Current Developments in Performance Testing of Bituminous Emulsions Used in Chip Seals

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***Abstract*—The use of bitumen emulsions in surface treatments has become prevalent due to advancements in emulsifier development, formulation techniques, and design of surface treatments. However, current practice for testing and selecting emulsion grades for chip seals remain mainly empirical, with little or no known relationship to the failures occurring in the field. The current practice appears to be more focused on quality control during the emulsion formulation process than on the in-service performance of the emulsions. Although significant progress has been made in developing performance-based test methods and specifications for hot mix asphalt binders, they cannot directly be adapted to emulsions used in chip seals.**

This paper carried out a literature review identifying common distresses occurring in chip seals, both during construction and in-service. Emulsion properties related to specific distresses as well as potential laboratory test methods for evaluating the identified emulsion properties were also identified. The information was used to propose a performance based testing framework for emulsions used in Southern Africa.

Keywords—Emulsions, perfomance testing, chip seals

I. BACKGROUND

The majority of the paved road network in Southern Africa is covered with surface treatments, of which chip seals are the most commonly used type of surface treatment [1]. A chip seal can be constructed using either hot binder or with bitumen emulsion. An emulsion is a mixture of bitumen and water in the presence of an emulsifier [2]. Emulsions have many advantages compared to hot binders such as low application temperature, ability to coat damp aggregate, low carbon emission, improved worker safety, and simple construction equipment [3].

The performance of a chip seal is greatly influenced by the properties of the emulsion used. However, the current approach for selecting an emulsion grade for surface treatment in Southern Africa remains mainly empirical, with little or no known relationship to the failures occurring in the field. In South Africa, current specifications for emulsions used in spray seals are contained in SANS 4001-BT3 and SANS 4001-BT4 for unmodified anionic and cationic emulsions respectively. These standards do not require testing to be done on the recovered residue as is the case in other countries such as in the United States and Europe; provision is only made for testing base bitumen properties. According to the TRH3 guidelines, testing on the residue is only specified for polymer modified emulsions as per TG1 guideline recommendations [3]. A summary of current emulsion tests used in South Africa are shown in Table I.

TABLE I. RECOMMENDED TESTINGOF POLYMER MODIFIED EMULSIONS FOR SURFACING SEALS.

Emulsion Property	**Test Method**
Properties of fresh emulsion (*Applies to both modified and unmodified emulsions**)	
Binder Content	MB-22/ASTM D244
Saybolt Furol Viscosity	MB-21/ASTM D244
Residue on Sieving	MB-23/SANS 4001-BT3/BT4
Particle Charge**	MB-24/SANS 4001-BT4
Sedimentation after 60 Rotations	SANS 4001-BT3/BT4
Properties of Recovered Binder Residue (MB-20) (*Polymer modified emulsions only*)	
Softening Point	MB-17
Force Ductility at 5°C	EN 13589 / EN 13703
Elastic Recovery at 15°C	MB-4

*Unmodified cationic emulsions are also tested for fluxing agent, binder deposit on electrodes and aggregate coating water resistance. Both unmodified anionic and cationic emulsions are tested for their coagulation value.
**not tested for anionic emulsions

Although the tests presented in Table I have been used successfully for decades, they bear minimal direct relation to common chip seal distresses realized in the field. South Africa is currently in the process of abandoning some empirical binder tests for asphalt binders, and replacing them with performance based tests [4]. However, specifications for asphalt binders cannot be adapted directly to surface treatments because they are developed with the focus of minimizing structural failures, and not functional failures which are addressed by surface treatments.

The absence of performance based guidelines for testing and selecting bituminous binders for surface treatments could have detrimental effects on their service lives. Therefore, emulsions for chip seals should be evaluated for their ability to resist common failures occurring in the field under given climatic and traffic conditions. Significant research has been carried out in the United States (US) in the last decades, which has focused on developing performance based tests and specifications for emulsions and binders used in surface treatments. This paper capitalizes on the US developments to deliver the following objectives for the Southern African region:

- Identify common distresses occurring in chip seals and the properties of emulsions related to these distresses,
- Identify potential performance based test methods for evaluating the emulsion properties identified,
- Make recommendations for developing a performance based testing framework for emulsions used in chip seals in Southern Africa, based on scientific understanding of factors affecting performance and the main mechanisms of chip seal failures.

II. PERFORMANCE CHARACTERIZATION OF BITUMINOUS BINDERS USED IN CHIP SEALS

The concept of developing a performance-based grading of emulsions used in surface treatment has been investigated by many researchers both in the United States, Europe and South Africa. This effort was first initiated by the Texas Department of Transportation (TXDOT) in 2000 and is presented in the Surface Performance Grading System (SPS) [5]. This study used SuperPave testing equipment (Dynamic Shear Rheometer (DSR) and Bending Beam Rheometer (BBR)) with adjustments to account for the use of emulsions and its application at the pavement surface. The small thickness of chip seals was accounted for by defining the high pavement temperature at the surface rather than at 20 mm below as used for asphalt mixtures. Adjustments were also made to aging and high and low temperature methods [5]. Field validation was carried out after one year in-service by comparing SPG results to the environmental conditions in various areas of Texas and visual field surveys. It was noted that for 76% of the materials used, the SPG agreed with the climatic grades required by analysis of surface temperature in the LTPP database [6]. The results of these research efforts contributed significantly to the advancement of emulsion testing technology. However, the results of the TXDOT studies were limited to the linear elastic performance parameters, and this may not be adequate to describe the distresses realized in chip seals under traffic loading.

The concept of emulsion selection based on critical failure mechanisms that impact the functionality of a surface treatment was first introduced by Bahia, Jenkins and Hanz [7]. This work identified failure mechanisms that compromise surface treatment functionality as loss of surface texture at high and intermediate temperatures due to bleeding or aggregate loss and loss of impermeability at intermediate and low temperatures due to cracking. This work also recognized that surface hardness and stiffness of underlying layers, traffic speed and loading, and climate in terms of temperature and moisture also influence performance [7]. This study proposed a testing framework that addresses critical modes of distress and considers the effects of these external factors through application of tests at a wide range of temperatures and modes of loading.

Further advances were also made in the Federal Lands Study (FLS) by defining test methods for evaluating polymer modified emulsions [8]. This work recognized that the high temperature vacuum distillation procedure (ASTM D244) is not suitable for recovering residues of latex modified emulsions, and piloted a low temperature residue recovery method (ASTM D7497 – Method A). The study also proposed a testing framework that uses the DSR and BBR to characterize emulsion residue properties after recovery and Pressure Aging Vessel (PAV) aging.

Hanz and co-workers [9] also developed a performance based testing framework for evaluating emulsion residues building on the foundation of the work carried out by earlier researchers. The study proposed using the DSR and the Bitumen Bond Strength (BBS) adhesion tester to characterize emulsion residue properties after recovery and PAV aging. Proposed tests included the Multiple Stress Creep and Recovery (MSCR) test at high temperatures, BBS and Linear Amplitude Sweep (LAS) test at intermediate temperatures, and the DSR to evaluate low temperature performance. The results indicate that the proposed test methods were able to differentiate between emulsion types, and showed sensitivity to temperature and traffic [9]. The main improvements of this study were the inclusion of bond strength, effects of moisture evaluation, resistance to fatigue and low temperature properties using the DSR and utilizing smaller amounts of recovered residue.

Efforts are also currently under way to develop related specifications for bituminous binders used in preservation treatments commonly used in the United States in the current on-going NCHRP9-50 project.

III. COMMON FAILURES OCCURING IN CHIP SEALS

Distresses commonly occurring in chip seals can be classified in three groups: (1) those that occur during construction (constructability), (2) immediately after construction (short-term performance), and (3) after some time of being in service (long-term performance) [7]. The distresses, corresponding emulsion properties and the temperature at which the distress occurs are given in Table II. The distresses are briefly described in subsequent sections, and the binder properties related to the respective distresses are identified.

TABLE II. COMMON FAILURES OCCURING IN CHIP SEALS CONSTRUCTED WITH EMULSIONS LINKED TO RELEVANT EMULSION PROPERTIES

Treatment Type	Distress Type	Emulsion/Residue Property	Temp
During Construction	Storage stability	Viscosity	Storage
	Streaking	Viscosity	Spraying
	Drain-out	Viscosity	Pavement
Short-term Perfomance	Aggregate loss	Cohesive & adhesive bond strength	Intermediate/ High temp
Long-term Performance	Raveling & moisture damage	Bond strength & strain tolerance	Intermediate
	Bleeding	Stiffness/creep compliance	High
	Reflective cracking	Stiffness & elasticity	Intermediate
	Low temp cracking	Creep stiffness & stress relaxation rate	Low

A. Storage Stability

Storage stability is defined as the ability of an emulsion to resist significant change in physical and rheological properties over time [1]. An un-stable emulsion will cause problems with pumping, spraying, breaking, and wetting of the aggregate. Instability can happen through a change in physical properties (creaming or sedimentation) or rheological properties (flocculation, coagulation, coalescence, and phase inversion) [2][3]. Factors such as, improper emulsion formulation; handling emulsions in metal containers; mixing with water that has high amounts of dissolved ions; cold temperatures; and mixing emulsions of different charges, all contribute to emulsion instability [2].

Current practice employs the Sedimentation (SANS 4001 BT3/BT4) and Residue on Sieving test (ASTM D244) to evaluate storage stability. Both tests measure physical properties, and do not evaluate the change in rheological properties, which are directly related to in-service chip seal performance. Viscosity could be used as an indicator of the rheological stability.

The viscosity of emulsions is currently measured with a Saybolt Furol Second (SFS) Viscometer (ASTM D7496). The advantages of the SFS are low cost, ease of cleaning, durability, and simplicity in the measurement. However, the SFS does not allow for emulsions to be evaluated at different shear rates similar to those experienced in the field. The shear rate used is also not representative of field conditions. Some emulsions behave like thixotropic or pseudoplastic liquids, i.e. their viscosity depends on magnitude and duration of shearing [10]. The Rotational Viscometer (RV) similar to that specified in AASHTO TP 48 and ASTM D4402 has been reported to be suitable test for evaluating viscosity of shear thinning liquids [10]. The RV is currently used in the SuperPave system to measure the viscosity of bituminous binders. The RV requires relatively small amounts of materials to run the test, allows for accurate control of the temperature, less dependent on operator, and requires less cleaning time.

One potential approach for evaluating storage stability is to use the procedure similar to the Laboratory Asphalt Stability Test (LAST) test developed for modified asphalt binders in the NCHRP 9-10 project [11]. The two performance parameters measured are: separation ratio (R_S) and stability (degradation) ratio (R_d), and are calculated using the equations (1) and (2) below.

$$\text{Separation ratio } (R_S) = \frac{\text{Viscosity of the top sample}}{\text{Viscosity of the bottom samples}} \tag{1}$$

$$\text{Stability (degradation) ratio } (R_d) = \frac{\text{Viscosity after conditioning}}{\text{Viscosity before conditioning}} \tag{2}$$

The R_s is used to measure percentage change in the viscosity of the emulsion sample taken from the top and bottom of a cylinder after a certain conditioning time. The R_d is used to measure the change in the rheological properties (viscosity) of the emulsion after a certain condition period and temperature.

Fig. 1 shows an example of the storage stability parameters of the different emulsions commonly used for chip seals. The results were tested at 60ºC and a shear rate of 4.65 s^{-1} to simulate the agitation process occurring in the field. The emulsion was conditioned at 60ºC for 24 hours before testing. Emulsions with stability parameters close to unity indicate excellent stability against both physical separation and rheological degradation; while those with large deviation from unity indicate the opposite.

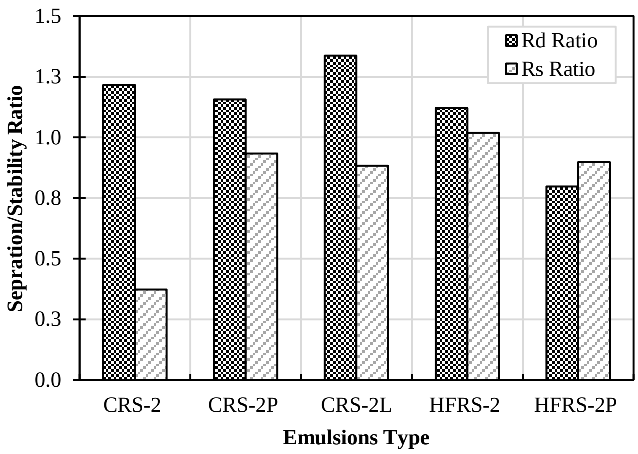

Fig. 1. Example of the use of viscosity results to evaluate storage stability.

It can be observed from Fig. 1 that the procedure can differentiate between emulsion type and the effects of modification. The CRS-2 emulsion experienced the highest physical separation with a separation ratio of 0.37, while the latex modified, CRS-2L shows the highest change in rheological property (degradation ratio) of 1.3. The high float emulsion, HFRS-2 emulsion shows the highest stability against both separation and change in rheological properties during storage. The results show potential for improving emulsion storage stability characterization based on viscosity.

B. Streaking and Drain-out

Streaking occurs when the emulsion is too viscous and cannot to be uniformly sprayed on the surface of the pavement [1]. It can also occur if the emulsion viscosity after application returns to a highly viscous state that prevents it flowing out to achieve uniform distribution. Areas with higher binder application may suffer from spot bleeding, while those with insufficient binder may experience aggregate loss. Factors contributing to streaking include emulsion viscosity, nozzle pressure and emulsion temperature, incorrect nozzle or spray bar setting, and blocked nozzles [12]. Drain-out on the other hand occurs when the viscosity of the emulsion is too low, such that it drains off the road camber by gravity after spraying [3]. Drain-out leads to premature aggregate loss as a result of insufficient binder present for proper aggregate embedment, and may cause environmental issues if the emulsion drains into natural water bodies. Factors affecting drain-out are emulsion viscosity, road geometry, and pavement temperature at the time of spraying.

Johannes and Bahia [13] proposed a new testing procedure for evaluating sprayability and drain-out with the Brookfield RV, using a testing procedure called the 3-Step Shear test. This procedure employs a higher shear rate to evaluate sprayability, and a low shear rate to evaluate drain-out. Prior to subjecting the emulsion to a high shear rate, the emulsion is first conditioned with a low shear rate to simulated agitation. Fig. 2 shows a graphical representation of the results from the 3-Step-Shear Test for three emulsions.

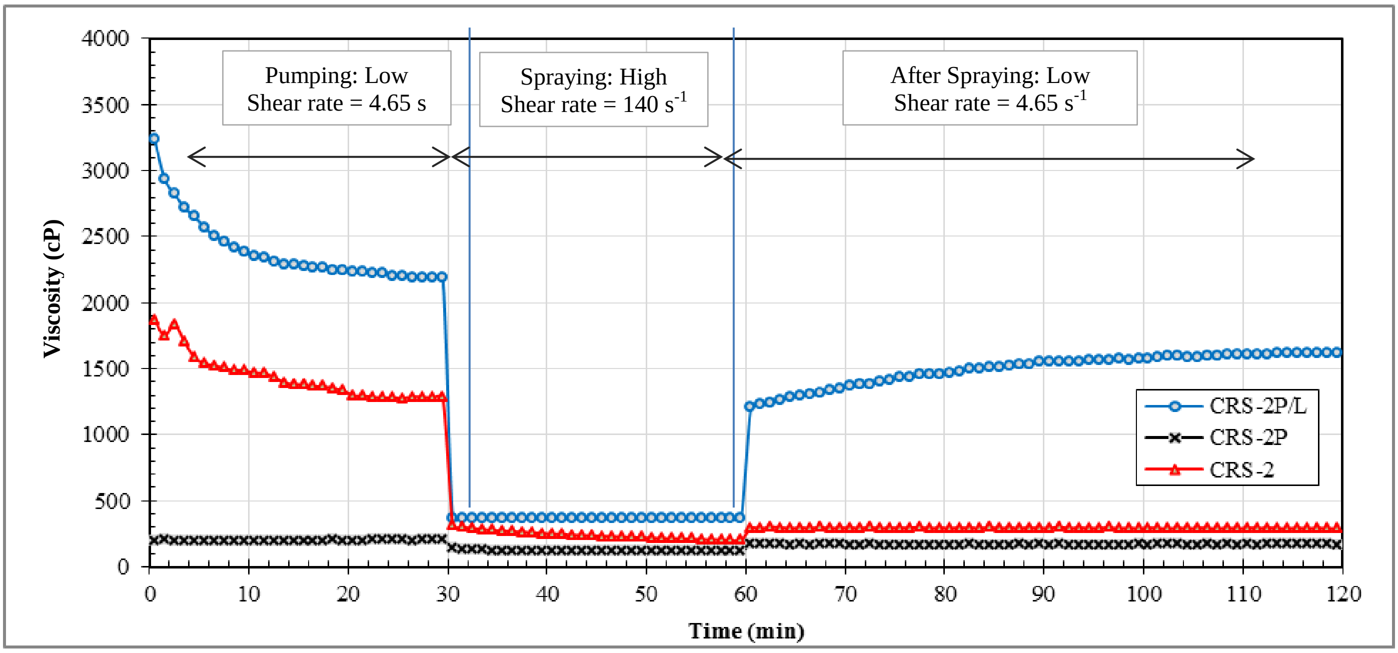

Fig. 2. Example of the emulsions viscosity from the representation of the 3-Step Shear Test at 60°C.

A low viscosity at high shear rate is desired to prevent streaking, while a high viscosity is preferred at low shear rate to prevent drain-out. It can be seen that the test can clearly differentiate between the viscosities of different emulsions under different shear rates. The change in viscosity from Step 1 to Step 2 shows that all three emulsions may have good spraying characteristics when subjected to a higher shear rate. The CRS-2L/P shows both desired characteristics for sprayability and good resistance to drain-out. However, the CRS-2 emulsion may potentially experience problems with drain-out because it does not recover its viscosity after being subjected to a higher shear rate. The trend observed for the different emulsions cannot be made by using the SFS test, and hence the need for a performance related test method for emulsion viscosity. However, specifications are needed to establish maximum viscosity at high shear rate and minimum viscosity at low shear rate.

C. Resistance to Early Raveling

Post construction, the main distress that can occur on chip seals constructed with emulsions is premature aggregate loss, also known as raveling. Emulsions need sufficient time to cure and revert back to a residue with rheological properties similar to those of the binder from which it was emulsified. Factors affecting the rate at which the emulsion develops cohesive and adhesive strength are curing temperature, emulsion type, wind, and humidity, aggregate mineralogy, and emulsion chemistry [3].

Miller [14] proposed using the bond strength of the emulsion cured and the aggregate under specific conditions as a parameter for evaluating resistance to early raveling. The test is carried out using the BBS test procedure as provisionally accepted as AASHTO Test Method (TP-91). The BBS test protocol requires a bond to be prepared between an aggregate substrate and the emulsion or emulsion residue under controlled conditions of temperature and humidity. A pull-off stub is attached to the binder and subjected to a pull-off tensile pressure. The maximum force required to detach the pull-out stub is used as the performance parameter, with a higher pull-off bond strength preferred. An example of the results of the BBS test for common emulsion and aggregate type used for chip seals is given in Fig. 3. The emulsions were cured at 30ºC and tested after 6 and 20 hours of conditioning.

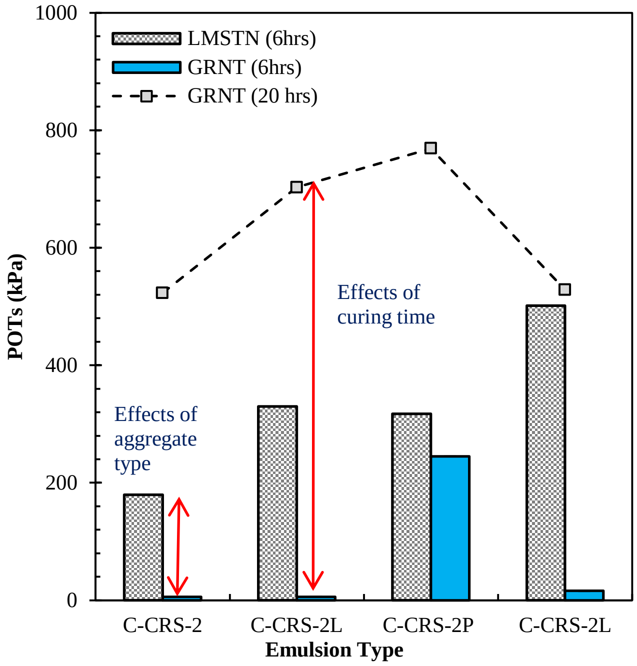

Fig. 3. Example of BBS test results for evaluating resistance to early raveling

The results show that the test can differentiate between emulsion types, aggregate type, and curing time. At six hours of curing, three out of four emulsions show bond strengths below 16 kPa when tested on granite, while all four emulsions experienced bond strengths above 180 kPa when tested with limestone under similar conditions. After 20 hours of curing, all four emulsions tested on granite show values of bond strengths above 530 kPa. The results show that when granite is used, the road needs to be closed off for more than six hour before opening to traffic, while a shorter opening time is needed when limestone is used. The results of the BBS presented show how the test could be used by road agencies to select material combination that would result in a shorter closing time of the road to the public for example. However, minimum acceptable bond strength values needs to be established based on field data.

D. *Late Ravelling*

Late raveling occurs as result of many factors including low temperatures, binder aging and oxidation, traffic loading, aggregate-binder interaction and moisture damage. Potential mechanisms for raveling in-service include adhesive failures at the asphalt/aggregate interface or cohesive failure within the bituminous binder, and low strain tolerance of the binder under different traffic loadings and repetitions [1][7][9].

To evaluate late raveling and the effects of moisture on raveling, Hanz et al. [9] proposed using a combination of the BBS and DSR equipment to evaluate the bond strength of recovered residue both dry and moisture conditioned, as well as strain tolerance respectively. Fig. 4 show an example of the BBS results for emulsion residues tested before and after water conditioning. The residue was recovered using the low temperature residue recovery procedure specified in ASTM D7497 and the BBS test procedure in AASHTO TP-91. Testing was carried out at 22ºC. For each emulsion type, two emulsions from different suppliers were tested using granite substrate. The results show all six emulsions with similar bond strength when tested in the dry condition. After moisture conditioning, the bond strength of three of the six emulsions tested reduced by 60%. The results also show that emulsions with the same generic name but formulated by different suppliers exhibiting different moisture damage behaviors. Even the ability of some polymer and latex modified emulsion to resist moisture is depended on the chemical formulation used by the company making the emulsion.

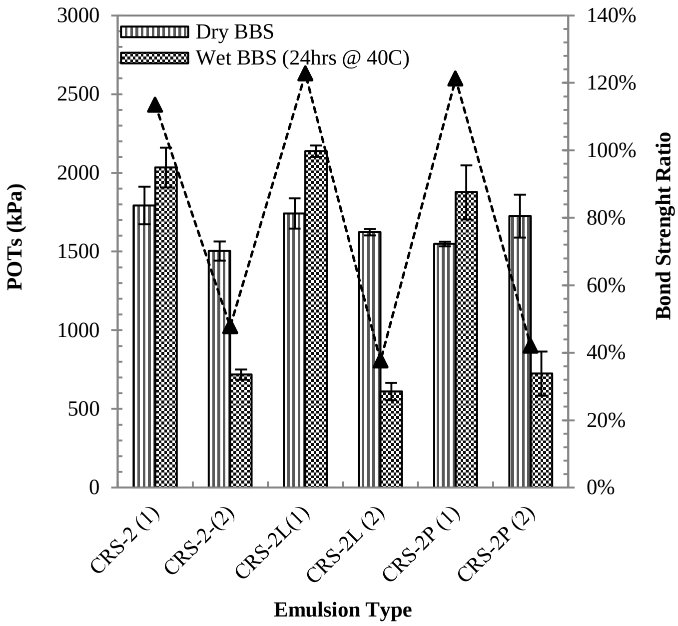

Fig. 4. Example of the effects of moisture on the bond strength of emulsion residues.

In addition to adhesive and cohesive strength, the thin film of binder between the bitumen-aggregate interfaces is subjected to high strains, particularly under slow or heavy traffic loading. Emulsion residues that lose strength following tire contact aggravate aggregate loss. Hanz et al. [9] proposed using the Strain Sweep Test of the Linear Amplitude Sweep (LAS) test to evaluate strain tolerance of emulsion residues. The LAS is carried out in the DSR by systematically increasing the strain applied binder from 0.1 % to a certain desired maximum level. The binder is subjected to 100 cycles at each strain before incrementally increased to the next level to accelerate damage. The strain at maximum stress is taken as the performance parameter for evaluating strain tolerance. Fig. 5 shows an example of the strain at maximum stress experienced by different emulsion residues in the LAS test before and after PAV aging.

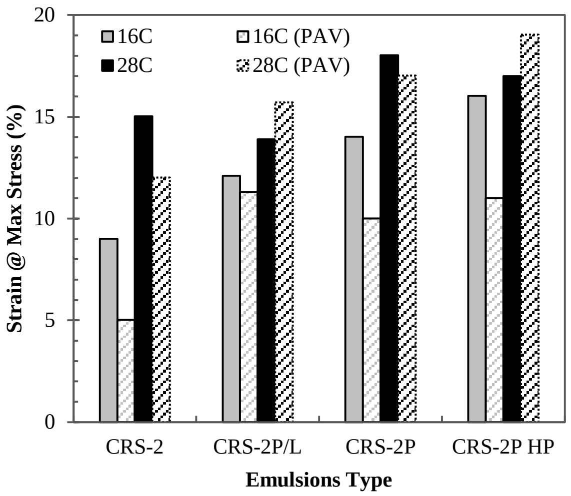

Fig. 5. Example of the LAS test results for the Strain at Maximum Stress

The results show that emulsion chemistry, temperature and aging affect the strain tolerance of emulsion residues. The strain at maximum stress increases with increase in temperature. The results also appear to show polymer (CRS-2P) and latex (CRS-2L) modified emulsions having higher strain tolerance than unmodified emulsions. The effects of aging also appear to be dependent on the chemistry of the emulsion.

E. Bleeding and Flushing

Common distresses occurring in chip seal at high temperatures are bleeding and flushing. Flushing is the loss of surface texture due to the rising of the binder to the seal surface as a result of high binder application rate, use of soft binder in hot climate, embedment of the aggregate into the existing surface, or breaking down of aggregate [12]. Bleeding occurs when the binder on the surface of a flushed surface becomes soft in hot weather, and adhere to the vehicle tire, getting tracked over the surrounding road. The binder coats the microscopic surfaces of the aggregate, creating a slick surface with lower skid resistance, and causes safety concerns. The practice in New Zealand and Australia has been to use hard binders that will prevent the aggregates from being pushed into the underlying layers or that won't get tracked over surface aggregate [12]. However, the use of hard binder has resulted in some premature failures of the chip seal during freeze/thaw cycles in New Zealand [12].

Current specifications for higher temperature performance characteristics of emulsion residues in the United States are specified according to the Penetration (ASTM D5) test. However, this testing system has been phased out of Hot Mix Asphalt (HMA) binder, as a result of the 1987 - 1993 Strategic Highway Research Program (SHRP), which documented many shortcomings with the method. To prevent rutting, flushing or bleeding, an asphalt binder (or residue) should be stiff (not deform too much under load), and should be elastic (able to recover its shape not accumulate permanent deformation) at higher temperature. The SuperPave Performance Grading (PG) uses the DSR to specify a minimum strength modulus G* and a maximum phase angle (δ) to limit higher temperature distresses (rutting). This test method is limited to the linear viscoelastic range, it does not allow for the damage properties of the different binders (specifically modified binders) to be evaluated beyond the linear range [11].

The in situ binder in the chip seal is subjected to such higher traffic stresses and strains, damage properties of the binder may give a better representation of field conditions. Hanz et al.[9] and King et al. [8] proposed using the MSCR test (AASHTO TP70) to evaluate bleeding. The MSCR test can evaluate the ability of a modified binder to maintain elastic response at two stress levels (100Pa, and 3200Pa) while being subjected to ten cycles of stress and recovery. It is intended for use with residues from Test Method ASTM D7497 without conditioning them in the Rolling Thin Film Oven test when used for emulsion residues. The MSCR test allows for the option of evaluating binder damage resistance properties under higher stress conditions similar to those experienced by the chip seal in the field to be simulated. The non-recoverable creep compliance (J_{nr}) and its sensitivity to temperature and stress have been proposed as a potential evaluation parameter for bleeding. Binders with lower J_{nr} have been reported to be more resistant to permanent deformation and possibly bleeding [15] [11] [8]. An example of the results of J_{nr} at different test temperatures is provided in Fig. 6.

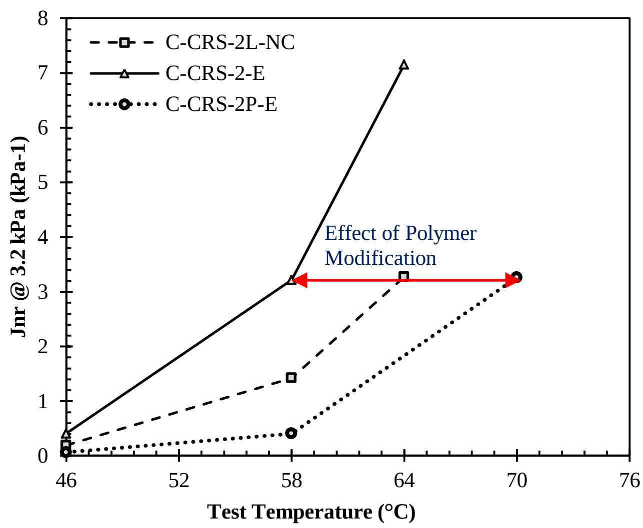

Fig. 6. J_{nr} vs. Temperature for Chip Seal Emulsion Residues.

The results show different emulsion residues with different J_{nr} values at the different temperatures. The C-CRS-2P-E potentially has better bleeding resistance characteristics than the C-CRS-2-E because of the lower J_{nr} values observed at different temperatures. The results also show a significant benefit to modification as both latex modified products achieves a J_{nr} value of 4.0 kPa^{-1} at test temperatures approximately 6°C or higher than most conventional emulsion residues. The results show potential for using the MSCR to evaluate bleeding potentials for binders used in chip seals.

F. Reflective Cracking

Reflective cracking occurs when cracks in the underlying layers reflect through a new surface treatment. Chip seals are not designed to bear any loading, and hence cannot be designed to resist fatigue cracking and reflective cracking. However, it is believed that damage properties of the bitumen used play an important role in delaying the occurrence of reflective cracking. When the bituminous binder is subjected to cyclic loading, the material's integrity deteriorates. The rate at which this integrity is lost is dependent upon the particular nature of the binder [16]. It is believed that asphalt binders that show poor resistance to fatigue may result in surface treatments that generally have a poor resistance to reflective cracking. Reflective/ fatigue cracking may also be worsened over time due to binder aging. The rate at which the binder hardens or oxidizes as it ages depends on the properties of the binder [11].

The Linear Amplitude Sweep Test (LAS) as provided in AASHTO TP101 has been used by other researchers [16] [9] to study the resistance to fatigue cracking for asphalt binders and emulsion residues, as well as to study the change in fatigue cracking resistance due to long-term aging. The procedure uses the fatigue law developed based on visco-elastic continuum damage (VECD) to predict fatigue life at different strain levels. Using the VECD analysis method, fatigue life is defined as the number of cycles to failure. Table III presents an example of test results of the LAS test for both un-aged and PAV aged residues conducted at 22ºC.

TABLE III. EXAMPLE OF TEST RESULTS OF THE LAS TEST

Emulsion	Fatigue Parameters		Numbers of Cycles to Failure @	
	A(intercept)	B (slope)	1% Strain	5% Strain
Un-aged Residue				
CRS-2	5.2E+04	-2.7	5.2E+04	6.4E+02
CRS-2L	5.1E+04	-2.7	5.1E+04	6.6E+02
CRS-2P	5.7E+04	-2.9	5.7E+04	5.6E+02
PAV-aged Residue				
CRS-2	2.7E+05	-3.7	2.67E+05	6.7E+02
CRS-2L	1.4E+05	-3.5	1.38E+05	5.3E+02
CRS-2P	3.9E+05	-3.8	3.88E+05	9.2E+02

The results show that different emulsions exhibit dissimilar fatigue characteristics. They differ in the number of cycles to failure of the un-aged and PAV-aged emulsion residues at different strain levels. Emulsion residues exhibiting a higher number of cycles to failure at higher strains are believed to have a greater ability of resisting the occurrence of reflective/fatigue cracking.

G. Low Temperature Cracking

Thermal cracking is caused by the buildup of thermal stresses that develop in the binder at low temperatures due to shrinkage. This process worsens with age, as the binder oxidizes and losses its flexibility. Current specification for low temperature performance of asphalt binder makes use of the BBR test specified in AASHTO T313. The same approach has been used to evaluate the low temperature properties of emulsion residues. However, the preparation of the BBR samples requires large amount of materials. Unfortunately, the current low temperature method for recovering asphalt residues specified in ASTM D7497 do not yield enough materials to cost-effectively produce the required number of BBR beams. Bahia et al. [17] presented a new method that uses interconversion methods developed by Ferry [18] and Anderson et al. [19] to estimate low temperature creep properties of asphalt binders from intermediate temperature shear properties measured in the DSR. The shear parameters (G*, δ) required to provide the estimates of stiffness and m-value, respectively, are obtained by developing a master curve based on data from a frequency sweep in the DSR at temperatures of 5°C, 10°C, 15°C and a frequency range of 1-150 rad/s. The testing temperatures and frequencies are selected based on the limitations of the DSR used to conduct the test. This test has shown a strong correlation and equivalency between measured and predicted values for both stiffness and m-value [17].

Figs. 7 and 8 show reasonable correlations of 20 selected binders in South Africa (8 unmodified and 12 modified) between the BBR at -6°C and DSR frequency sweeps done at 5°C.

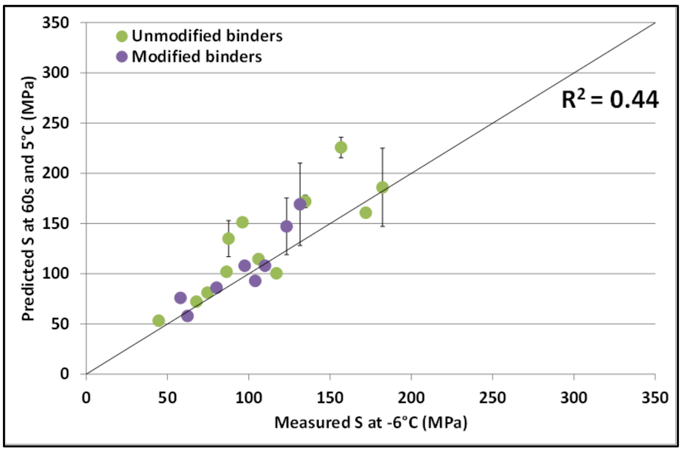

Fig. 7. Creep stiffness measured at -6 °C with the BBR and predicted at 5 °C with the DSR data [20].

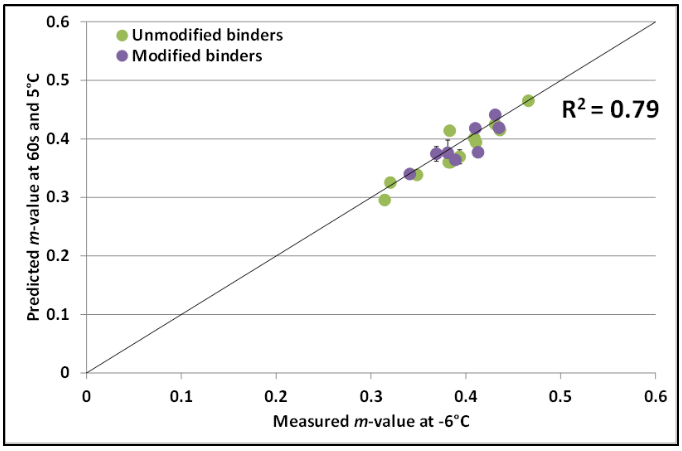

Fig. 8. m-value measured at -6 °C with the BBR and predicted at 5 °C with the DSR data [20].

The results show 40% correlation of the stiffness modulus (s) and 80% correlation with the relaxation modulus. The results shows potential in using the DSR to determine low temperature performance properties of emulsions residues.

H. Test Method for Identifying Polymer

Current protocol for the evaluation of polymer modified asphalts and emulsions uses the elastic recovery test specified in AASHTO T51 or TG1 MB-4 as an acceptance test. The test is not directly applicable to emulsion residues because the testing geometry requires excessive heating of the samples to ensure the material is fluid enough to be poured into a dog-bone shaped specimen. In addition, the procedure also requires large amount of materials for testing. To eliminate the need of over-heating the samples, the elastic recovery test using the DSR (ER-DSR) was proposed [9]. The test simulates the AASHTO T51 procedure in the DSR by subjecting an 8 mm sample to a shear strain rate of 2.32%/sec for 120 seconds followed by a controlled un-stressed condition for one hour. The percent recovery is calculated as the ratio of the strain after the recovery step to the strain at the end of the loading step. A strong correlation has been shown between ER-DSR results and the standard elastic recovery test. An example of the results of the ER-DSR is given in Fig. 9 for unmodified, polymer modified, and latex modified emulsion residues. The results show the effects of emulsion chemistry and modification on the elastic recovery of emulsion residues.

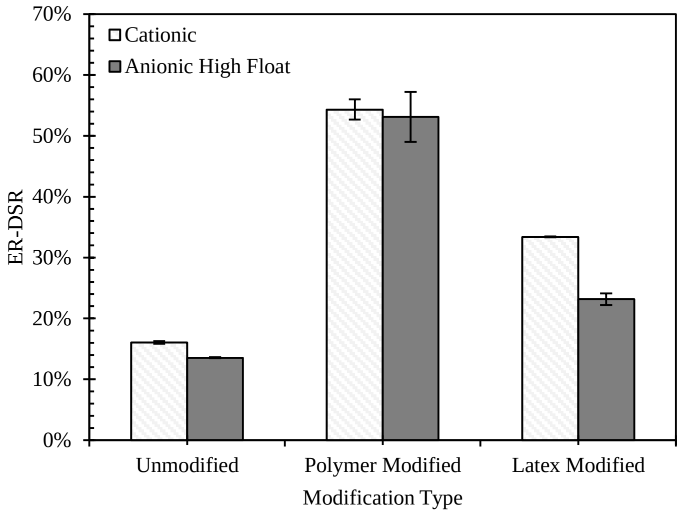

Fig. 9. Example of results from the ER-DSR test.

IV. CONCLUSION AND RECOMMENDATIONS

Current testing procedures for emulsions used for chip seals throughout Southern Africa do not include tests providing insight into common distresses prevalent in surface treatments. Significant effort has been carried out to improve tests and specifications for asphalt binders, and similar effort should be established for fresh emulsion properties and emulsion residues. This paper identified the primary failures that dictate performance of chip seals and binder properties associated with those distresses based on literature reviews. Potential performance related test methods recommended by various researchers were identified for each distress. Based on previous work, a framework for evaluating fresh emulsion properties and emulsion residue properties was assembled and is presented Tables IV. The testing framework presented in Table IV test allow for performance properties of emulsions during construction, at high, intermediate, and low temperatures to be evaluated under conditions that simulate varying traffic volumes, speeds, and aging conditions. It is recommended that the testing framework in Table V be used as a starting point for discussion, and developing performance-based specifications for material locally available in Southern African countries.

TABLE IV. PROPOSED TESTING FRAMEWORK FOR DEVOLOPING PERFOMANCE-BASED GRADEING FOR EMULSIONS

Engineering Property	Test Method	Parameter(s) Measured
Tests on Fresh Emulsion Properties (Constructability)		
Storage Stability	Modified ASTM D6930 – Settlement and Sedimentation	▪ Rotational Viscosity, η, ▪ B-24-hour Separation Ratio (R_s) ▪ C-24-hour Stability Ratio (R_d)
Sprayability	Modified AASHTO TP48 - Rotational Viscometer	▪ Rotational Viscosity, η, ▪ @ high shear at (XX 1/sec)
Drain-Out	Modified AASHTO TP48-Rotational Viscometer	▪ Rotational Viscosity, η, ▪ @ low shear rate (XX 1/sec)
Resistance to Early Raveling /Curing	AASHTO TP 91-11 Bitumen Bond Strength (BBS)	▪ A-Minimum Pull-Out Tensile Strength (POS) @ XX hrs. of Curing Time
Residue Recovery Method: ASTM D7497 Method B		
Resistance to Bleeding and Flushing	Multiple Stress Creep and Recovery Test (AASHTO TP 70)	▪ J_{nr} ▪ Stress Sensitivity
Resistance Raveling	Bitumen Bond Strength Test (AASHTO TP-91)	▪ Wet and Dry Pull-off Bond Strength ▪ Moisture Damage ratio
	DSR-Linear Amplitude Test	▪ Strain at maximum Stress
Early Fatigue	Linear Amplitude Sweep Test (LAS)	▪ Number of Cycles to failure (N_f) at specified % Strain
Polymer Identifier	Elastic Recovery DSR	▪ % recovery
Tests on PAV Aged (AASHTO R28) Materials		
Late Fatigue	Linear Amplitude Sweep Test (LAS)	▪ Cycles to failure (N_f) at specified % Strain ▪ Aging Susceptibility
Resistance to Thermal Cracking	DSR Frequency Sweep to estimate BBR properties.	▪ Estimated S(60), m(60)

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