

DEVELOPMENT OF A TEST METHOD FOR DETERMINING EMULSION BOND STRENGTH USING THE BITUMEN BOND STRENGTH (BBS) TEST - A SOUTH AFRICAN PERSPECTIVE

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Abstract

The need to understand and scientifically quantify the expected behavior of surfacing seals has been around for as long as bitumen and aggregate have been used to surface roads. The design of surfacing seals has generally been based on available materials, skills and current client preferences.

Tests performed on surfacing seal aggregate and bitumen binders are normally limited to ensure that the separate materials comply with their relative classification specifications. During the seal design process, no tests are conducted to quantify the bond strength that develops between various binders and aggregate combinations. Developing practical and effective test methods to characterize this bond strength is therefore critical for pavement designers and contractors to predict how a surface seal will perform over the expected service life.

Research conducted at the University of Wisconsin – Madison (UWM) identified the Pneumatic Adhesive Tensile Testing Instrument, commonly known as PATTI, as an appropriate instrument for evaluating bond strength development in the newly developed Bitumen Bond Strength (BBS) test. (AASHTO TP-91, 2011) Recently developed at the UWM in conjunction with the University of Ancona – Italy and the University of Stellenbosch – South Africa, the BBS test procedure has been used successfully to characterize moisture sensitivity and bond strength development in hot-applied binders and bitumen emulsions, respectively (Miller 2010). This paper describes the test method and evaluates the relevance of the procedure using bitumen and bitumen emulsions produced in South Africa and U.S.A.

1- INTRODUCTION

Chip and spray surfacing seal design has experienced renewed interest and continuous improvement and development is several countries over the past two decades. In South Africa, seals are continually used as more and more attention is given to the periodic maintenance of existing surfaced roads. There is also a significant increase in the use of surfacing seals in North America as the need to develop more energy and resource efficient surfacing options becomes a priority.

Despite this growing surface seal use, the selection of binder type and grade does not always follow rigorous scientific processes. Most seals are designed based on experience and relying on common practice and best judgment. Historically, empirical information and contractor experience strongly influence surface seal design.

With increasing traffic volumes and heightened performance demands, performance-based specifications are being developed in the USA and Europe to account for deficiencies in surface seal design methodologies (Bahia et al, 2010;Opus International Consultants, 2010) Performance-based specifications for surface seals identify the need for a simple and inexpensive technique for evaluating emulsion bond strength development over time as well as binder-aggregate compatibility.

Although various tests exist for investigating adhesion between bituminous emulsions and aggregate chips (Comité Européen de Normalisation, 2009), some of these tests have limited application to performance-based specifications. The Bitumen Bond Strength (BBS) test method aims to address some of the limitations encountered in evaluating bond strength. Researchers at the University of Wisconsin – Madison (UWM) recently developed the BBS test (AASHTO TP-91, 2011) in partnership with the University of Ancona – Italy (UAI) and the University of Stellenbosch – South Africa (USSA) for hot applied binders and emulsions, respectively.

USSA became involved in BBS test efforts in 2008 to assist in the development and evaluation of the BBS test method, while UAI contributed significantly to the development of the test apparatus over the past four years. Due to limited time and resources, the involvement of the USSA was limited to various discussion sessions, the evaluation of the BBS test, and conducting a series of control tests.

The developers of the BBS test envision that the test method will be able to quantify and characterize bond strength development, adhesive properties and aggregate-binder compatibility, thereby improving the effectiveness of surface seal design. Further research is needed to identify other parameters, such as traffic-related loading rates, in order to more accurately simulate field distresses encountered in early-life phases of surface seals.

Bond strength development is critical for new surface seals as stone loss and loose aggregate must be minimized once a road enters into service following construction. Bond strength development depends on several factors, including the material characteristics of the emulsion, environmental conditions during construction, and the mineralogical characteristics of the aggregate chips (James, 2006; Redelius, and Walter, 2006).

The rate at which bond strength develops directly affects an acceptable time threshold at which the seal may be opened to traffic. The seal must have sufficient bond strength to retain aggregate chips, but the seal must also gain this strength in a sufficiently short period of time to minimize user delay.

Current evaluation and validation practices for certifying newly applied chip seals often rely on subjective judgment, though various specification systems are under development. Because bond strength development between emulsions and aggregate chips in early-life phases has implications for early raveling, developing a standard test method that evaluates bond strength is critical for reducing premature seal failures.

This paper is a revision of a paper published by Miller et al in 2010 at the 2nd International Spray Sealing Conference and focuses on the development of the test procedure and the results of tests conducted at USSA and UWM. The test was specifically conducted to characterize bitumen emulsions commonly used in surfacing seals.

2- BBS TEST DEVELOPMENT

2.1 BACKGROUND

The need to understand and scientifically quantify the expected behavior of surfacing seals has been around for as long as bitumen and aggregate have been used to surface roads. The design of surfacing seals has generally been based on available materials, skills and current client preferences.

Tests performed on surfacing seal aggregate and bitumen binders are generally limited to ensuring that the separate materials comply with their relative classification specifications. During the seal design process, no tests are conducted to quantify the bond strength that develops between binders and aggregate combinations. Developing practical and effective test methods to characterize this bond strength is therefore critical for pavement designers and contractors to predict how a surface seal will perform over the expected service life.

Pull-off tests have been widely used and developed in other industries for various test procedures. It was found that these tests could be adapted for evaluation of adhesion in surfacing seal materials. The painting industry initially developed pull-off tests to evaluate the pull-off strength of coatings on rigid substrates such as metal, concrete and wood.

The goal of such pull-off test methods is to measure the maximum normal force that a solid surface coating can withstand before the adhesive detaches from the surface at failure. Such tests allow for the evaluation of the failure type (e.g. adhesive or cohesive) through inspection of the failure surface after detachment has occurred (Meng, 2010; ASTM D4541-, 2009).

2.2 ORIGINAL PATTI TEST

The bitumen industry first utilized the Pneumatic Adhesive Tensile Testing Instrument, or PATTI, in the late 1990s to evaluate adhesive loss of binder-aggregate systems exposed to moisture conditioning. (Kanitpong & Bahia, 2003) Recent research at UWM continues to investigate the effects of moisture damage for hot applied binders. (Meng, 2010; Bahia and Meng, 2010; Kanitpong & Bahia, 2003)

Initial tests identified several significant effects, including variations in preparing the test assembly (operator dependence), binder film thickness, and curing and testing temperatures. Recent generations of the PATTI, notably the PATTI Quantum Gold (PQG), address some of these these shortcomings while ensuring compliance with surface seal industry requirements (Miller, 2010). Further modifications and the development of a new BBS Testing procedure (AASHTO TP-91, 2011) made the testing of the bitumen aggregate bond a reality.

Early generations of the PATTI consisted of a pressure hose, adhesion tester, piston, reaction plate and a metal pull-out stub. Figure 1 below shows a typical assembly.

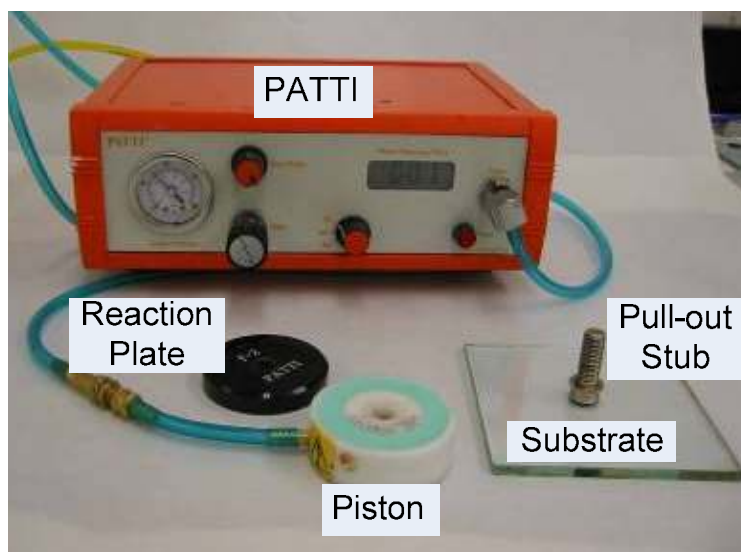


Figure 1 – Original PATTI assembly.

The original test procedure entailed the following steps:

- A hot bitumen sample is applied to a glass substrate and allowed to cure for a fixed time interval.
- A metal pull-out stub is applied to the bitumen sample and allowed to set for a given time interval.
- After placing the piston over the pull-out stub, the reaction plate is fixed to the stub.
- The pressure hose introduces compressed air to the piston, resulting in an upward force on the specimen and eventual failure of the binder. Failure occurs when the applied pressure exceeds the cohesive strength of the binder or the adhesive strength of the binder-aggregate interface.
- The pressure at failure is recorded and the procedure is repeated for other test specimens.

While the original test procedure did yield quantitative information related to bond strength characteristics and failure behavior, research at UWM and UAI identified several factors influencing the effectiveness of the test method. Some of these factors include:

- The binder film thickness between the stub and substrate could not be controlled easily.
- Because the original pull-out stub measured only 12.7 mm in diameter, the stub geometry limited the measurement of smaller tensile strengths. Recent modifications to the pull-out stub design at UWM and UAI improved the geometry by nearly doubling the stub diameter.
- The device did not report pressure over time, making the calculation of loading rate difficult. Rather, PATTI reported only the real-time applied load but not within a computer-based graphical user interface.
- The loading rate varied and could not be set easily. While the PATTI is equipped with a rate control dial, the dial did not effectively control the loading rate or report the real-time loading rate.
- Initial tests were performed on glass substrates, hardly a suitable surface seal material.

2.3 INITIAL TEST METHOD LIMITATIONS & MODIFICATIONS

The original PATTI test was developed for non-viscous paint and had limitations which were addressed in various ways. Improvements to the pull-out stub design, loading rate control and substrate preparation procedures represented significant advancements from the original PATTI test to its current form as the BBS test method.

Binder film thickness is effectively controlled in the BBS test with an improved stub design. Loading rate is effectively controlled with new functions of the PATTI Quantum Gold. Substrate surface characteristics are controlled with improved substrate preparation procedures. Each of these improvements will be discussed briefly below.

2.3.1 FILM THICKNESS

Previous research identified film thickness as a critical parameter in investigating pull-off behavior. (Meng, 2010; Youtcheff et al, 1999; Kanitpong & Bahia, 2003; Miller et al, 2010). Early experimentation by Youtcheff and Aurilio to evaluate moisture sensitivity utilized glass beads of 200 µm diameter mixed with bituminous binder to control film thickness (Youtcheff et al, 1999).

With input from UAI, Kanitpong and Bahia further modified the pull-out stubs to better control binder film thickness (Canestrari, 2010; Kanitpong & Bahia, 2003). They proposed using a smooth-surface aluminum stub and two metal support blocks to replace the glass beads. Figure 2 shows the modified stubs with metal support blocks, and Figure 3 depicts a later iteration of the pull-out stubs with aluminum frame supports.

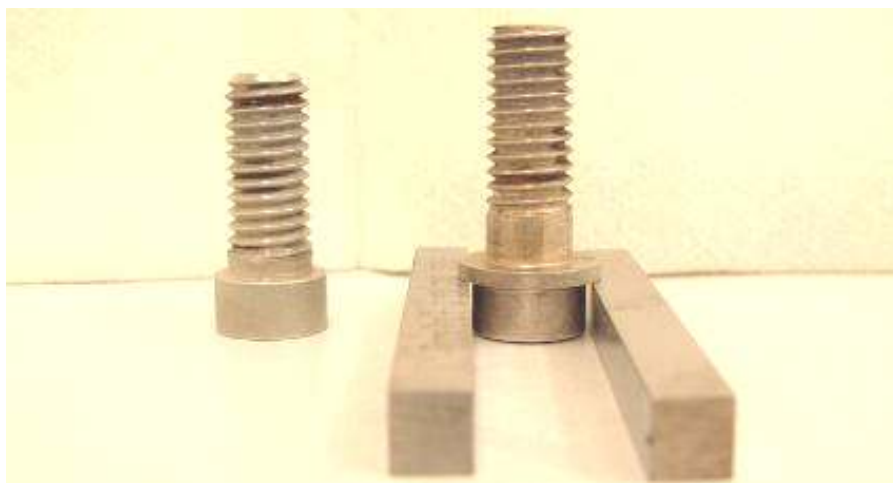


Figure 2 – Modified pull-out stubs with metal support blocks (Kanitpong & Bahia, 2003).

In early rounds of experimentation, it became clear that film thickness was still not adequately controlled with the pull-out stub support system shown in Figure 3 (Fratta & Daranga, 2006). Figure 4 shows an improved pull-out stub designed at UWM in conjunction with UAI. Improvements to the original stub include an increase in stub diameter to 22 mm and the addition of circumferential support edges to limit the vertical position of the stub surface. Perimetrical channels in the stub edge allow excess binder to flow out from beneath the stub surface.



Figure 3 – Modified pull-out stub with aluminum frame supports.



Figure 4 – Modified BBS test pull-out stubs .

2.3.2 LOADING RATE

Bitumen's viscoelastic nature necessitates effective loading rate control for the consistent evaluation of the pull-off tensile strength. Research by Meng confirms that load control is critical for consistent pull-off tensile test results (Meng, 2010). Early versions of PATTI were found to inadequately control loading rate so at the beginning of 2009, SEMicro launched the PATTI Quantum Gold[®] (PQG) test instrument that incorporated user feedback into the revised design, including improved loading rate control. The ability to control the loading rate with a graduated rate control dial further improves consistency. The PQG comes equipped with LabView[®] software and effectively captures load over time, allowing for calculation of the loading rate.

2.3.3 SUBSTRATE & SURFACE ROUGHNESS

Improved substrate preparation procedures involve the use of aggregate substrates that are actually used in practice. However, crushed aggregates commonly used in surface seals are not suitable substrate materials due to variations in in shape, surface roughness and texture. A procedure developed at UWM to prepare aggregate plates involves cutting large rocks into flat plates (Miller, 2010). The aggregate plates and disks are then lapped with a silicon carbide compound to achieve a consistent surface texture. While aggregate plates and disks may not fully capture aggregate surface characteristics, they represent substantial improvements over glass plates, which are still used as a control surface. The smooth aggregate surfaces are seen and treated as a worst case scenario.

2.4 SIGNIFICANT FACTORS INFLUENCING BOND STRENGTH DEVELOPMENT

With the refined substrate preparation procedures, improvements in stub design to control film thickness, and loading rate control, Miller investigated factors critical to bond strength development (Miller, 2010). The factors investigated included substrate type, moisture condition, surface roughness, loading rate, curing temperature and curing humidity. An analysis of variance (ANOVA) for the screening experiment is shown in Table 1.

The experiment identifies loading rate, curing temperature and humidity, and substrate type as significant main effects contributing to bond strength development. Experimental results indicate that loading rate most significantly influences the pull-out tension response. Other significant factors investigated in subsequent studies included material variables related to substrate and binder type as well as curing variables related to temperature, humidity and time.

Table 1 – Analysis of variance for the factor screening experiment.

Source	DF	Seq. SS	Adj. SS	Adj. MS	F	P
Substrate	1	1051.6	1051.6	1051.6	8.2	0.006
Moisture	1	0.5	0.5	0.5	0.00	0.952
Roughness	1	90.9	90.9	90.9	0.7	0.404
Loading Rate	1	31926.2	31926.2	31926.2	248.5	0.000
Temperature	1	1967.0	1967.0	1967.0	15.3	0.000
Humidity	1	1105.3	1105.3	1105.3	8.6	0.005
Error	57	7322.4	7322.4	128.5		
Total	63	43463.8				
S = 11.3342		R-Sq = 83.15%		R-Sq (adj) = 81.38%		

2.4.1 LOADING RATE EXPERIMENT

Loading rate was clearly identified as a factor significantly influencing the pull-out tension response. Miller did extensive testing and proved that a power law model adequately captures the relationship between loading rate and pull-out tension. The results in Figure 5 show that loading rates between 690-1030 kPa/s (100-150 psi/s) appear to exhibit a linear relationship above pull-out tension values of 690 kPa (100 psi).

Loading rates exceeding 2700 kPa/s (400 psi/s) lead to increasing variability in both the pull-out tension values and loading rate. Therefore, loading rates exceeding 2700 kPa/s (400 psi/s) should be avoided to minimize experimental error in order to obtain valid results.

Initial test done by the USSA confirmed these results. Figure 6 shows the influence of loading rates on two different aggregates and emulsion combinations. The figure clearly indicates that there is an increase in the pull out tension as the rate of application increases. The results are however limited to the 400 kPa/s to 950 kPa/s range.

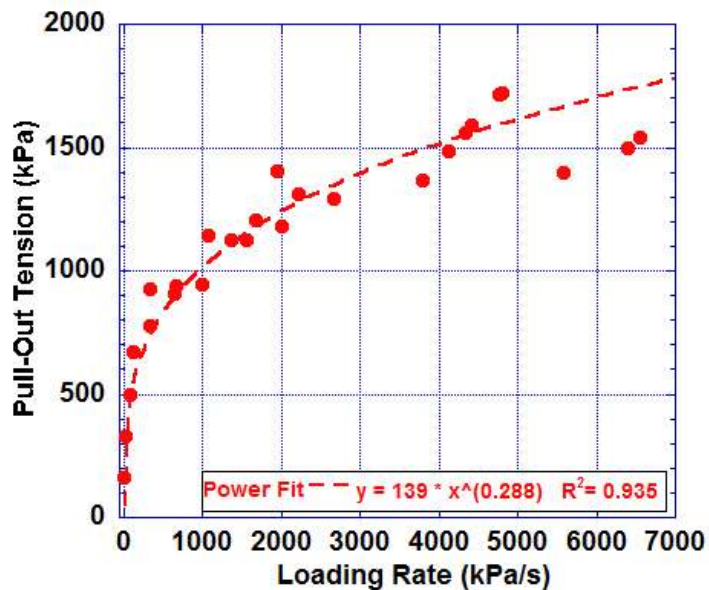


Figure 6 – Loading rate and pull-out tension are described by a power law model.

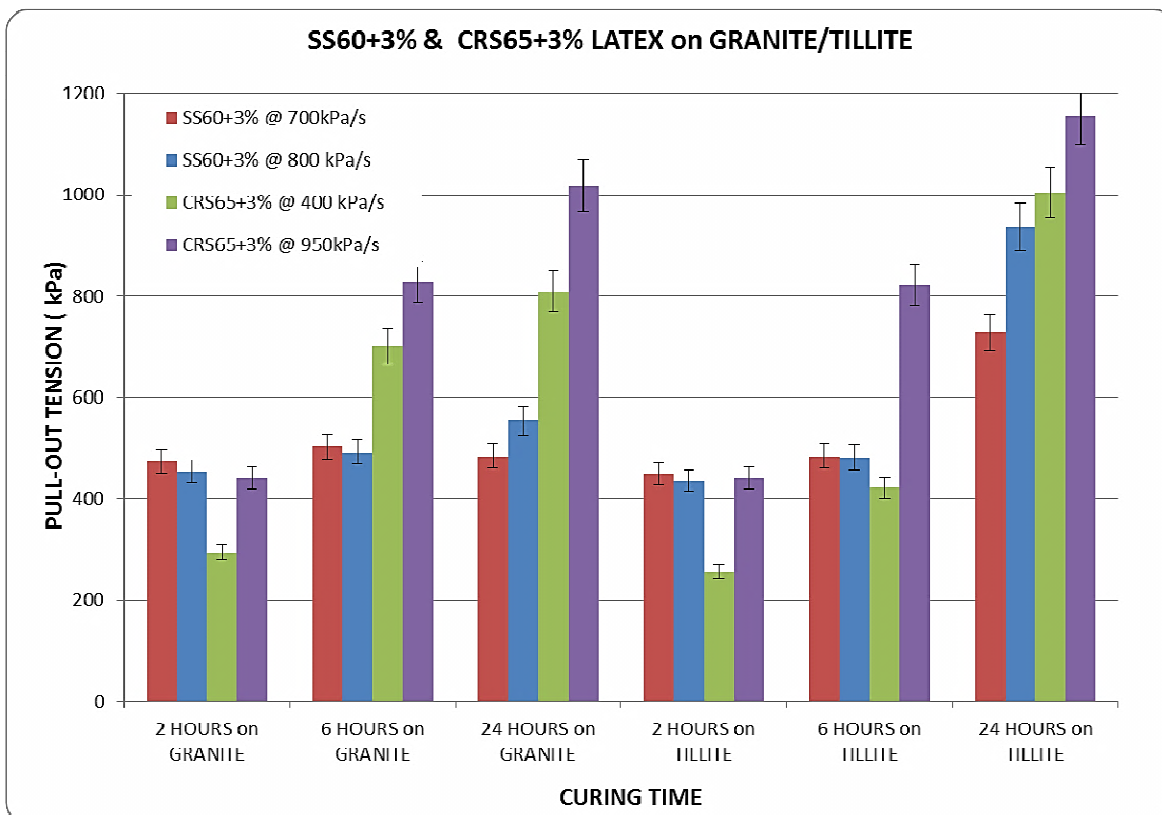


Figure 5 – Loading rate and pull-out tension results USSA

2.4.2 CURING CONDITIONS EXPERIMENT

The effect of curing temperature and humidity plays a very important role in the bond strength development between bitumen and aggregate. Miller investigated the effects of curing temperature and humidity on pull-out tension (Miller, 2010)

In his experiment, the loading rate was fixed at approximately 700 kPa/s for four curing conditions. Samples cured in an environmental chamber at prescribed curing intervals of 2, 6 and 24 hours. The experiment utilized a cationic rapid-setting emulsion with high viscosity (CRS-2), granite and limestone substrates, and the following curing conditions:

- Samples cured at 35 °C and 30 percent relative humidity.
- Samples cured at 35 °C and 70 percent relative humidity.
- Samples cured at 15 °C and 30 percent relative humidity.
- Samples cured at 15 °C and 70 percent relative humidity.

An ANOVA for the curing conditions experiment, shown in Table 2, indicates that substrate type, curing temperature, and curing interval are statistically significant main effects at a 95% confidence level, while temperature-curing interval and humidity-curing interval interactive effects are also statistically significant at this confidence level. Other important results suggest that:

- Significant strength gains were observed between two and six hours at the 35 °C temperature level.
- Granite outperformed limestone in three of four curing conditions after six hours.
- Humidity did not significantly affect the pull-out tension response.
- Samples tested at 35 °C and 30 percent relative humidity performed better than samples tested at other curing conditions.
- Samples exhibited only slight differences in the pull-out tension response after 24 hours of curing.

Table 2 – Analysis of variance for the curing conditions experiment.

Source	DF	Seq. SS	Adj. SS	Adj. MS	F	P
Substrate	2	2862.9	2862.9	1431.4	16.44	0.000
Curing Temperature (°C)	1	2079.2	2079.2	2079.2	23.88	0.000
Curing Humidity (% RH)	1	60.6	60.6	60.6	0.70	0.417
Curing Interval	2	113689.5	113689.5	56844.8	652.96	0.000
Substrate-Temperature	2	247.0	247.0	123.5	1.42	0.271
Substrate-Humidity	2	559.2	559.2	279.6	3.21	0.067
Substrate-Interval	4	838.9	838.9	209.7	2.41	0.092
Temperature-Humidity	1	54.4	54.4	54.4	0.63	0.441
Temperature-Interval	2	3695.7	3695.7	1847.8	21.23	0.000
Humidity-Interval	2	1354.8	1354.8	677.4	7.78	0.004
Error	16	1392.9	1392.9	87.1		
Total	35	126835.1				
S = 9.33046		R-Sq = 98.9%		R-Sq (adj) = 97.6%		

2.4.3 EMULSION TYPE EXPERIMENT

Miller developed a detailed materials experiment to investigate a variety of emulsion and substrate combinations (Miller, 2010) The experiment included five emulsion types and three substrate types at four curing intervals. Figure 8 and Figure 9 show results from this experiment.

Two initial observations can be made in Figure 6: that both cationic rapid-setting emulsions (CRS-2 lab and CRS-2 field) perform better than polymer modified cationic rapid-setting emulsions (CRS-2P) and high-float anionic rapid setting (HFRS-2) emulsions; and that all emulsion types exhibit sharp increases in pull-out tension initially, with relative gains in tensile strength diminishing over time. A power law model adequately characterizes the relationship between curing interval and pull-out tension. In Figure 8, glass plates yield a near-perfect correlation using a power law model, with solid aggregate plates and chip substrates also yielding very strong relationships.

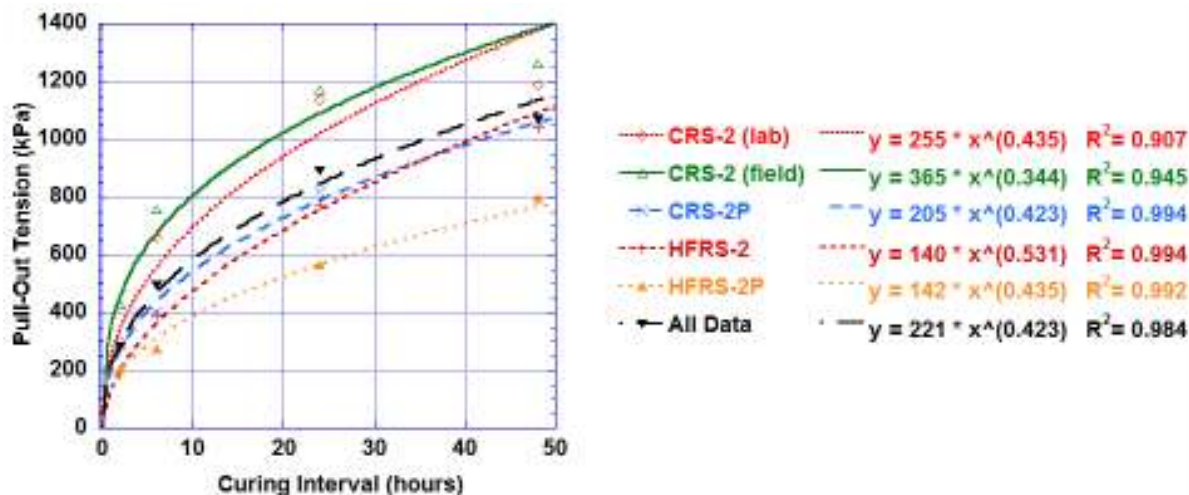


Figure 7 – Pull-out tension values differ for various emulsion types at a range of curing intervals (Miller, 2010)

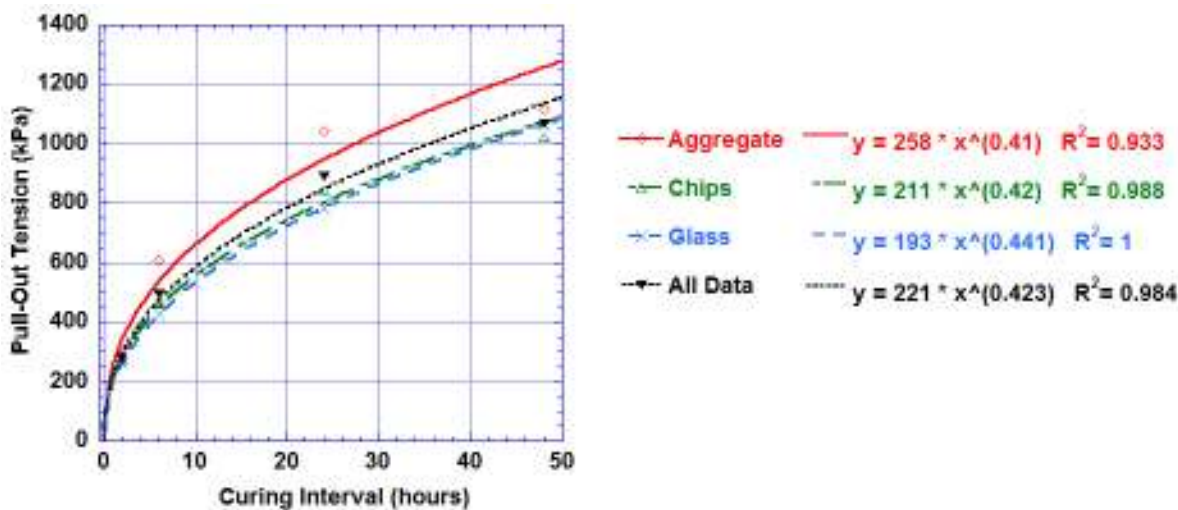


Figure 8 – Pull-out tension values differ for various substrate types at a range of curing intervals (Miller, 2010)

The USSA conducted test on granite and tillite aggregates using various modified and unmodified emulsion combinations. The results of these tests correlate well with the results from UWM and are shown in the Figure 9 below:

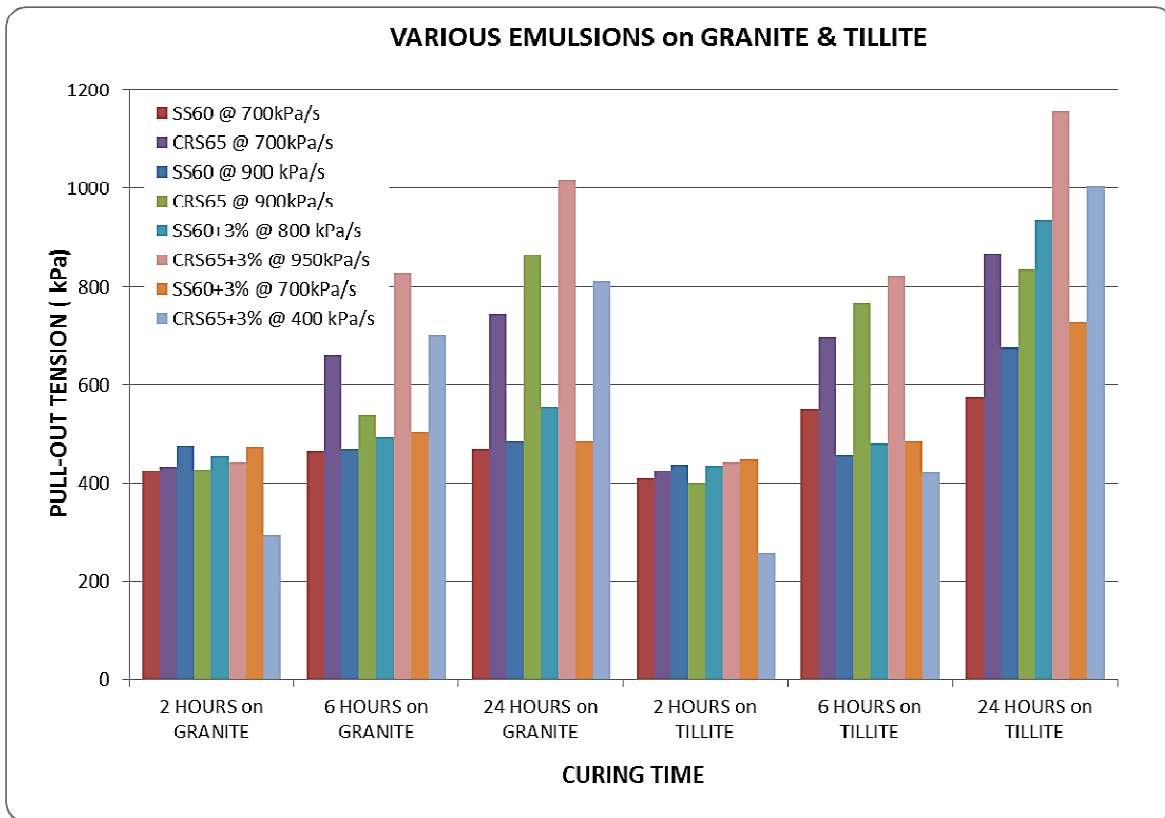


Figure 9 – Pull-out tension values differ for various emulsion types at a range of curing intervals

2.4.4 CORRELATIONS OF BBS TEST RESULTS

In order to validate the BBS test procedure, Miller correlated BBS test results to two other common test procedures. To gain insight into chip retention, Miller correlated BBS test results to results obtained using the ASTM D7000 sweep test procedure (Miller, 2010; ASTM D7000, 2008). In the sweep test, bitumen is applied at a fixed application rate to a felt disk before aggregate chips are applied and compacted. The test apparatus brushes the sample for 1 minute in an attempt to simulate the mechanical brooming action experienced by newly-constructed chip seals. The response variable considered in the sweep test is percent aggregate loss.

SWEEP TEST

Establishing a correlation between BBS test results and sweep test results entailed comparing the pull-out tensile strength values obtained using the BBS test to aggregate loss measured using the sweep test at identical curing conditions. Given the existing recommended sweep test performance limit of 10 percent aggregate loss, Miller devised a test correlation between BBS and sweep test results. Sweep test samples prepared with granite and limestone aggregates and CRS-2 and CRS-2P emulsions are compared to BBS test results for similar material combinations, as shown in Figure 10.

At 2 hours curing, neither the sweep test samples nor the BBS test samples exhibit good performance in terms of aggregate retention or pull-out tension as indicated by high aggregate loss in the sweep test and low pull-out tension values in the BBS test. At 6 hours curing, cohesion and adhesion become more evident with improved aggregate retention and pull-out tension values. After 24 hours curing, samples exhibit greater performance in both tests. As with other experiments, a power law model appears to adequately characterize the relationship between BBS results and sweep test results, with $R^2 > 0.995$. Based on this relationship, a minimum BBS specification limit of 850 kPa (123 psi) may be suggested, a limit that signifies when the binder has gained sufficient bond strength to achieve less than 10 percent aggregate loss as measured by the sweep test.

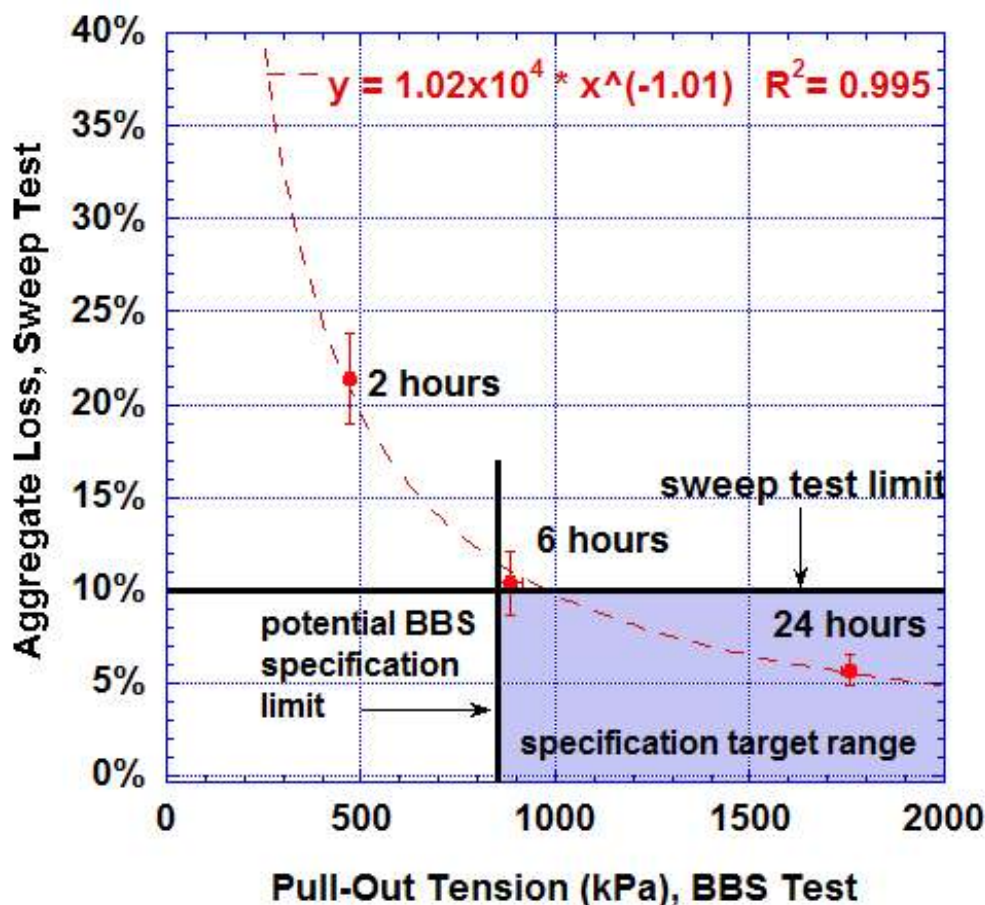


Figure 10 – When sweep test results are compared to BBS test results, a potential BBS specification limit may be proposed at 850 kPa (123 psi) to define a specification target range (Miller, 2010)

DYNAMIC SHEAR RHEOMETER (DSR) STRAIN SWEEP

Strain sweep procedures developed for the dynamic shear rheometer (DSR) were also compared to BBS results (Miller et al, 2010; Arega, 2009). DSR strain sweep results were considered for two evaluation criteria. Test results were analyzed in the linear range ($G^* / \sin \delta$ at 12 percent strain) and non-linear range ($G^* / \sin \delta$ at 40 percent strain). Emulsion residues cured on granite and limestone substrates demonstrated the effect of curing temperature on strength gain, particularly at early curing intervals. None of the samples attained the full strength of the neat base binder, indicating the presence of water in the emulsion even after 24 hours of curing.

BBS test results are correlated with emulsion residue properties in Figure 11. Results demonstrate a strong correlation between pull-out tensile strength and resistance to deformation ($G^* / \sin \delta$) of the emulsion residue. The effect of curing time is also seen in comparing the results, with binder stiffness and bond strength increasing with time. DSR strain sweep results suggest that the BBS test is capturing a fundamental engineering property in bond strength. The BBS-DSR correlation reinforces the notion that bond strength development can be quantified as the emulsion breaks and begins to release water.

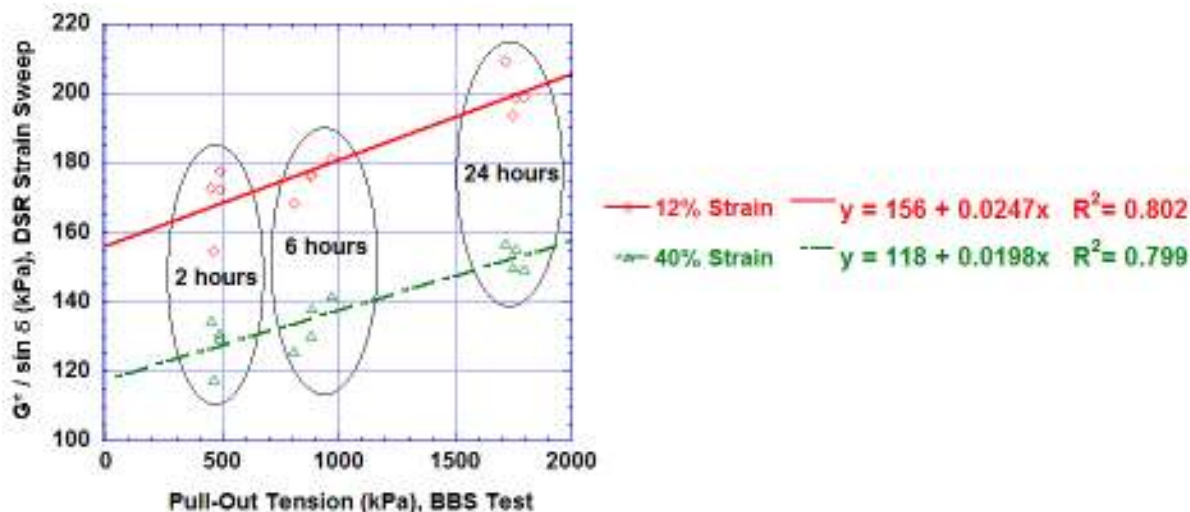


Figure 11 - BBS test results compare well to DSR strain sweep results at two strain levels.

3- INTER-LABORATORY EVALUATION OF BBS TEST METHOD

To validate BBS test methods with inter-lab experimentation, research personnel at the University of Stellenbosch – South Africa (USSA) conducted a series of tests based on the draft test method developed by Miller and UWM research personnel. The South African evaluation utilized an identical experimental setup (e.g. PQG testing instrument and modified pull-out stubs) for a different set of emulsified binders and substrate types.

Substrate preparation procedures differed slightly due to differences in available substrate preparation equipment. UWM tests utilized large aggregate plates that accommodated four pull-out stubs, while USSA tests utilized aggregate slices from cored rock samples that accommodated only a single pull-out stub.

Researchers at USSA conducted initial material evaluation tests at 400 kPa/s and 900 kPa/s but later fixed the loading rate at approximately 700 kPa/s based on UWM results and recommendations. Inter-lab evaluation considered four emulsion types and two substrate types (e.g. granite and tillite). Availability of an environmental chamber at the University of Stellenbosch limited the curing conditions to 30 °C and ambient levels of relative humidity. The following emulsions were considered for both substrate types at 2, 6 and 24 hour curing intervals:

- Cationic rapid setting (CRS65) bitumen emulsion.
- Anionic slow setting (SS60) bitumen emulsion.
- Cationic rapid setting (CRS65) bitumen emulsion modified with 3% latex.
- Anionic slow setting (SS60) bitumen emulsion modified with 3% latex.

Figure 12 and Figure 13 depict results for different emulsion types and substrate types, respectively. These findings corroborate the findings of Miller and research personnel at UWM that 1) bond strength development can be quantified over time; 2) the BBS test method can characterize bond strength development for different emulsion types; and 3) that advantageous combinations of aggregate-binder can be identified using the BBS test method.

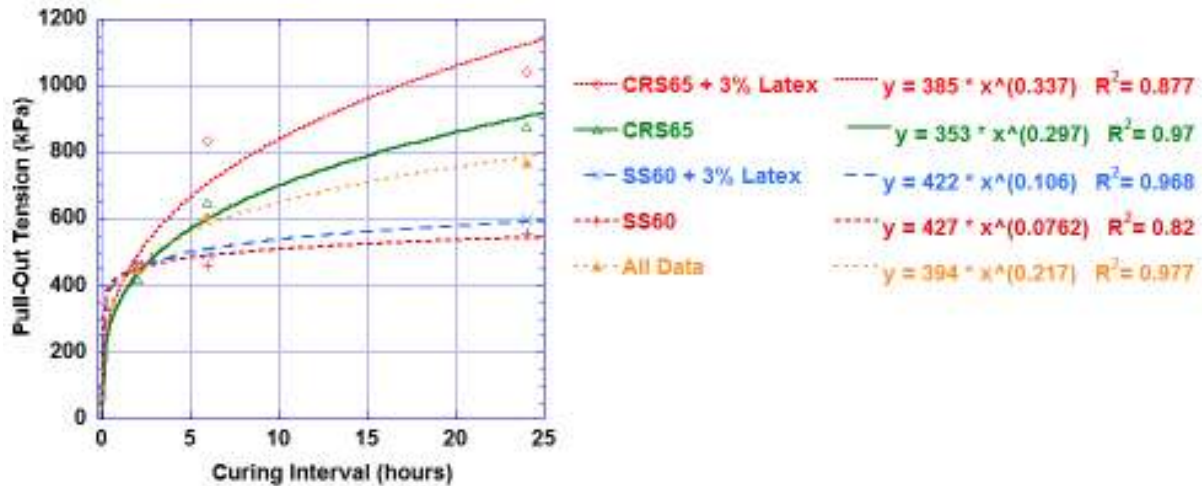


Figure 12 – Pull-out tension values differ for various emulsion types at a range of curing intervals.

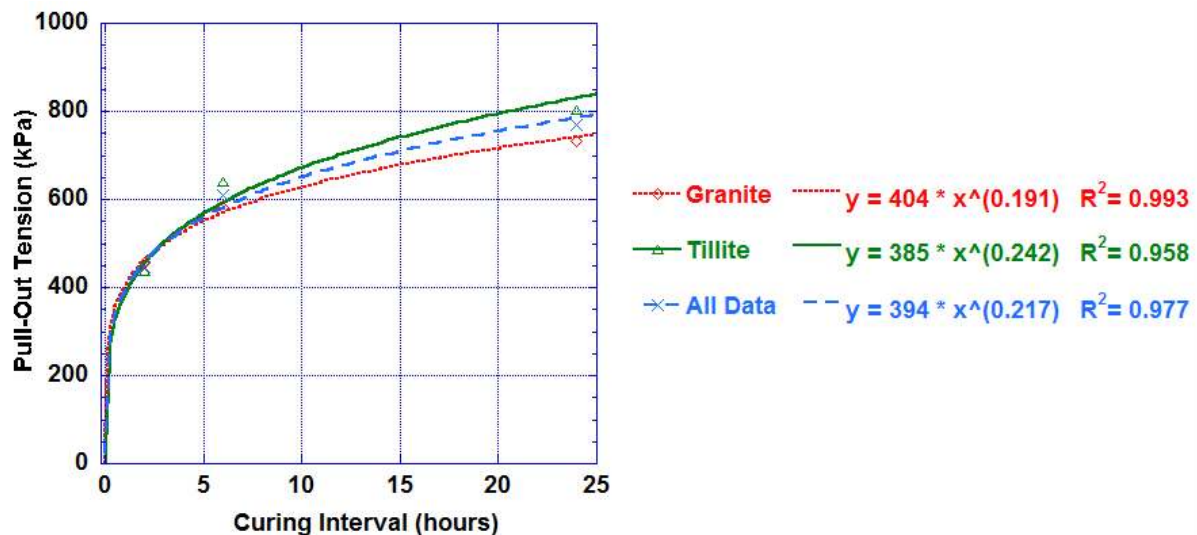


Figure 13– Pull-out tension values differ for various substrate types at a range of curing intervals.

Table 3 displays experimental results from inter-laboratory testing. Values of the coefficient of variation (COV) are typically less than 10 percent, indicating good repeatability for three replicates in spite of a different substrate preparation procedure. Experimental results are also depicted in Figure 14 for unmodified bitumen and Figure 15 for modified bitumen.

Table 3 –BBS test results for materials tested at the University of Stellenbosch.

Experimental Factors	Pull-Out Tensile Strength (kPa)
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Binder	Substrate	Cure Interval (hr)	Average	St Dev	St Error	COV
CRS65	Granite	2	424.6	4.7	2.7	1.1%
		6	533.0	19.5	11.3	3.7%
		24	919.7	46.7	26.9	5.1%
	Tillite	2	406.6	15.9	9.2	3.9%
		6	765.2	77.2	44.6	10.1%
		24	835.6	57.1	33.0	6.8%
SS60	Granite	2	482.4	13.4	7.7	2.8%
		6	466.2	5.6	3.3	1.2%
		24	545.7	106.9	61.7	19.6%
	Tillite	2	445.4	8.3	4.8	1.9%
		6	459.9	9.8	5.6	2.1%
		24	568.3	51.5	29.7	9.1%
CRS65 + 3% LATEX	Granite	2	439.1	4.1	2.4	0.9%
		6	824.8	13.9	8.0	1.7%
		24	989.2	169.9	98.1	17.2%
	Tillite	2	446.3	12.4	7.2	2.8%
		6	846.5	60.4	34.9	7.1%
		24	1095.8	104.8	60.5	9.6%
SS60 + 3% LATEX	Granite	2	472.5	6.8	3.9	1.4%
		6	505.9	12.4	7.2	2.5%
		24	477.9	5.6	3.3	1.2%
	Tillite	2	449.9	6.8	3.9	1.5%
		6	484.2	2.7	1.6	0.6%
		24	717.3	52.8	30.5	7.4%

Figure 14 shows a combination of test results for CRS65 and SS60 bitumen emulsions on granite and tillite aggregates for different loading rates. The following points of interest are noted:

- The CRS65-granite combination outperforms the CRS65-tillite combination at all curing intervals. The pull-out tension appears to increase linearly with curing time.
- SS60 results show very little strength increase over 24 hours, except on tillite at 24 hours. The result is expected from a slow setting emulsion applied on acidic aggregates such as granite and tillite. These aggregates contain silica and have a strong negative charge in the presence of water. This negative charge attracts positively charged cationic bitumen particles, leading to destabilization of the surfactant system and subsequent coagulation of the bitumen particles. This breaking mechanism is absent when anionic emulsions are used with acidic aggregates (Louw et al,2004)
- Tests conducted at 900 kPa/s show slight increases in pull-out tensions values over those tested at 700 kPa/s, thereby confirming that higher loading rates result in higher pull-out tension values.

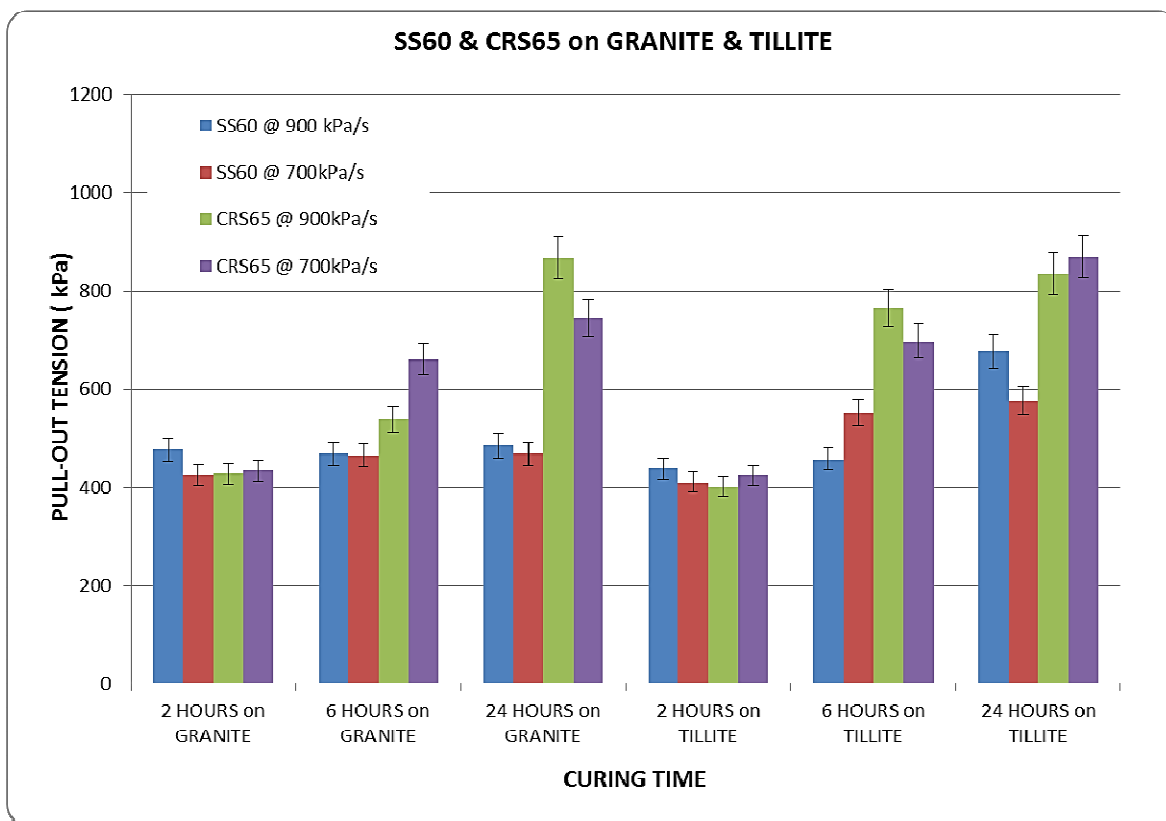


Figure 14 – BBS testing of unmodified bitumen shows bond strength development over time.

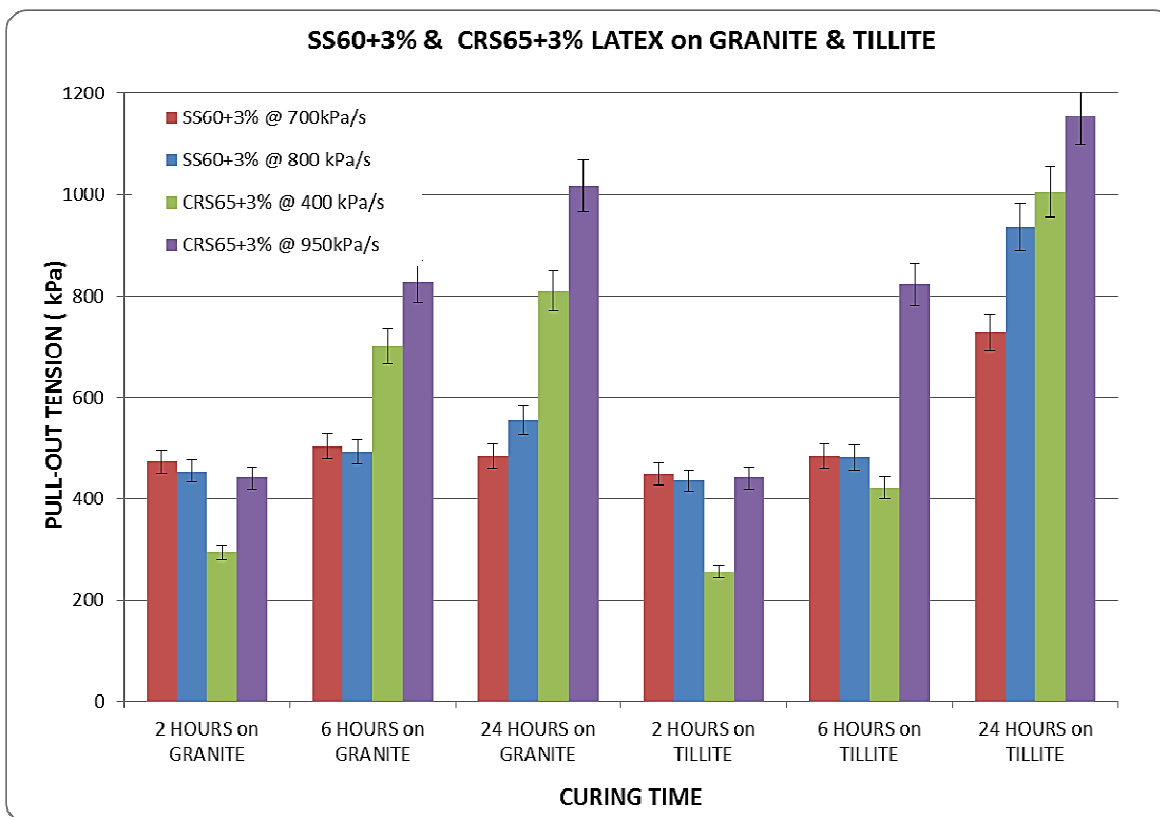


Figure 15 – BBS testing of modified bitumen also shows bond strength development over time.

Figure 15 shows a combination of test results for CRS65 + 3% latex and SS60 + 3% latex on granite and tillite aggregate substrates. The following points of interest are noted:

- Tests performed at 950 kPa/s show higher results and confirm the findings of Miller that higher loading rates contribute to higher pull-out tension values.
- After 2 hours curing time, results exhibit minimal differences in the results on all four emulsion/aggregate combinations.
- After 6 hours the results for CRS65 + 3% latex-granite show higher tensile strength values than SS60 + 3% latex-granite.
- After 6 hours, there are limited differences in the results of the CRS65 + 3% latex-tillite and SS60 + 3% latex- tillite.
- After 24 hours, the CRS65-granite combination shows significantly higher strength values than the SS60-granite combination but smaller values than the CRS65 + 3% latex-tillite and SS60+ 3 % latex-tillite combinations.
- The modified emulsions performs better than the unmodified emulsions after 24 hours.
- The CRS65 + 3% latex-tillite and SS60 + 3% latex-tillite combinations values relate well and seem to be superior to granite.

4- CONCLUSION

This paper reviewed the development of a new test called the Bitumen Bond Strength (BBS) test and its application to bituminous emulsions. Inter-laboratory test results reinforce the hypothesis that the BBS test protocol (AASHTO TP-91, 2011) can be used to effectively evaluate bond strength of different emulsion types and substrate types. Aside from loading rate, emulsion type and curing interval are identified as the most significant factors contributing to bond strength development. Substrate type is also identified as a significant factor leading to bond strength. Interactions between emulsion type and curing interval are identified as the most significant interaction. Further validation of the BBS test method is needed for the test to be integrated into a performance-based specification system for surface seals.

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