THE EVALUATION OF SIX MODIFIED BINDERS FOR RETARDATION OF CRACK REFLECTION THROUGH LABORATORY STUDIES AND FIELD WORK

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Three bitumen-rubber binder technologies and three polymer-modified binders were evaluated both in field trials and extensive laboratory work to assess their ability to retard reflection cracking. The work conducted, included the measurement of crack activity and fatigue testing under simulated crack movement. Laboratory results and field performance data were related in a model to assist in the selection of surface treatments for the retardation of reflection cracking.

INTRODUCTION

Large amounts of money are spent annually on sealing or overlaying cracked road pavements, however, the reflection of cracks through these materials is a problem experienced worldwide. In countries with well-developed road infrastructures where the road networks are ageing (and available funds are often decreasing) it is becoming increasingly important to apply successful and cost-effective rehabilitative measures. Even though materials such as bitumen-rubbers, geofabrics and polymer-modified binders demonstrate some ability to retard reflection cracking, they still sometimes fail prematurely. In South Africa, the lack of performance-related design procedures, criteria and specifications for the selection of materials to solve specific problems, has led to a number of research projects.

These projects conducted at the Division of Roads and Transport Technology of the CSIR involved :

- the measurement of crack movement in the field;
- the monitoring of trial sections to determine the field performance of surface treatments under traffic;
- fatigue testing of various materials under simulated crack movement, and
- the determination of the rheological properties of the materials and the effect of ageing on these.

The ultimate objective of this work is to develop performance-related design procedures, criteria and specifications for the use of modified binders in surface treatments with particular emphasis on the ability of the materials to retard crack reflection.

This paper contains a brief description of the Crack-Activity Meter (CAM) which was developed to measure load-associated crack movement. The focus then shifts to laboratory fatigue testing and the performance of several binders under heavy traffic. The laboratory test results are related to the field performance of these materials in trial sections. Finally, a framework is defined for developing a model to predict crack reflection, in order to assist in the selection of binders to be used in surface treatments applied to roads with active cracks.

THE CRACK-ACTIVITY METER (CAM)

In contrast to concrete roads, load-associated movements of cracks are higher than thermal crack movements on pavements containing cemented layers which are cracked into blocks (2). In South Africa, 80 per cent of the paved roads contain cemented bases and/or subbases, with the result that load-associated movements are relatively more important than thermal movements. The Crack-Activity Meter (1) (see Figure 1) has therefore been developed to measure load-associated crack movement. The most recent development is a change in design to allow the CAM to be installed below the surface of a road in order to measure thermal movements. Over the last six years the CAM has been used in conjunction with the Heavy Vehicle Simulator (HVS) as well as in a portable system, to measure crack movement on a variety of road structures (2,3). From this work it was interesting to note that, apart from vertical movement caused by moving wheel loads, very significant horizontal movement was also caused by the rocking of blocks between the cracks as well as by the shape of the deflection basin combined with the size of the blocks. The CAM measures both the horizontal and the vertical crack movement simultaneously which allows the geometric addition of the two values to result in the total crack movement (see Figure 1).

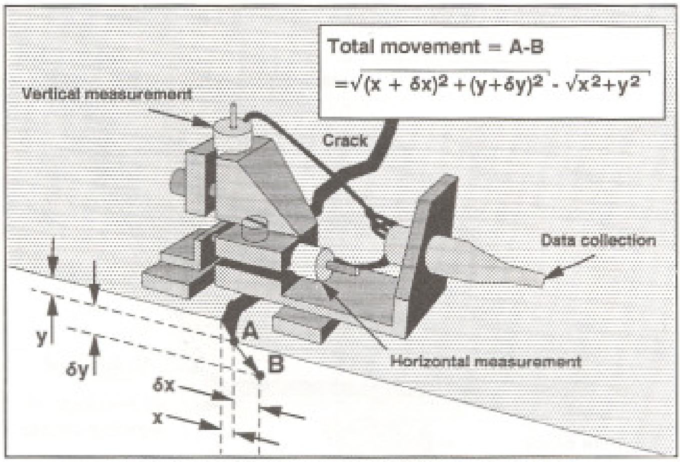

Figure 1 : The Crack-Activity Meter (CAM).

TRIAL SECTIONS

Description

Trial sections (3,4) were constructed in 1987 to determine the capability of a number of modified bituminous binders in retarding the reflection of active cracks to the road surface, when used in a single seal application. The sections were constructed in the slow lane of a heavily trafficked urban freeway carrying approximately 900 to 1 000 standard 80 kN axles daily. In addition, the general performance of the materials with respect to factors such as bleeding, loss of chips and durability was monitored. In order to simulate crack movement, 32 concrete blocks (see Figure 2) 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. The movement of the joints or "cracks" were measured with the CAM prior to spraying of the surface treatments.

The sections were subsequently covered with a single seal (nominal stone size of 13,2 mm; stone application rate of 0,0087 m^3/m^2), using nine different modified binders on 14 of the sections at various spray rates. Each section included two blocks - with a higher and lower activity respectively. The following binders were used :

- bitumen-rubbers from three suppliers, each prepared by the addition of approximately 20 per cent crumbed tyre rubber to 80/100 pen bitumen with the suppliers' additives and technology;
- two locally produced polymer-modified bitumens, modified by the addition of Styrene Butadiene Rubber (SBR) (2 per cent and 5 per cent), and one imported polymer-modified binder;
- tar, modified by the addition of PVC (not generally used in either the RSA, Europe or the US);
- a tar-bitumen blend modified with crumbed rubber;
- a tar modified by the addition of crumbed rubber, and
- a conventional 80/100 penetration grade bitumen as control.

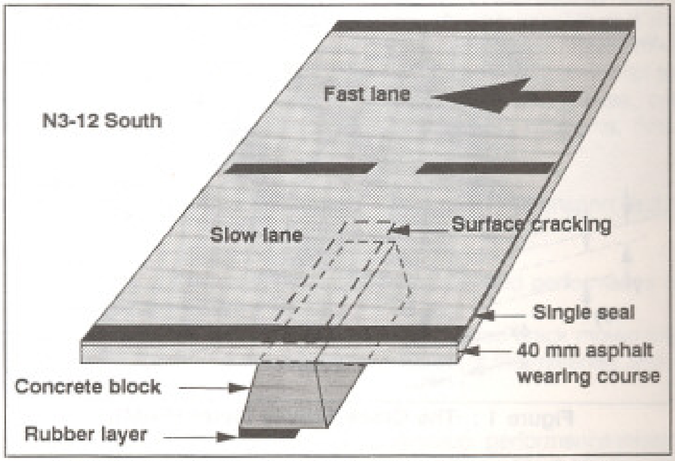

Figure 2 : Shape and Position of Concrete Blocks.

Table 1 gives a summary of the material and the spray rate used on each section. Due to the fact that tar is no longer used, this paper will focus on the three bitumen-rubbers and the three polymer-modified bitumens.

Block no.	Binder	Application (ℓ/m²)	Block no.	Binder	Application (ℓ/m²)
1	Bitumen-rubber 2	1,64	15	Bitumen-rubber 3	1,80
2	Bitumen-rubber 2	2,15	16	Bitumen-rubber 3	1,86
3	Bitumen-rubber 2	2,39	17	Bitumen-rubber 3	2,49
4	Bitumen-rubber 2	2,37	18	Bitumen-rubber 3	2,42
5	PVC tar	1,20	19	PB1	1,20
6	PVC tar	1,30	20	PB1	1,06
7	Bitumen-rubber 1	2,24	21	Tar-bitumen-rubber	2,19
8	Bitumen-rubber 1	2,37	22	Tar-bitumen-rubber	1,98
9	Bitumen-rubber 1	1,89	23	Tar-bitumen-rubber	1,57
10	Bitumen-rubber 1	1,95	24	Tar-bitumen-rubber	1,72
11	2% SBR	1,08	25	5% SBR	1,15
12	2% SBR	1,07	26	5% SBR	1,14
13	Conventional	1,14	27	Tar-rubber	2,14
14	Conventional	1,03	28	Tar-rubber	2,05

Table 1 : Materials and Spray Rates Used on the Trial Sections.

Reflection cracking

Prior to sealing, the crack movement on each block was measured with the CAM. These measurements were repeated in 1990 and 1991. Figure 3 gives these measurements. The decrease in movement is ascribed to material that entered the openings on the sides of the blocks, thereby inhibiting free block movement to varying degrees. The sections have been monitored over a period of five years and Table 2 shows the performance of the materials regarding crack reflection.

The first sealed section to show cracking contained a PVC-modified tar. It must be stressed that, when evaluating the effectiveness of a binder to retard the reflection of cracks, the degree of crack activity must be regarded as well. In the case of the section containing PVC-tar, it was found that the initial crack movement measured was the highest relative to the other sections.

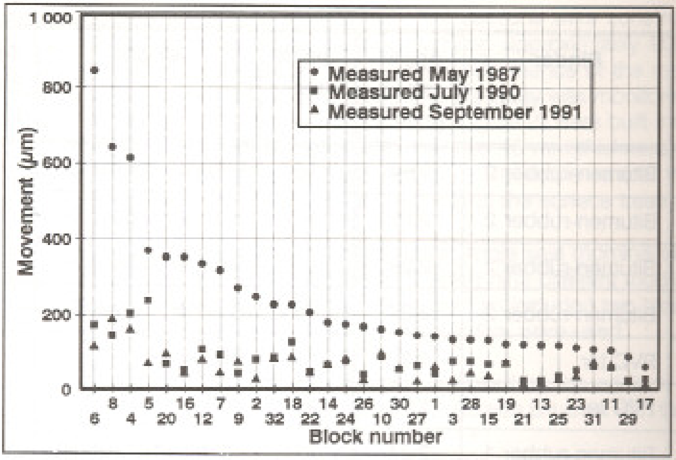

Figure 3 : Block Movements on the Trial Sections.

Block no.	Binder	Application (ℓ/m^2)	Block movements (μm)			Equivalent traffic to cracking
			1987	1990	1991	
6	PVC tar	1,30	845	174	116	292 000
12	2% SBR	1,07	335	109	79	510 000
5	PVC tar	1,20	369	239	70	955 000
8	Bitumen-rubber 1	2,37	641	146	188	1 047 000
2	Bitumen-rubber 2	2,15	248	82	28	1 141 000

Table 2 : Performance of Binders in Terms of Crack Reflection.

Cracks have also been noted during the first five years since construction on five of the other sections, as well as on the remaining block of the PVC-tar section. Again these sections contained blocks with very high initial activities. Of these sections, two contained bitumen-rubbers and one an SBR-modified bitumen (2 per cent). To date no cracks have been noted on the sections where movements of the blocks were low. Table 2 shows a summary of results to date, including the cumulative traffic calculated in equivalent standard axles at the time of crack reflection (using a reference axle of 8 tons and a damage coefficient of 4).

From Table 2, it can be seen that the type of binder and the activity of the blocks had a major influence on the time to cracking. Furthermore, Bitumen-rubber 1 (sprayed at 2,37 ℓ/m^2) and Bitumen-rubber 2 (sprayed at 2,15 ℓ/m^2) lasted for similar periods of time although the crack movements differed significantly. The spray rate therefore had a significant effect on the ability of the material to inhibit crack reflection in the field.

General performance

After four years of heavy traffic, the general performance of the seals was very good (5), with only slight stone loss reported on the sections laid with the conventional penetration grade bitumen. Two years after construction, some signs of fatting were evident on the sections with binder application rates in excess of 1,9 ℓ/m^2. This seems to have decreased during the past two years and only slight fatting is noticeable on some of the bitumen-rubber sections laid at the higher application rates.

Durability

The binders were sampled at regular intervals and the physical properties determined and compared with the properties at the time of construction in order to assess the ageing characteristics of the binders. The binders were recovered by means of hot centrifuge which strips the binder from the heated aggregate at 2 500 to 3 000 revolutions per minute through a 15 μm sieve. This method, however, can not be applied to heterogeneous binders (bitumen-rubbers) because of the size of the rubber crumbs. These binders were therefore only tested at the initial stage. The testing included the following :

- viscosity at 25 °C by using a sliding plate viscometer;
- elastic recovery in the sliding plate viscometer;
- viscosity/temperature relationship;
- Fraass brittle temperature;
- polymer content (using infra-red spectometry), and
- oxidation level (using the IR spectrum).

Figure 4 shows the increases in viscosity of three of the modified binders and the conventional bitumen. Some of the outliers could be due to the fact that the materials were sampled at different positions within the test section. The general trend is that the SBR-modified bitumens tend to show a lower increase in viscosity with time than the conventional bitumen or the imported modified bitumen. The behaviour of the imported bitumen could be explained by the fact that it was designed for European base bitumen and conditions.

Films with thicknesses of 50 μm to 100 μm were tested on the sliding plate viscometer at temperatures at which their viscosities were between $4,0\times10^5$ and $7,5\times10^5$ Pa.s. A load producing a shear rate of between 0,04 and 0,065 s^{-1} was applied to shear the film to about five times the film thickness. The elastic recovery was measured after removal of the load. Figure 5 shows significant decreases in elastic recovery with time. After four years all the binders were showing similar changes in elastic recovery. The final values were much lower than the original values although still significantly higher than that of the conventional bitumen.

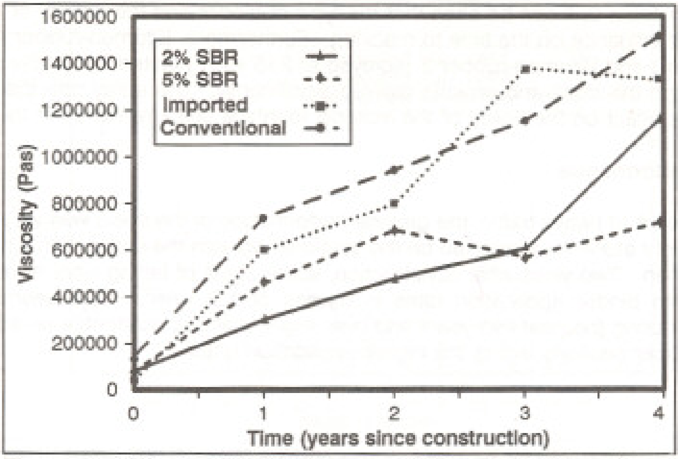

Figure 4 : Effect of Field Ageing on Sliding Plate Viscosity.

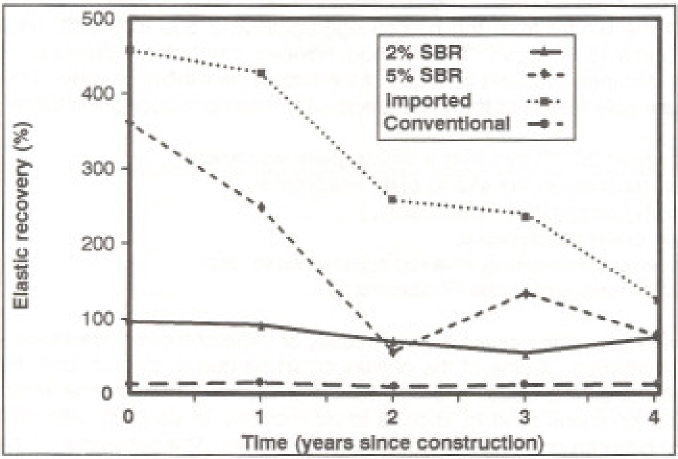

Figure 5 : Effect of Field Ageing on Elastic Recovery (Sliding Plate Viscometer).

LABORATORY FATIGUE TESTING

In order to investigate the influence of various parameters on the fatigue life of surface treatments, a laboratory apparatus, the Crack-Movement Simulator (CMS) (2) has been developed. The CMS can simulate a number of complex forms of crack movement under controlled conditions of loading and temperature, using an INSTRON testing facility controlled by a personal computer and specialised software. The apparatus consists of a frame onto which the sample is fixed, a temperature-controlled cabinet and an LVDT which measures the movement applied to the sample. The CMS can be used in a number of configurations, simulating either horizontal or vertical crack movement or a combination thereof. In the configuration for horizontal crack movement, the plates onto 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 (see Figure 6).

The factors influencing fatigue life and which were investigated are :

- the testing temperature (usually 5 °C and 12,5 °C but lower temperatures were also used in some cases);
- the level of crack movement;
- the material tested;
- the load frequency, and
- the thickness of the layer.

Current work includes research into the influence of variables such as loading wave form and rest periods between the loading cycles.

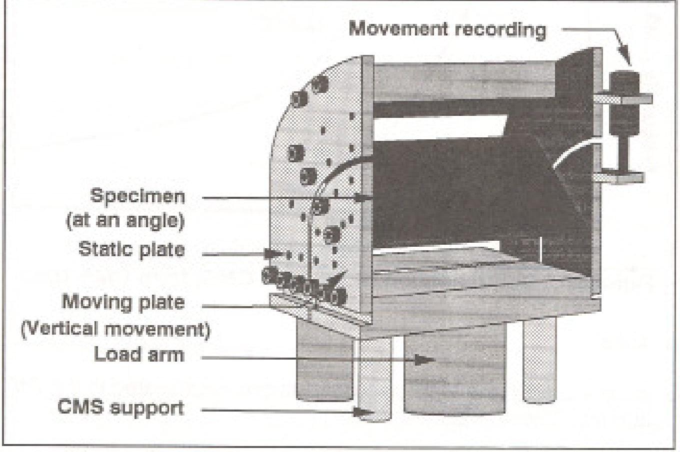

Figure 6 : The Crack-Movement Simulator (CMS)

Calculated CMS-parameters

To allow the evaluation of the relative fatigue performance of binders in CMS testing, two parameters describing the fatigue performance were defined (6). These were termed M_{50} and CMS_f. Figure 7 shows the meaning of these two parameters. M_{50} is defined as the amplitude of crack movement on the CMS at which the binder will last for 50 000 repetitions at a specified temperature (the parameter must be noted in conjunction with the test conditions). This parameter can be used to quantify the relative performance of the binders. A high value for M_{50} indicates good performance.

CMS_t is an indication of the temperature sensitivity of a binder in terms of fatigue performance. It is the ratio between M_{50} at 12,5 °C and M_{50} at 5 °C. A high value for CMS_t indicates a high sensitivity to temperature changes. For example, the CMS_t value for the bitumen-rubbers were significantly different from the imported binder. This parameter can still be improved by including another temperature in the calculation (e.g. 1 °C) in order to establish whether the relationship is linear or not.

In similar fashion, parameters describing the influence of the other variables in the CMS test can be defined, especially the frequency of loading, thickness of the layer and rest periods. Such definitions should specify the test conditions regarding these other variables.

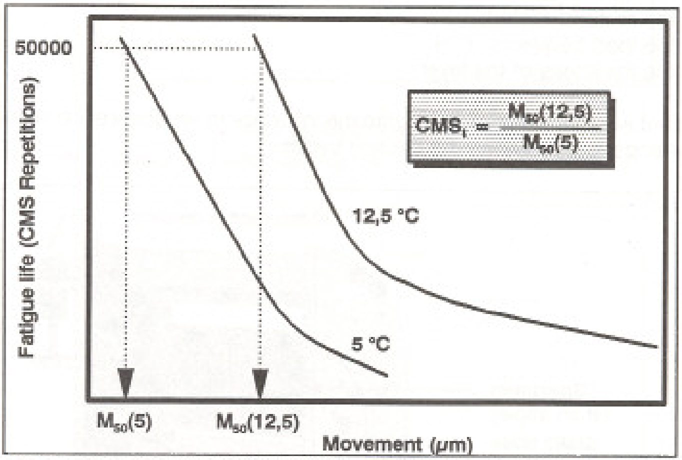

Figure 7 : Determination of M_{50} and CMS_t from CMS Data.

CMS test results

Eight of the binders used in the trials discussed above, were tested in the CMS, including the control bitumen. These materials were :

- the three bitumen-rubbers mentioned earlier;
- the three polymer-modified bitumens;
- the PVC-modified tar, and
- the control bitumen (80/100 penetration grade).

The binders can be divided into homogeneous and heterogeneous binders, the first being the control bitumen and the polymer-modified binders and the latter being the bitumen-rubbers. The CMS results have shown that the bitumen-rubbers were superior in terms of resistance to cracking, to the homogeneous binders. The 80/100 penetration grade bitumen was also used as a basis for the preparation of most of the other modified binders. The bitumen was tested at 12,5 °C and the modified binders at temperatures ranging from 0 °C to as high as 20 °C. Table 3 gives the M_{50} and CMS_t values for all binders tested.

Binder	Ductility W/L_{200}	M_{50} at :		CMS_t
		5 °C	12,5 °C	
Bitumen-rubber 1	168	370	800	2,16
Bitumen-rubber 2	146	310	640	2,06
PVC tar	245	300		
Bitumen-rubber 3	121	150		
Imported binder	94	80	360	4,50
5% SBR modified	82	80	180	2,25
2% SBR modified	67		50	
Conventional bitumen			50	

Table 3 : Values of M_{50} and CMS_t for the Binders Tested on the CMS.

Unmodified bitumen.

The control bitumen was found to be very stiff at 5 °C and failed almost immediately, even at movements as low as 50 μm. The testing temperature was then raised to 12,5 °C and this gave meaningful results at movements of between 50 and 150 μm. Subsequent testing of similar bitumen has shown very similar fatigue curves. Due to the fact that the material had cracked so quickly at 5 °C, M_{50} and CMS_t values could not be calculated.

Homogeneously modified binders.

Figure 8 shows that, relative to the control bitumen, these materials lasted significantly longer at 12,5 °C. Due to the fact that reflection cracking is usually associated with low temperatures, it was decided to standardize the test at 5 °C. The beneficial effect of increasing the percentage modifier can clearly be seen from the fatigue curves of the 2 per cent and 5 per cent SBR-modified bitumens. Future research will include binders with modifiers such as SBS (Styrene-Butadiene-Styrene).

Bitumen-rubbers.

The bitumen-rubbers were tested mainly at 5 °C, but tests were also conducted at both higher and lower temperatures. Marked differences between the three bitumen-rubbers were noted at different temperatures. At 5 °C two of the binders had the same performance curves, while at 12,5 °C and movement of 700 μm, the one lasted 30 000 repetitions longer than the other (see Figure 9). The third binder did not perform nearly as well as the other two, but was still superior to the unmodified and the SBR-modified binders.

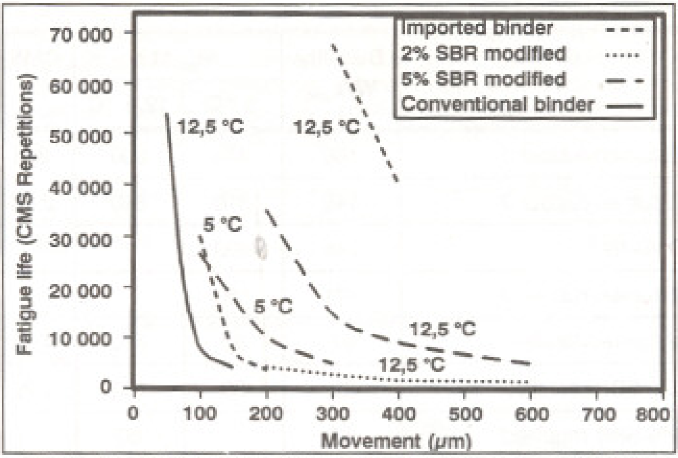

Figure 8 : CMS-fatigue Curves for Homogeneous Binders.

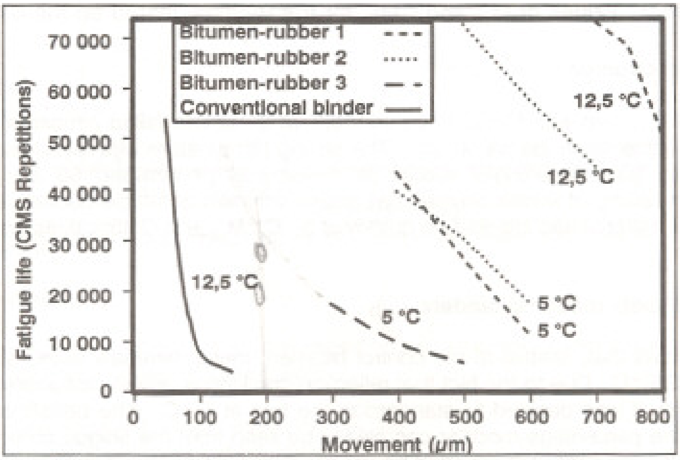

Figure 9 : CMS-fatigue Curves for Bitumen-rubbers.

Modified bitumen emulsions.

Recently the use of modified bitumen emulsions (SBR) in the construction of chip-and-spray surface treatments has emerged in South Africa. Sample material was tested in the CMS and it compared very well with the SBR-modified bitumens. Taking into account that the residual binder is tested on the CMS, it can be expected that the result will be similar to that of the SBR-modified bitumens. The test can however not take into account the practical aspects of the use of these emulsions, concerning, for example, the application rate or the breaking of the emulsion.

Discussion of M_{50} and CMS_t values

Table 3 shows the M_{50} and CMS_t values for all materials tested. In addition, the work done in a low-temperature ductility test (over the first 200 mm at 11 °C) is shown.

The above shows that the first two bitumen-rubbers are very similar, both in terms of their ability to retard reflection cracking and their sensitivity to temperature change. The third bitumen-rubber showed only half of the ability to retard crack reflection (M_{50} = 150 vs 300). The 5 per cent SBR-modified binder did not perform as well as the bitumen-rubbers (M_{50} = 80 vs 300) even though its temperature sensitivity was similar to that of the bitumen-rubbers. The 2 per cent SBR-modified binder cracked very early at 5 °C and therefore M_{50} is given as less than 50 and CMS_t could not be calculated. The imported binder was similar to the 5 per cent SBR-modified in terms of M_{50}, but was more than twice as sensitive to reduction in temperature (CMS_t = 4,5 vs 2,1). Furthermore, the performance of the materials in the CMS test correlates well with the work done during the ductility test. Correlations such as these can assist in the development of performance-related specifications, in terms of easily measured physical properties, for modified binders to be used in layers covering roads with active cracks.

Testing under varying frequency.

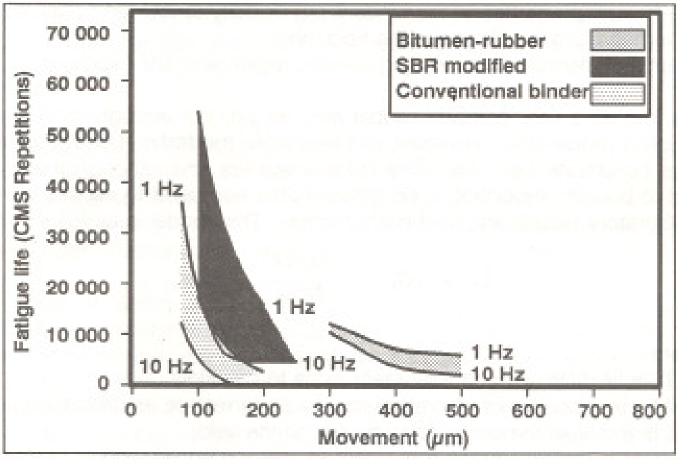

Figure 10 : The Influence of Changing Loading Frequency on CMS Results.

It is well-known that the visco-elastic nature of bituminous binders makes them susceptible to increases in loading frequency. Heukelom and Klomp (8) showed that, for conventional bitumen, load frequency and testing temperature are interrelated in terms of their effect on fatigue. This needs to be verified for modified binders under simulated crack movement. A crack movement sphere of radius 4 m combined with traffic travelling at 75 km/h, implies a 5 Hz frequency, which was used as a standard frequency in most of the CMS testing. The effect of variations in loading frequency was also investigated by using frequencies of 10 Hz (simulating a speed of 144 km/h) and 1 Hz (15 km/h).

The initial results indicate that, in terms of fatigue life, the bitumen-rubbers were least affected by a change in loading frequency (see Figure 10). However, the conventional bitumen and the SBR-modified binders were significantly more sensitive to loading frequency.

A FRAMEWORK FOR PREDICTING CRACK REFLECTION

The above can be used to define a framework for designing and specifying modified binders for use in surface treatments that are applied to retard reflection cracking. In order to achieve this aim a number of parameters addressing specific factors need to be defined in a model which can predict fatigue life. The most important of these factors and parameters include :

- fatigue life in the laboratory (described by M_{50} in μm);
- spray rate or thickness of the layer (mm);
- vertical and horizontal crack movement in the field (in μm);
- durability of the binder in the laboratory;
- temperature sensitivity in the laboratory (described by CMS_t);
- crack width (mm);
- traffic volume and spectrum (indicated by number of equivalent axles);
- frequency of loading in the field (determined by traffic speed);
- physical properties of the binders (eg ductility at low temperature);
- temperature conditions in the field, and
- environmental conditions (eg climatic region and UV exposure).

This implies a very complex model and, as yet, not enough data is available to develop such a model fully. However, in these trials the traffic, UV exposure and field temperature conditions were the same for all materials and although these factors are considered to be very important, a simplified model was used to assess the correlation between laboratory results and field performance. This model is as follows :

$$L_f = \left(C_1 \times \frac{M_{50} \times t}{TCM} + C_2\right)^n$$

where

L_f is field life given in equivalent axles to cracking;
M_{50} is indicative of laboratory fatigue performance as described above;
t is the layer thickness or spray rate in the field;
TCM is the total crack movement as defined above, and
n, **C_1** and **C_2** are constants.

The limited data available was thus used in regression analysis to determine n, C_1 and C_2. The very reasonable correlation obtained between field life and the predicted life is shown in Figure 11 (an R^2 value of 0,83 was obtained). Based on this limited data, the result is promising in that differences measured in the field are well represented by the model. The incorporation of more of the parameters discussed above as well as further field data obtained in the future, will allow the verification and improvement of the above model.

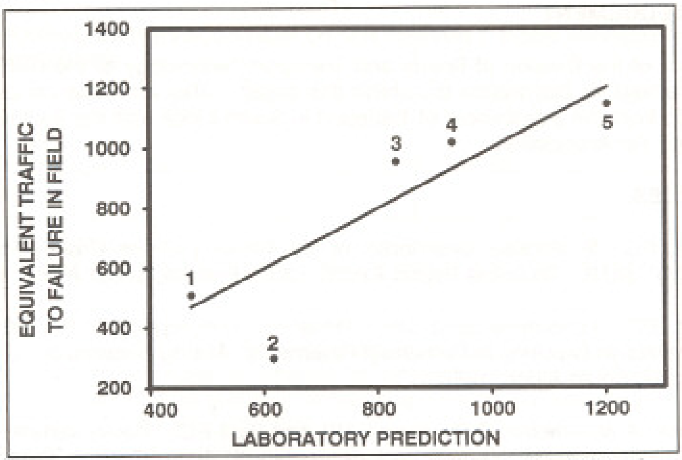

Figure 11 : Predicted Life vs Field Life (Equivalent Axles).

The authors believe that the above approach, in conjunction with more field performance data and the characterisation of the physical properties of these materials, will in the future form an essential basis for the development of performance-related design criteria and specifications for the use of surface treatments to seal active cracks.

CONCLUSIONS

The development of the Crack-Activity Meter and the Crack-Movement Simulator has led to the quantification of both crack activity and the ability of materials to retard crack reflection. The relative ability of materials, available in South Africa, to retard crack reflection was determined in the laboratory. The performance of the same materials in trial sections under relatively heavy traffic has been monitored since 1987.

The effect of factors such as the magnitude of crack movement, temperature, frequency and layer thickness was investigated in the laboratory. In addition, the ageing of the above binders in the field was investigated and quantified in terms of their physical properties. The laboratory results were correlated with field performance and a model for the prediction of crack movement was proposed. Although, to date, only five data points were obtained from the trial sections, the indications are that the model can predict crack reflection through surface treatments, with reasonable accuracy. The incorporation of parameters describing ageing and temperature sensitivity will improve the model considerably. Further work will also be conducted to investigate the effect of cumulative damage, thereby defining a damage factor for crack reflection rather than using the well-known value of 4,2 to calculate equivalent axles.

The above work has not only resulted in a better understanding of crack reflection and the factors controlling it, but has as its ultimate objective the development of performance-related design procedures, criteria and specifications for the use of modified binders to seal active cracks. This approach will lead to more cost-effective use of resources and could potentially save road authorities significant amounts of money.

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