RETARDING CRACK REFLECTION USING BITUMEN-RUBBER SEALS AND OVERLAYS – HISTORIC OVERVIEW OF CSIR RESEARCH

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ABSTRACT: Crack reflection on roads with cemented layers is a significant problem world-wide and can lead to premature failure. Innovative road materials such as bitumen-rubbers possess the potential to successfully retard crack reflection, thereby minimizing damage to roads from water ingress. The research work conducted on bitumen-rubbers in conjunction with the knowledge generated on the retardation of crack reflection has led to several developments and innovations for the road industry. One such innovation is the development of the Crack Activity Meter (CAM), a device capable of measuring horizontal and vertical crack movements simultaneously. The CAM has been successfully used in conjunction with the Heavy Vehicle Simulator (HVS) during several accelerated pavement tests of road sections containing bitumen-rubber materials. Results from various laboratory investigations in conjunction with these field tests spans over decades of research into aspects such as crack movement monitoring, fatigue testing of bitumen-rubber asphalt and their performance under varying environmental and loading conditions. This paper provides a historic overview of the research conducted at the CSIR relating to the use of bitumen-rubber materials to successfully retard crack reflection. The paper additionally discusses the initial history, developments and early laboratory work conducted on the performance of bitumen-rubber materials in South Africa. Finally the paper identifies gaps in research in line with current day trends and developments that may be explored further for new methods of improving the successful retardation of crack reflection.

KEYWORDS: Crack Reflection, Rubber-Modified Binders, Bitumen-Rubbers, Bitumen-Rubber Asphalt

1. Introduction

The reflection of primary cracks through pavement surface overlays and seals is recognized as a severe problem which may impact significantly on a country's road infrastructure network. When water ingresses through cracks it causes pumping of fines due to the repetitive action of wheel loads. This can lead to potholing, deformation and premature failure of road pavements. This situation is exacerbated by additional strains placed on these roads by ever-increasing traffic loading and climate change effects. This calls for innovative solutions in order to ensure sustainable performance of roads over time. To address these challenges, pavement engineers have for many years been improving the characteristics of road building materials and technologies, often through using low-cost techniques and products that incorporate recycled waste materials. One such technique is the use of crumb rubber recycled from old vehicle tyres to form the well-known bitumen-rubber material that can be used to provide improved surface treatments (bitumen-rubber seals) as well as enhanced asphalt mixes (bitumen-rubber overlays).

The CSIR initially developed considerable interest into the use of bitumen-rubber materials for road applications in the early 1980's, following the completion of several HVS tests on pavement structures constructed with strong cemented bases and subbases on the N3/9 between Warden and Villiers (Rust, 1984). Results from these tests evidently illustrated the propagation and reflection of cracks through strong cemented pavement layers onto a pavement surface, thereby making it prone to water ingress. The development and introduction of new innovative materials such as rubber-modified binders as well as bitumen-rubber surface treatments at the time therefore showed significant potential for the sealing and rehabilitating of cracked surfaces, thereby minimizing potential damage. Some of the HVS tests indicated that the asphalt surface layer can be more than halved in thickness if a bitumen-rubber binder is used (Rust, 1984; Rust *et al.*, 1994). This could provide millions of Rands in potential cost-savings for local road agencies. These potential benefits therefore led to the initiation of an extensive research program at the CSIR into rubber-modified binders and bitumen-rubber seals, specifically focused around their performance under load-associated crack movement and their potential ability to successfully retard crack reflection. The additional field and laboratory work conducted on the fatigue and rutting performances of these bitumen-rubber materials in conjunction with the knowledge generated on the retardation of crack reflection spans over decades of research, which has furthermore resulted in various technological developments and innovations for the road industry. These developments and innovations have been successfully used in conjunction with the HVS during several accelerated pavement tests on road sections consisting of various bitumen-rubber materials across South Africa.

The primary aim of this paper is to provide a historic overview of the research conducted at the CSIR relating to the use of bitumen-rubber materials for road surface treatments and overlays. The scope of this paper is however mostly aimed at discussing research results in the ambit of crack reflection and the successful prevention of this phenomenon using various bitumen-rubber materials. The paper additionally discusses the initial history, developments and early laboratory work conducted on the performance of bitumen-rubber materials in South Africa. Finally, potential gaps in research that may be applicable to enhancing bitumen-rubber products for successfully retarding crack reflection in line with current day trends and developments are discussed.

2. Bitumen-Rubber Materials in South Africa

2.1 Initial History and Developments

Bitumen-rubber was initially introduced to the South African roads market as an imported material. Arm-R-Shield bitumen-rubber products were imported in October 1982 from the Arizona Department of Transport in Phoenix, USA (Renshaw, 1989). Renshaw (*ibid*) claims that the main reason for the introduction of bitumen-rubber (in the form of Arm-R-Shield) into South Africa was to address the problem of reflection cracking that was prevalent amongst many pavement structures that contained cement and lime. Renshaw (*ibid*) further mentions that the first locally developed bitumen-rubber technology was based on an Australian method of production which was only introduced in July 1983. However despite the introduction of local bitumen-rubber products, Arm-R-Shield was still constituting approximately three quarters of all quantities of bitumen-rubber production in South Africa until 1988.

2.2 Bitumen-Rubber Binders and Seals

2.2.1 Bitumen-Rubber Binders

Although Arm-R-Shield was predominantly imported as a crack sealant to successfully deal with reflection cracking, it was additionally used for applications in the form of stress absorbing membranes (SAM's), stress absorbing membrane interlayers (SAMI's) as well as in hot premix asphalt (Renshaw, 1989). However, according to Renshaw (1984), Arm-R-Shield was only to be considered as an acceptable product by local road agencies in South Africa after demonstrating a sound performance history over a reasonable period of time. The Arm-R-Shield products were therefore evaluated on their prolonged performance on South African roads under various local traffic and environmental conditions.

2.2.2 Early Laboratory work

Following the conditional requirements set out for bitumen-rubber implementation in South Africa in the early 1980's, a comprehensive full-scale test programme was embarked upon consisting of twenty two bitumen-rubber roads constructed across various parts of South Africa (including roads with bitumen-rubber seals, interlayers as well as asphalt overlays) (Renshaw *et al.,* 1989). Schnitter *et al.,*

(1984) subsequently helped to identify and develop laboratory test criteria for bitumen-rubber binders which were based on correlations between binder properties and their corresponding fatigue characteristics. These criteria were used to conduct initial laboratory tests on the bitumen-rubber test sections with their results being stored in a data bank (Renshaw, 1984). Some of the initial tests conducted on the bitumen-rubber blends included the following as indicated by Renshaw (1984):

- Softening point (Ring and Ball)
- Standard penetration (Needle)
- Resiliency (Ball) Test
- Flow Test
- Viscosity Test
- Elastic Recovery

Renshaw (1989) states that although the performance of bitumen-rubber materials can be evaluated in terms of countering several types of distress, they were predominantly evaluated for reflection cracking during the full-scale test programme. Results published by Renshaw *et.al* (1989) after a six year period of evaluation concluded that Arm-R-Shield bitumen-rubber products (i.e. asphalt overlays constructed with both the wet and dry methods) effectively reduced by 85% (on average) and in many cases, eliminated the problem of reflection cracking on roads that contained cement stabilized pavement layers.

2.2.3 Bitumen-Rubber Seals

According to Hoffman & Potgieter (2007), bitumen-rubber is the most common modified binder for surface treatments in South Africa with seals being successfully used since 1982 on most rehabilitation projects, especially on roads where normal binders are ineffective. According to industry sources, there is currently 50,000 tons of bitumen-rubber binder currently being used for surface treatments such as chip and spray seals in South Africa. Hoffman & Potgieter (2007) additionally confirm that bitumen-rubber chip seals outperform conventional chip seals (penetration grade bitumen) as well as other modified binder seals (SBS, SBR, EVA) and is especially suited to highly cracked pavements or pavements susceptible to ingress of water.

2.3 Current State of Bitumen-Rubber Asphalt Mix Design in South Africa

Bitumen-rubber asphalt has performed exceptionally well on heavily trafficked roads as is illustrated by the 12 year's service life at the Buccleuch Interchange on the National Route N3 in South Africa (Potgieter et al, 1998; Potgieter, 2004).

The South African guideline on the design of and manufacturing of bitumen-rubber asphalt in South Africa was recently published by the South African Bitumen Association (Sabita, 2016). This manual comprehensively deals with material and blend requirements; occupational health, safety and the environment; the wet method mix design process; plant and equipment; general precautions for storage of mixes; and quality assurance. It particularly also deals with the design of continuously graded, gap-graded, and open-graded bitumen rubber asphalt. It provides a matrix for selection of the appropriate mix type based on a number of performance requirements (flexibility, rut-resistance, functional performance). Lastly, it provides a range of mix design criteria for the typical grading's used.

3. Overview of CSIR Research

3.1 Fatigue Resistance of Bitumen-Rubber Asphalt

It is well known that bitumen-rubber asphalt provides good resistance to fatigue under repetitive loading. This has been verified through many laboratory experiments (Visser and Verhaeghe, 2000). It has also been verified during HVS testing. One such example was the project to evaluate mixes from the California Department of Transport (Caltrans) in a trial section in South Africa (Rust *et al.*, 1994). In this test, on a pavement with a surface deflection of 1,25mm, a 75 mm gap graded asphalt started cracking after only 100,000 repetitions of a 40 kN wheel load. A 38mm thick bitumen-rubber asphalt layer was subjected to 175,000 repetitions of a 40kN load and 25,000 repetitions of an 80 kN wheel load with no apparent cracking. The surface temperature was then reduced to -5 ^{0}C and a further 250,000 repetitions of loading applied after which only half of the test section was cracked. This clearly indicated the superior performance of the bitumen-rubber asphalt and informed the decision by Caltrans that they can half the thickness of the surfacing if they use a bitumen-rubber binder.

3.2 Resistance of Bitumen-Rubber Asphalt to Permanent Deformation

Long-term pavement performance evaluations conducted on pavements surfaced with bitumen-rubber asphalt have shown that no rutting could be observed on a number of trial sections (Visser and Verhaeghe, 2000). Bitumen-rubber asphalt rutting resistance was excellent even when used on very heavily trafficked routes in South Africa, such as the National Route 3, the National Route 1 north of Cape Town and the N1-N3 Buccleuch Interchange located between Johannesburg and Pretoria. A number of these monitored sections were older than 10 years and had carried traffic in excess of 30 million equivalent axles.

A similar result was observed in HVS testing of a 40 mm bitumen-rubber porous asphalt overlay on 40 mm compounded seals and a 600 mm gravel structure (Du Plessis *et al.*, 1994). The pavement was very flexible (1.44 mm deflection) and the purpose of the test was to determine the performance of a porous asphalt mix in terms of permanent deformation at both ambient (23ºC) and elevated (37ºC) temperatures. After 125,000 load repetitions at 40 kN and 50,000 repetitions at 70kN, the rut depth in the porous asphalt layer was less than 1 mm. No raveling or other signs of surface deterioration could be observed. These tests led to a recommendation that bitumen-rubber be used as binder for heavily-trafficked porous asphalt mixes with void contents in excess of 20 percent.

3.3 Retarding Crack Reflection using Bitumen-Rubber Materials

The reflection of cracks in road pavements through overlays and seals with the associated ingress of water into road pavements is a significant problem in a number of countries and regions. This mode of distress can invalidate the expenditure on road maintenance. This has been a particular problem in South Africa where cemented base and subbase layers had historically been built. Many of these pavements are still in use.

Since the mid 1980's, a significant amount of work has been done in South Africa (Rust, 1987) to investigate and solve this problem. This work lead to the development of the following:

- The CAM that can be used to measure actual crack movement under a moving dual truck wheel load in the horizontal and well as vertical directions;
- The Crack Movement Simulator (CMS) that can simulate both horizontal and vertical movement of a crack in the laboratory and can be used to conduct fatigue testing of modified binders under simulated crack movement;
- The classification of crack movement into four categories based on testing with the HVS as well as performance monitoring of overlays in the field, with associated recommendations for the design of overlays or surface treatments on active cracks, and
- The development of a design procedure based on these results.

3.3.1 The CAM

The CAM was originally developed in the 1980's to measure the actual movement of cracks under truck wheel loads. Subsequently this device has been improved and offered to all owners of HVS machines world-wide as part of the HVS-associated equipment package. A number of HVS owners are currently using the equipment to date. Figure 1 shows a photograph of the CAM.

The CAM provides an influence line of crack movement as the wheel load passes over the crack. A typical crack movement influence line is shown in Figure 2.

Figure 1: The Crack Activity Meter (CAM)

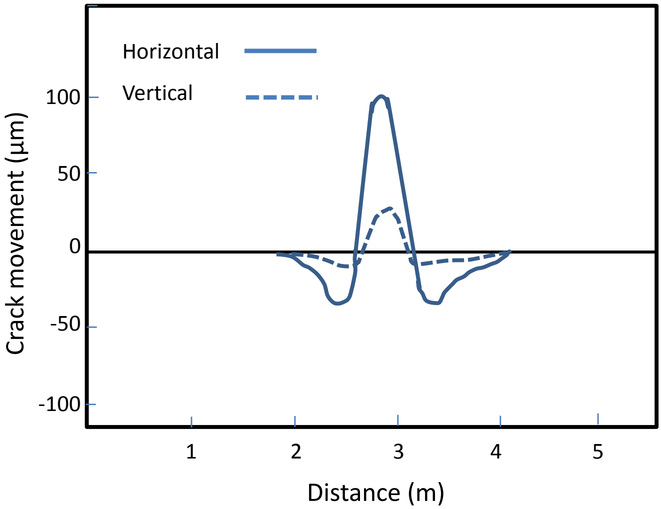

Figure 2: Typical horizontal and vertical crack movement as measured by the CAM

It is interesting to note that the horizontal crack movement shows a negative (tensile strain) peak as the wheel approaches and another tensile peak as the wheel passes. This implies for every wheel passing over the crack the overlay or surface treatment is subjected to ***two*** tensile strain periods. This has implications for designs based on laboratory fatigue curves where singular repetitions of tensile strains are applied (halving of the estimated design life).

The opening and closing of the cracks due to the wheel movement is depicted in Figure 3 below. In the concave (centre) part of the deflection basin, the cracks close. In the convex (edges) parts of the deflection basin, the cracks open.

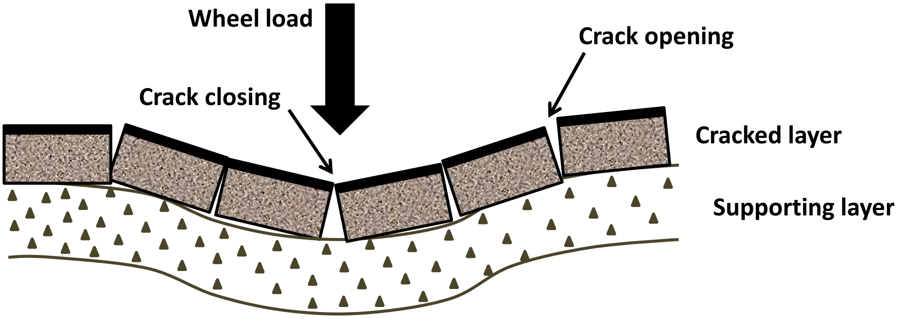

Figure 3: Opening and closing of cracks due to the shape of the deflection basin

The study of the shape of the curves, as well as the changes in the size of blocks between cracks measured during this work, led to the conclusion that crack movement is related to the size of the blocks between the cracks. This is depicted in Figure 4 below.

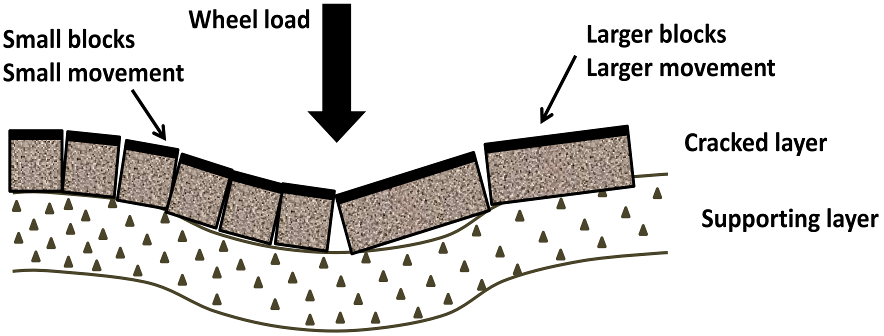

Figure 4: Relationship between block size and crack movement

The combination of the block size with the shape of the deflection basin where smaller blocks are less active is the foundation of the practice to "crack and seat" cemented or concrete layers before overlaying, thus reducing the activity of the cracks and the risk of crack reflection (Williams *et al.*, 2015).

3.3.2 The Crack Movement Simulator (CMS)

In order to study the performance of modified binders in sealing of active cracks, the CSIR developed the CMS. Figure 5 shows a schematic diagram of the CMS.

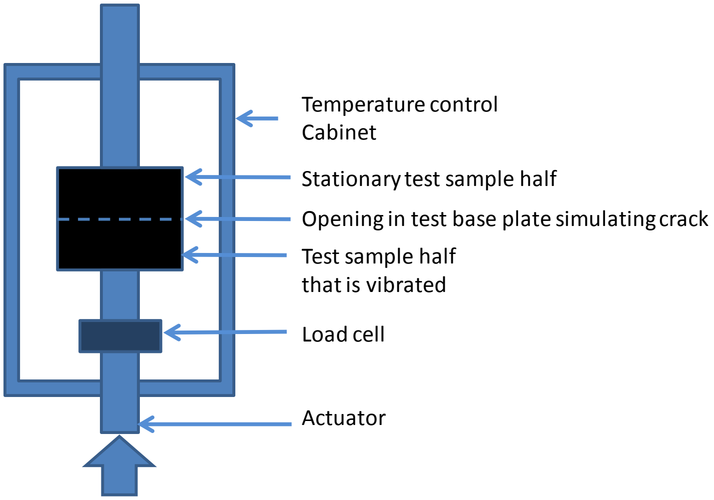

Figure 5: Schematic diagram of the Crack Movement Simulator

This device could simulate both vertical and horizontal crack movement under controlled temperature conditions. A variety of binders available in South Africa at the time, were tested for fatigue under simulated crack movement including bitumen-rubber binders. Figure 6 shows the results of the CMS fatigue testing. It can be noted that the bitumen-rubber binders performed superior to the other binders.

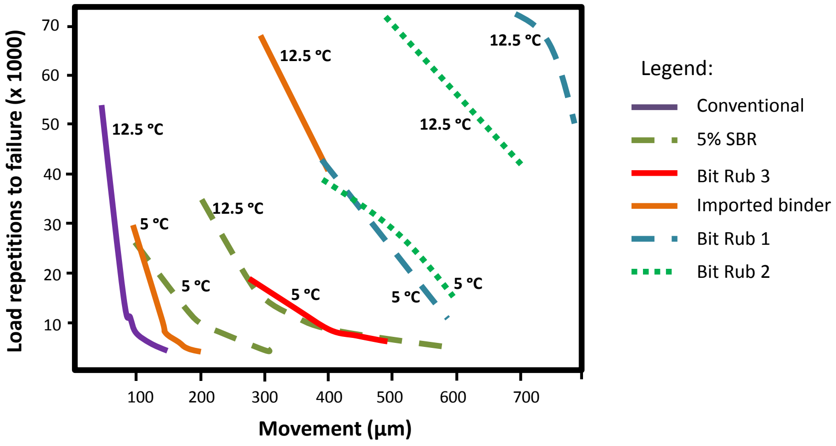

Figure 6: Fatigue curves of binders tested in the CMS

Two parameters were defined to evaluate the relative performance of binders in this test, M_{50} and CMS_t. M_{50} is the level of crack movement at which the binder will last for 50,000 repetitions in the CMS test at a specific temperature. CMS_t is the ratio of M50 at º5 C and 12,5 ºC, indicating the temperature sensitivity of the binder for fatigue. These parameters can be used to compare the relative performance of binders in fatigue under simulated crack movement.

Results of fatigue testing with the CMS on historic binders available in South Africa at the time are shown in Table 1 below (Rust *et al.*, 1992).

Table 1: *Relative performance of binders in the CMS test*

Binder	M_{50} fatigue life at Temp		CMS_t
	5 °C	12.5 °C	
Bitumen Rubber 1	370	800	2.16
Bitumen Rubber 2	310	640	2.06
PVC tar	300		
Bitumen rubber 3	150		
Imported polymer binder	80	360	4.5
5% SBR modified	80	180	2.25
2% SBR modified		50	
Conventional bitumen		50	

It is noteworthy to observe that the bitumen-rubber binders outperformed the other binders, both in fatigue life as well as sensitivity to colder temperatures.

3.3.3 Field Evaluation of Surface Treatments on Active Cracks

Trial sections were constructed on the National Route 3, Section 12 to evaluate the performance of several modified binders over active cracks under real traffic. In order to ensure some comparative crack movement for each section of modified binder, concrete blocks as shown in Figure 7 were constructed on 14 sections containing two blocks each. Underneath one end of the blocks a rubber layer was placed to allow the blocks to "rock" under traffic, thus simulated crack movement. The blocks were designed to give a relatively higher and a lower crack movement on each section. The movement of the blocks was measured with the CAM prior to application of the surface treatment. The sections were then surfaced with a 13.2mm single seal containing several modified binders as well as a conventional bitumen.

The following binders were used:

- Three different types of bitumen-rubber;
- Two locally produced SBR polymer modified binders;

- An imported modified binder;
- PVC-modified tar;
- A tar-bitumen blend with crumb rubber;
- A tar-modified with crumb rubber, and
- A conventional 80/100 pen grade bitumen.

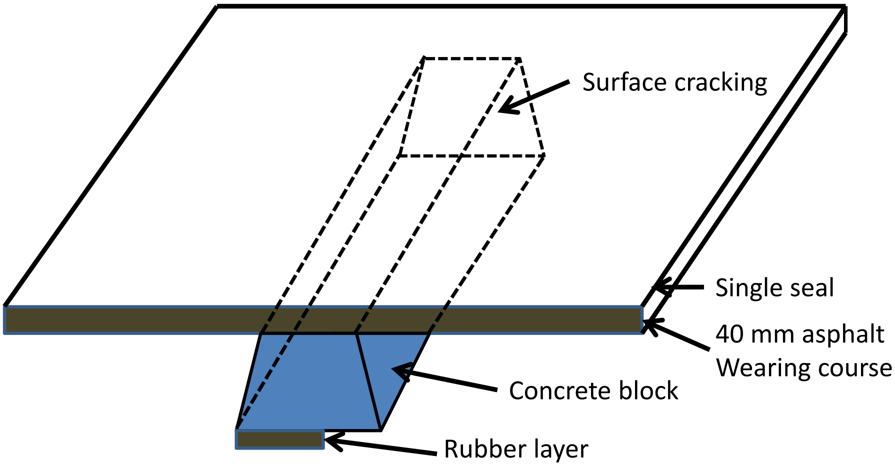

Figure 7: Schematic of blocks built into the test sections at

Due to construction variability, some of the blocks had very low crack movement. The sections were monitored over a five year period to evaluate their ability to withstand very active cracks. These results are given in Table 2.

Table 2: *Performance of binders in field trials*

Binder	Application rate (l/m^2)	Initial block movement (µm)	Equivalent traffic to cracking (E80s)
PVC tar	1.3	845	292,000
2% SBR	1.07	335	510,999
PVC Tar	1.2	369	955,000
Bitumen rubber 1	2.37	641	1,047,000
Bitumen rubber 2	2.15	248	1,142,000

Although the block movements were variable, the data in Table 2 indicates that the bitumen-rubber binders performed very well.

Rust (1987) recommended the classification of crack movement measured with the CAM and the associated solutions as given in Table 3.

Table 3: *Recommended solutions for crack reflections*

Crack movement	Classification	Suggested solution
< 100 µm	Low	Conventional surface treatment
100 µm - 200 µm	Medium	Surface treatment with modified binder
200 µm - 300 µm	High	Modified binder asphalt
> 300 µm	Very High	Thick overlay or recycling

4. Gaps in Research and Future Developments

Studies conducted by Marais *et al.* (2017) conclude that latest developments in crumb rubber modified bitumen for use in surface overlays and seals in South Africa are showing significant promising improvements, particularly with regards to their rheological properties. There is therefore still a significant gap in research pertaining to the effective characterization of bitumen-rubber materials in South Africa. This is also potentially a significant research field wherein new technologies developed for the nanotechnology field may lead to the more effective characterization of bitumen-rubber materials and hence improve the retardation of crack reflection. The use of advanced observational techniques such as a Scanning-Electron Microscope (SEM) is also becoming exceedingly popular in the road industry. Numerous studies exist on the mechanisms in which characterization techniques such as SEM images may be used to successfully determine and understand the rheological properties of various products in the road industry (Yang and Tighe, 2013).

Recent findings at the Harvard University of Engineering and Applied Sciences also show a potentially significant future development for the bitumen-rubber industry (Engineers Australia, 2017). A new type of hybrid rubber with self-healing properties is currently being explored for further applications in the road engineering sector. Early observations of the rubber indicate that the material is able to distribute stress more effectively without the possibility of localized stresses causing cracking or failure. There is therefore a significant gap in research pertaining to the use of these self-healing hybrid rubber materials to formulate enhanced bitumen-rubber products.

5. Conclusion

Although crack refection from cemented layers has been a severe problem in South Africa, bitumen-rubber binders have been used successfully since the 1980’s to prevent and minimize this phenomenon. The binder has additionally been successfully used in surface treatments such as seals, bitumen-rubber asphalt layers and porous asphalt layers. Innovations such as the CAM used in conjunction with the HVS have led to the definition of load-associated crack movement and consequently an improved understanding of the mechanisms of crack reflection for the road industry. Subsequently, HVS testing and field performance observations of various bitumen-rubber materials have led to the development of a design matrix for retarding crack reflection.

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