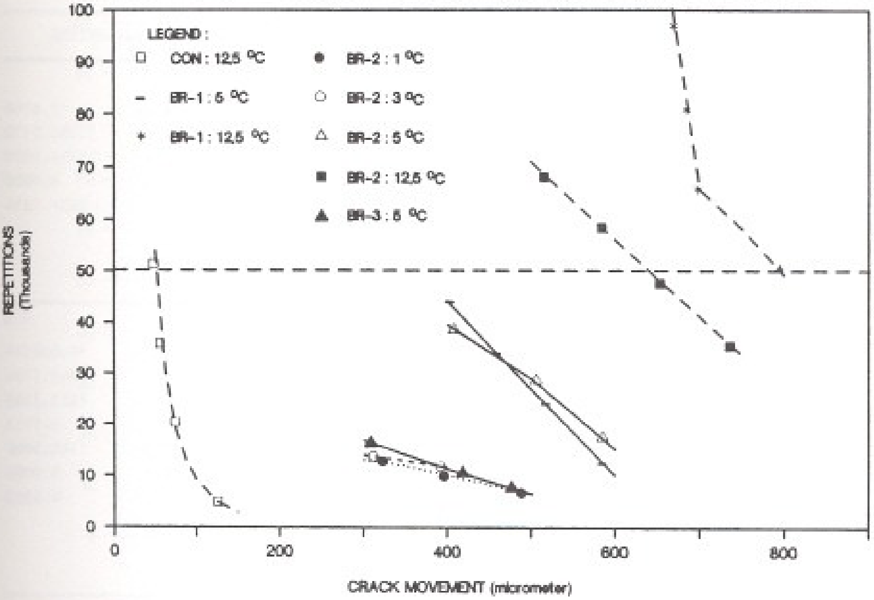

Figure 7. CMS fatigue of bitumen-rubbers

the purpose of this discussion these materials will be referred to as MOD1 through MOD4. Table 4 shows the results of the regression analyses of these materials. Once again the coefficients for the models of the four materials in this table differ significantly. Similarly to the bitumen-rubber results, the correlation coefficients (R^2) are very high apart from that of MOD3.

Figure 8 shows fatigue curves of the modified binders at temperatures of 5 C and 12.5 C. In contrast to the bitumen-rubbers, the fatigue performance of the modified binders varied markedly under simulated crack movement. It can be noted that, apart from MOD1 at 5 C none of the homogenous modified binders performed nearly as well as the bitumen-rubbers.

The fatigue curves given in Figures 7 and 8 give a good visual indication of the relative performance of the materials under simulated crack movement. However, these lack a parameter that can describe the relative performance of the materials in terms of a number or index. In order to quantify the performance of the materials in the CMS two parameters have been defined. These are:

- M_{50} which is the crack movement at which a material will last for 50,000 repetitions in the CMS at 5 C and at 12.5 C, and
- CMS, which is the ratio between M_{50} at 12.5 C and M_{50} at 5 C for any material and is an indication of how temperature sensitive the material is.

TYPE	TEMP	MOV	LIFE	MOV^n	TEMP^n	REGRESSION PARAMETERS	
BR-1	5	400	43152	48273.41	5	X1 :	-0.6268
	5	500	26354	72135.00	5	X2 :	11380.5970
	5	550	18291	85635.30	5	C :	15814.8635
	5	600	11141	100154.91	5	RSQD :	0.9908
	12.5	700	73182	132183.26	12.5	STD DEV :	2835.7834
	12.5	750	68606	149661.56	12.5	n 1 :	1.8
	12.5	800	50393	168097.78	12.5	n 2 :	1
BR-2	1	300	11000	27000000	1.00	X1 :	-0.000124
	1	350	10018	42875000	1.00	X2 :	10048.7754
	1	500	4734	125000000	1.00	C :	7223.1505
	5	400	39543	64000000	3.74	RSQD :	0.9913
	5	500	30770	125000000	7.93	STD DEV :	2342.5966
	5	600	17394	216000000	3.74	n 1 :	3.0000
	12.5	500	72778	125000000	7.93	n 2 :	0.8200
	12.5	600	57737	216000000	7.93		
	12.5	700	44211	343000000	7.93		
	12.5	750	35080	421875000	7.93		
BR-3	5	300	17137	0.0033		X1 :	8842249.8917
	5	400	9184	0.0025		X2 :	0.0000
	5	500	5454	0.0020		C :	-12496.0755
						RSQD :	0.9961
						STD DEV :	526.0235
						n 1 :	-1.0000
						n 2 :	0.0000
CONVENTIONAL BITUMEN	12.5	50	53667	0.000084		X1 :	660403857.4471
	12.5	75	21000	0.000032		X2 :	0.0000
	12.5	100	6667	0.000016		C :	-1385.5959
	12.5	150	3667	0.000006		RSQD :	0.9941
						STD DEV :	2161.6945
						n 1 :	-2.4000
						n 2 :	0.0000

Table 4. Regression models for bitumen-rubbers

Table 5 gives the above two parameters for the materials used in the N3 trials. It can be noted that the M_{50} number at 5 C for the eight materials varied from 370 to 50. In the case of the bitumen-rubbers it can be noted that BR-1 and BR-2 showed similar values of M_{50} at 5 C (in the order of 300). The M_{50} value for BR-3 was, however, only 150. In the case of the homogenous modified binders the M_{50} value at 5 C for MOD1 was in the order of 300 which

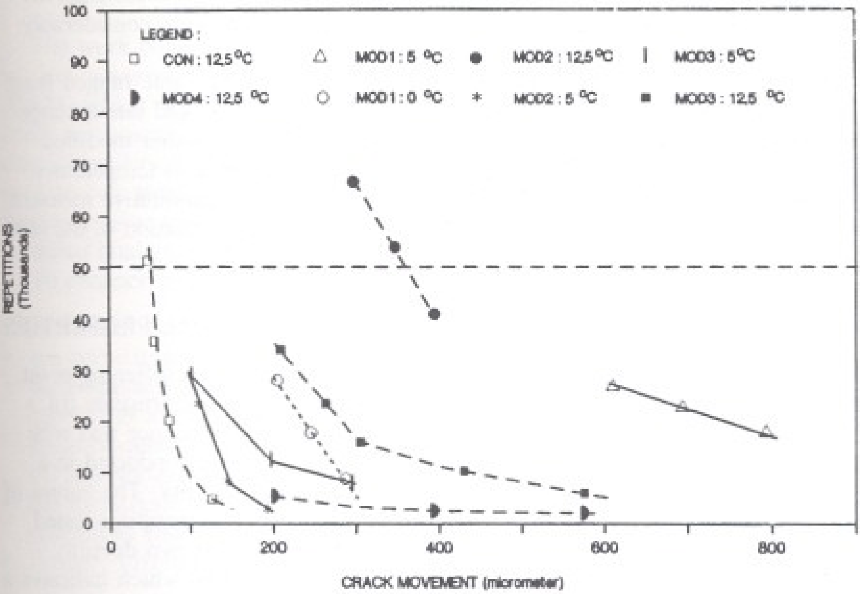

Figure 8. CMS fatigue of modified binders

MATERIAL	RANK-ING	TEMPERATURE (°C)					CMS_t
		0	1	3	5	12.5	
BR-1	1	-	-	-	370	800	2.16
BR-2	2	-	± 150	± 150	310	640	2.06
MOD 1	3	145	-	-	± 300	-	-
BR-3	4	-	-	-	150	-	-
MOD 2	5	-	-	-	80	360	4.5
MOD 3	6	-	-	-	80	180	2.25
MOD 4	7	-	-	-	-	± 50	-
CONVENTIONAL BITUMEN	8	-	-	-	-	50	-

Table 5. M_{50} and CMS_t for binders used in N3 trials

indicates performance similar to that of the two top bitumen-rubbers whereas the M_{50} values for the other homogenous modified binders were considerably lower.

In the case of the temperature sensitivity ratio CMS_t, the value ranged from 2.06 to 4.5. For three of the materials (two bitumen-rubbers and one homogenous modified binder) CMSt, was just over 2 whereas for another modified binder the value was 4.5. This implies that the latter is twice as temperature sensitive as the others. Thus, these parameters can give a quantitative measure of the relative performance of the materials as well as an indication of the temperature sensitivity of the materials.

CORRELATION OF CMS FATIGUE WITH RHEOLOGICAL PROPERTIES

A wide variety of rheological properties (e.g. ring-and-ball softening point, flow, Fraass brittle point) were correlated with the fatigue performance (in terms of M_{50}) of the materials. The only correlation of significance was with the work done during two ductility tests. These two tests are conducted in a modified ductilometer as well as in an INSTRON testing facility. The values of M_{50} and the work done during the two ductility tests for the materials tested are given in Table 6. A multiple regression analyses with the two ductility values as independent parameters yielded an R^2 value of 0.94 which indicates a very good correlation.

The purpose of correlations such as above is to determine which of the rheological properties that can be easily measured can be used to best predict laboratory fatigue performance. The initial work described above will be followed up to strengthen the findings. However, it is believed that this work is a significant step towards obtaining performance-related criteria and specifications. Similar correlations will be conducted to determine the relationship between field performance and rheological properties. The final objective of this work is to develop design criteria and specifications for these materials in terms of properties that can be easily measured and that are based on performance.

MATERIAL	M_{50} AT 5 °C	INSTRON	DUCTILOMETER (200 MM)
BR-1	370	145	168
BR-2	310	149	146
BR-3	150	102	138
MOD 1	300	168	245
MOD 2	80	80	94
MOD 3	80	77	82
MOD 4	0	58	67

Table 6. Correlation of M_{50} with ductility of modified binders

CONCLUSIONS AND FUTURE WORK

The work conducted on modified binders and the crack reflection problem has led to several developments. These include the Crack-activity Meter (CAM) which can measure load-associated crack movement in a road. Typical crack movements caused by moving wheel loads have been measured on a variety of pavement types. The Crack Movement Simulator (CMS) was developed to determine the fatigue performance of these materials. In addition, a comprehensive trial section was built where the performance of nine different modified binders as well as a conventional bitumen are monitored.

To enhance the above, future research work will include:

- continued monitoring of the field performance of the N3 trial sections;
- the correlation of field performance with laboratory results;
- the continued fatigue testing of thin layers of modified binders and bitumen-rubbers to improve the understanding of the influence of: temperature, load cycle frequency, loading wave shape, rest periods, the combination of vertical and horizontal movement, thickness of the layer etc.;
- the investigation of the durability (ageing) of modified binders under field conditions and its influence on laboratory fatigue, and
- further correlation of rheological properties with fatigue performance.

The authors believe that the above work provides a sound basis towards obtaining comprehensive performance-related design criteria and specifications for modified binders.

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Discussion

MR. JOHN HUFFMAN: I need some explanation of the modified materials. It is assumed that the bitumen rubbers include reclaimed rubber like tire rubber and involve a reacted material. Under Section 4.3, you refer to a rubber modified material and since you have polymer modified as well, then does this imply a natural rubber?