THE EFFECT OF BITUMEN STIFFNESS ON THE ADHESIVE STRENGTH MEASURED BY THE BITUMEN BOND STRENGTH TEST

[1]Hussain Bahia, [2]Raquel Moraes, and [3]Raul Velasquez
[1] Professor, hubahia@facstaff.wisc.edu
[2]Graduate Research Assistant, moraes@wisc.edu
[3]Research Associate, ravelasquez@wisc.edu
[1, 2, 3]University of Wisconsin-Madison, 3350 Engineering Hall, 1415 Engineering Drive, 53706, Madison, WI, USA

ABSTRACT

The resistance of bituminous pavements to traffic and environmental loading depends on mechanics of bonding at bitumen-aggregate interface as well as cohesion of bitumen. Research has shown that adhesive strength between bitumen and aggregate is highly affected by the composition of the two components and by moisture conditions. Therefore, selecting the right combination of materials that are less susceptible to moisture damage is important to ensure performance of bituminous pavements. In a previous study, a test called Bitumen Bond Strength (BBS) has been developed to measure bond strength before and after moisture conditioning. Concerns about the effect of bitumen stiffness ($|G^*|$) on bond strength test results have been raised. This paper addresses these concerns and proposes a method to account for the stiffness of the binder on BBS measurements.

Experimental program included different bitumens, aggregates and modifications to account for different conditions in the bitumen-aggregate interface. Testing in the Dynamic Shear Rheometer (DSR) was conducted at three temperatures to determine the iso-stiffness testing temperature of eight bitumens. This iso-stiffness temperature was then used to perform the BBS test.

Results indicate that bond strength of bitumen-aggregate systems is highly dependent on the stiffness of bitumen. They also show that polymers can improve adhesion of bitumen to aggregate and cohesion within bitumen. Strength results are found to be significantly affected by bitumen's stiffness and, therefore, temperature needs to be controlled during BBS test. A single linear model is proposed for correction of bond strength when testing at a single temperature and different stiffness conditions.

Keywords: Moisture Damage, Bitumen Bond Strength, Stiffness, DSR.

1. INTRODUCTION

Moisture sensitivity of bituminous pavements is one of the important performance-related issues confronting highway agencies. In bitumen, moisture damage is defined as the loss of stiffness and strength due to moisture exposure under mechanical loading. Bituminous pavements suffer moisture damage as a result of many processes occurring simultaneously. Moisture sensitivity has been identified as a major contributor to premature distresses including rutting, fatigue cracking, and raveling [1].

It is recognized that resistance of bituminous pavements to distresses depends on the mechanics of the bonding at the bitumen-aggregate interface, which could be highly affected by moisture conditions. There are three mechanisms by which moisture degrades asphalt: (*a)* loss of cohesion within the bitumen or mastic, (*b*) adhesive failure between aggregate and bitumen (i.e., stripping), and (*c*) degradation of the aggregate [2].

The loss of cohesion occurs when water interacts with the bitumen resulting in a reduction in material integrity [1]. The loss of adhesion happens when water penetrates the interface between bitumen and aggregate stripping away the bitumen film. The effect of moisture on the performance of the pavement can be the result of the combination of both loss of cohesion and loss of adhesion.

The literature describes five primary mechanisms that can lead to either cohesive or adhesive failure types in bituminous pavements: detachment, displacement, pore pressures, hydraulic scouring, and spontaneous emulsification [3, 4]. The nature of these mechanisms and their interaction makes it difficult to predict whether a particular characteristic will be the main cause in determining moisture susceptibility. In general, moisture susceptibility is increased by any factor that increases moisture content in the bitumen, decreases the adhesion of bitumen to the aggregate surface, or physically scours the bitumen [3].

To investigate the moisture sensitivity of bituminous pavements bond strength is a critical parameter in evaluating a bitumen's ability to resist moisture damage. Konitpong et al. [5] and Canestrari et al. [6] suggested a repeatable, reliable, and practical method to investigate the adhesion and cohesion properties of bitumen-aggregate systems before and after moisture conditioning based on the Pneumatic Adhesion Tensile Testing Instrument (PATTI).

Meng [7] and Moraes et al. [8] modified the simple test procedure proposed by Canestrari et al. [6] and developed a standard procedure to measure bond strength of bitumen-aggregate systems (i.e., Bitumen Bond Strength (BBS) test).

The standard protocol for the BBS includes testing at ambient temperature. Recently concerns have been raised regarding the effect of variation of bitumen stiffness ($|G^*|$) on adhesive bond strength results. This paper gives a summary of a study to quantify the effects of bitumen stiffness on adhesion and cohesion obtained with the Bitumen Bond Strength (BBS) test.

2. LITERATURE REVIEW

2.1 Bitumen-Aggregate Adhesion Mechanisms

Adhesion determines the tendency of two materials with dissimilar molecules to cling to one other [9]. It can be measured directly with contact angle approaches (i.e., wetting potential) [10] or with practical approaches, such as a suitable pull-off tensile test.

Most likely a combination of mechanisms occurs simultaneously to produce adhesion. These mechanisms can be classified into one of three categories: mechanical interlocking, physicochemical adhesion due to surface free energy of materials, and bonding due to interfacial chemical reactions [11].

The theories that fundamentally explain the adhesive bond between bitumen and aggregates are: mechanical theory, chemical theory, weak boundary theory, and thermodynamic theory [5, 12]. There is no clear agreement among experts describing the dominant theory and its associated mechanisms to explain moisture damage in bituminous pavements. However, many researchers agree that a combination of mechanisms could take place and that a direct measurement of the bond strength is required.

2.2 Bitumen Stiffness

The stiffness of bituminous pavements in presence of moisture can be affected by many factors, such as: amount of moisture that is held within the bitumen; solubility of the chemical constituents of the bitumen; amount of bitumen that becomes emulsified; adhesive bond strength of the bitumen-aggregate interface, with and without presence of moisture; and cohesive bond strength within the bitumen, with and without presence of moisture [13].

The properties of the bitumen that can influence the bond with aggregates are the chemistry of the bitumen (e.g., polarity and constitution), viscosity, film thickness, and surface energy [14, 15]. According to Robertson [16], the bitumen has the capability of incorporating and transporting water. Therefore, the cohesive strength of the bitumen in the presence of moisture will be influenced by the chemical nature of the bitumen and its processing techniques.

The viscosity of the bitumen does play a role in the propensity of the binder to strip. It has been reported that bitumens with high viscosity resists displacement by moisture better than those that have low viscosity [5]. Aged (or oxidized) bitumens, which have greater amounts of polar components (oxidation products), tend to incorporate water to a greater extent than fresh, unaged bitumens.

It has also been reported that the bond strength is directly related to film thickness [7]. Samples with thicker bitumen film tend to have cohesive failure after moisture conditioning. On the other hand, specimens with thinner bitumen film have adhesive failure [5].

3. MATERIALS AND TESTING PROCEDURE

3.1 Materials

Two bitumens commonly used in the Mid-West region of the United States were selected in this study: Flint Hills (FH) PG 64-22 and CRM PG 58-28. Also, eight modified bitumens were prepared by modifying these base bitumens : FH64-22+Acid (PG 70-22), which was modified with 1% by weight of Poly-Phosphoric Acid (PPA); FH64-22+Elastomer1 (PG 70-22) and FH64-22+Elastomer2 (PG 70-22), each one modified with 0.75% by weight of different types of elastomers with 0.17% of PPA; FH64-22+Elastomer3 (PG 70-22), modified with 2% of linear Styrene-Butadiene-Styrene (SBS) polymer; FH64-22+Plastomer1 (PG 70-22), modified with 2% of oxidized polyethylene polymer; FH64-22+AS (PG 64-28), modified with 0.5% of amine anti-stripping additive; CRM58-28+Acid (PG 64-28), modified with 1% by weight of PPA; and CRM58-28+Elastomer3 (PG 64-28), modified with 2% by weight of SBS.

The thermoplastic elastomers, if mixed in an appropriate amount with bitumen, can confer their elastic properties to the modified bitumen, thus enhancing its elastic recovery capacities and, therefore, its resistance to permanent deformations. Plastomers when add to bitumen confer a high rigidity to the bitumen and strongly reduce deformations under the load. Also, plastomers increase the viscosity of the bitumen [17]. PPA is a bitumen modifier used for improving both high and low temperature performance. The intention of adding PPA to polymer modified bitumen is to reduce the polymer content leading to improved processing conditions, high temperature viscosity and storage stability.

3.2 Bitumen Bond Strength Test

It remains a challenge to bituminous pavement technologists to develop a highly reliable and practical test procedure for determination of moisture damage, and to quantitatively evaluate the adhesive bond between bitumen and aggregate. In this study, the Bitumen Bond Strength Test (BBS), which is a significantly modified version of the original PATTI, was used to evaluate the bitumen-aggregate bond strength. Meng [7] and Moraes et al. [8] investigated the feasibility of the BBS test for moisture damage characterization and results from these studies indicated that the BBS test is repeatable and reproducible.

As indicated in Figure 1, the BBS device is comprised of a portable pneumatic adhesion tester, pressure hose, piston, reaction plate and a metal pull-out stub. During the test, a pulling force is applied on the specimen by the metal stub. Failure occurs when the applied stress exceeds the cohesive strength of the binder or the bond strength of the binder-aggregate interface (i.e., adhesion). The pull-off tensile strength (POTS) is calculated with:

$$POTS = \frac{(BP \times Ag) - C}{A_{ps}} \qquad (1)$$

where Ag is the contact area of gasket with reaction plate (mm^2), BP is the burst pressure (kPa), Aps is the area of pull stub (mm^2), and C is the piston constant.

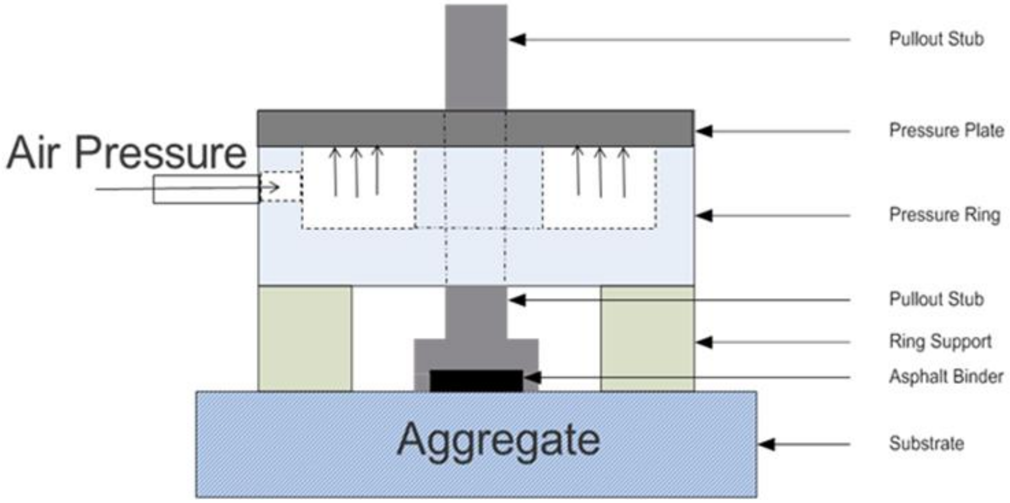

Figure 1: Bitumen Bond Strength (BBS) Schematic [18].

Aggregate Sample Preparation

Aggregate plates were cut with similar thickness and parallel top and bottom surfaces. After cutting and lapping, aggregates plates are immersed in distilled water in an ultrasonic cleaner for 60 minutes at 60°C to remove residues from the cutting process, and neutralize the surface of aggregate to its original condition.

Bitumen Sample Preparation

The bitumen sample preparation can be summarized with the following steps [8, 18]: (1) Aggregate surface and pull-out stubs are degreased with acetone to remove moisture and dust which could affect adhesion; (2) Pull-out stubs and aggregate plates are heated in the oven at 65°C for a minimum of 30 minutes; (3) Bitumens are heated in an oven at 150°C; (4) Stubs are removed from the oven and an bitumen sample is placed immediately on the surface of the stub for approximately 10 seconds. Then, the aggregate plate is removed from the oven and the stub with the bitumen sample is pressed into the aggregate surface firmly until the stub reaches the surface and no excess of bitumen is observed to be flowing; (5) Before testing, dry samples are left at room temperature for 24 hours; (6) For wet conditioning, samples are first left at room temperature for 1 hour to allow for the aggregate-bitumen-stub system to reach a stable temperature. Then, samples are submerged into a water tank at 40°C for the specified conditioning time. After conditioning time is completed, samples are kept at room temperature for 1 hour before testing.

Testing Procedure

The BBS testing procedure can be summarized with the following steps [8, 18]: (1) Before testing, air supply and pressure hose connection should be checked. Set the rate of loading to 100 psi/s; (2) Place circular spacer under the piston to make sure that the pull-off system is straight and that eccentricity of the stub is minimized; (3) Carefully place the piston around the stubs and resting on the spacers not to disturb the stub or to induce unnecessary strain in the sample. Screw the reaction plate into the stub until the pressure plate just touches the piston; (4) Apply pressure at specified rate. After testing, the maximum pull-off tension is recorded and the failure type is observed. If more than 50% of the aggregate surface is exposed, then failure is considered to be adhesive (Figure 2b); otherwise, it is a cohesive failure (Figure 2a).

Granite **Limestone** **Granite** **Limestone**

a) **b)**

Figure 2: BBS Test Failure Type: a) Mainly Cohesive, and b) Mainly Adhesive.

3.3 Dynamic Shear Rheometer for Determination of Bitumen Iso-Stiffness Temperature

The Dynamic Shear Rheometer (DSR) has the capabilities to control very accurately temperature and mode and time of loading. Therefore, the DSR can be used to measure the rheological responses (e.g., shear stresses and complex modulus) of bitumen films.

Testing Procedure

Testing in the DSR was conducted at three temperatures: 20, 25 and 30°C. These temperatures are thought to encompass the typical range of ambient temperatures in the laboratory. At each temperature, an oscillatory strain of 1% was applied at 1.59Hz frequency to obtain a measure of complex modulus |G*| within the linear viscoelastic range of the bituminous material. The range in moduli measured is an indicator of the possible range of stiffness experienced when conducting the BBS at ambient, room temperature.

The iso-testing temperature of eight bitumens was determined by interpolating between the three DSR test temperatures to calculate the temperature at which the |G*| is equal to 1 MPa (Figure 3). This iso-stiffness temperature of each bitumen was then used to perform the BBS test.

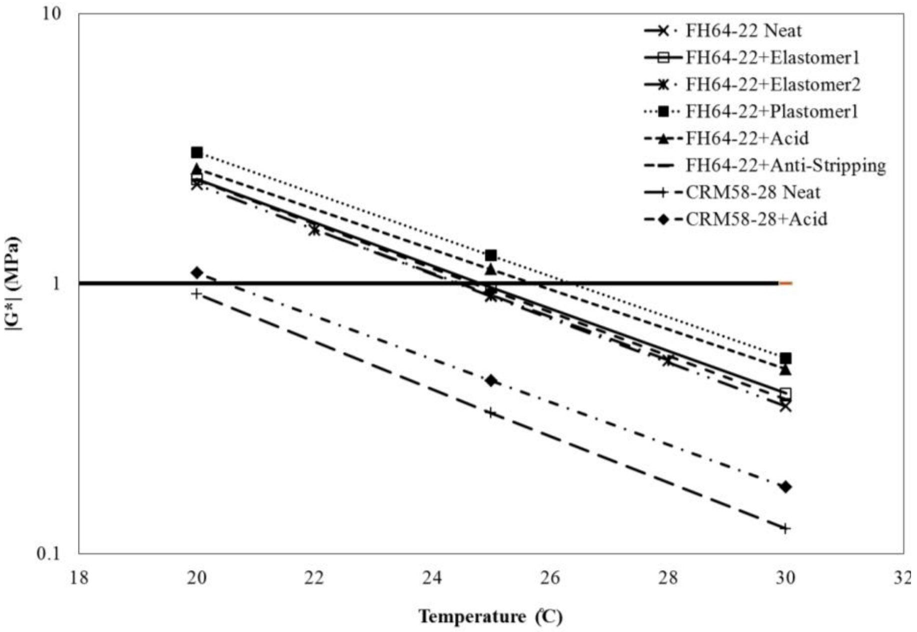

Figure 3: Determination of the iso-stiffness temperature (T at which the |G*| is equal to 1 MPa).

4. ANALYSIS AND RESULTS

4.1 Effect of Conditioning Time

Moisture damage is a time-dependent phenomenon and an indirect way to investigate this time-dependency behavior is to measure the variation in the bond strength with time in the presence of water. In this study, samples were conditioned in tap water for 0, 6, 24, 48, and 96 hours. The effect of conditioning time on the pull-off tensile strength (POTS) for the bitumen-aggregate systems tested using the BBS can be observed in Tables 1 and 2 for granite and limestone aggregate, respectively. Note that results in Tables 1-2 correspond to BBS testing performed at room temperature. The coefficient of variation (i.e., CV) reported in Tables 1-2 indicate the good repeatability of the test.

Table 1: Pull-off Strength (POTS) Values of Bitumens on Granite Aggregate.

Sample	Dry Conditioning		Wet Conditioning							
			6 hours		24 hours		48 hours		96 hours	
	POTS (MPa)	CV* (%)	POTS (MPa)	CV (%)	POTS (MPa)	CV (%)	POTS (MPa)	CV (%)	POTS (MPa)	CV (%)
FH64-22 Neat	**2.63**	3.40	**1.75**	2.50	**1.28**	3.80	**1.49**	0.13	**1.12**	0.08
FH64-22+Acid	**2.95**	1.50	**2.84**	1.00	**2.37**	0.40	**2.20**	0.02	**1.62**	0.09
FH64-22+Elastomer1	**2.68**	3.80	**2.03**	2.50	**1.62**	5.80	**1.45**	0.03	**1.91**	0.02
CRM58-28 Neat	**1.86**	5.60	**1.41**	3.20	**1.34**	10.10	**1.72**	0.07	**0.96**	0.11
CRM58-28+Acid	**1.72**	4.60	**1.72**	3.50	**1.72**	2.30	**1.26**	0.08	**1.33**	0.14
CRM58-28+Elastomer3	**1.90**	3.00	**1.47**	5.50	**1.18**	7.00	**1.62**	0.05	**0.86**	0.08

*CV: Coefficient of Variation

Table 2: Pull-off Strength (POTS) Values of Bitumens on Limestone Aggregate.

Sample	Dry Conditioning		Wet Conditioning							
			6 hours		24 hours		48 hours		96 hours	
	POTS (MPa)	CV (%)	POTS (MPa)	CV (%)	POTS (MPa)	CV (%)	POTS (MPa)	CV (%)	POTS (MPa)	CV (%)
FH64-22 Neat	**2.39**	0.20	**1.66**	4.50	**1.67**	4.70	**1.04**	0.21	**0.71**	0.23
FH64-22+Acid	**2.42**	1.20	**1.83**	2.30	**1.61**	4.00	**1.66**	0.14	**1.81**	0.13
FH64-22+Elastomer1	**2.81**	1.90	**1.84**	1.20	**1.77**	1.40	**1.14**	0.13	**1.10**	0.07
CRM58-28 Neat	**1.90**	3.10	**0.99**	3.00	**1.04**	1.80	**0.93**	0.14	**0.65**	0.06
CRM58-28+Acid	**1.92**	3.00	**1.69**	3.50	**1.43**	9.70	**1.21**	0.09	**1.31**	0.06
CRM58-28+Elastomer3	**2.05**	4.10	**1.52**	4.50	**1.42**	5.10	**1.03**	0.07	**0.51**	0.17

The average pull-off strength was calculated from four replicates. As shown in Tables 1 and 2, the conditioning of specimens in water caused a significant reduction in the bond strength and, in some cases, a change in failure mode from cohesive to adhesive type (Table 3). The change in failure mode is expected since water penetrates through the aggregate, which is a porous material, and hence weakens the bond at the interface [9]. The longer the conditioning time in water, the weaker the interface bond and the lower the pull-off strength value observed.

Table 3: Failure Mode in BBS Testing.

Sample	*CT (hr)	Failure Type		Sample	*CT (hr)	Failure Type	
		Granite	Limestone			Granite	Limestone
FH64-22 Neat	Dry	Cohesion	Cohesion	FH64-22+ Elastomer1	Dry	Cohesion	Cohesion
	6	Adhesion	Cohesion		6	Cohesion	Cohesion
	24	Adhesion	Cohesion		24	Adhesion	Cohesion
	48	50%A -50%C	50%A -50%C		48	Cohesion	50%A -50%C
	96	Cohesion	Cohesion		96	Cohesion	Cohesion
FH64-22+ Acid	Dry	Cohesion	Cohesion	CRM58-28 Neat	Dry	Cohesion	Cohesion
	6	Cohesion	Cohesion		6	Cohesion	Cohesion
	24	Cohesion	Cohesion		24	Cohesion	Cohesion
	48	Cohesion	Cohesion		48	Adhesion	Cohesion
	96	Cohesion	Cohesion		96	Adhesion	Adhesion
CRM58-28+ Elastomer3	Dry	Cohesion	Cohesion	CRM58-28+ Acid	Dry	Cohesion	Cohesion
	6	Adhesion	Cohesion		6	Cohesion	Cohesion
	24	Adhesion	Cohesion		24	Cohesion	Cohesion
	48	50%A -50%C	Adhesion		48	Cohesion	Cohesion
	96	Adhesion	Adhesion		96	Cohesion	Cohesion

*Conditioning Time (CT)

4.2 Effect of Bitumen Modification

The effects of bitumen modification on POTS values are clearly detected by the BBS testing results. For example, Table 1 and Table 2 show that the modified FH64-22 bitumens have higher dry average pull-off tensile strength in comparison to the neat bitumen for both granite and limestone aggregates.

The bitumens modified with PPA show less susceptibility to moisture conditioning in comparison to neat bitumens [8]. Note that the effect of PPA is better in granite than in limestone aggregates, due to the acidic nature of the granite aggregate. Bitumen modified with Elastomer1 also show moisture resistance improvements for the granite case compared to the neat bitumen. However, for the limestone case, no significant difference between FH64-22 neat and FH64-22+Elastomer1 are observed.

Failure mechanisms are also affected by modification type. Table 3 indicates that failure type (i.e., cohesive and adhesive failure) changes according to modification, aggregate type and conditioning time. Note that all unconditioned (i.e., dry) samples showed cohesive failure (i.e., failure within bitumen). On the other hand, adhesive failure (i.e., between aggregate and bitumen) was observed for some conditioned specimens.

The results also show that the failure type after 6 hours of conditioning time for the FH 64-22 bitumen changes from adhesive to cohesive when PPA is used as modification. These observations indicate that PPA improves the bond of the interface between the bitumen and granite aggregate. All samples containing PPA have cohesive failure, which indicates that the bond at the bitumen-aggregate interface is greater than the cohesive strength of the bitumen at the specified testing conditions. Note that these observations cannot be generalized to all combinations of bitumens and granites. The purpose of stating these observations is to confirm that the BBS is a system that can detect differences in bond strength and its change with water conditioning for various combinations of bitumen modification.

4.3 Influence of Bitumen Stiffness on Adhesive Bond Strength

The iso-stiffness temperature of eight bitumens was determined by interpolating between three DSR test temperatures (20, 25, and 30°C) to calculate the temperature at which the $|G^*|$ is equal to 1 MPa. Table 4 shows the determined iso-stiffness temperature of the selected asphalt binders.

For each bitumen, the BBS test was performed after dry and wet conditioning (i.e., 96 hours of moisture) at the iso-stiffness temperature. During the BBS test, the temperature was controlled in a water bath as shown in Figure 4. Table 5 presents the BBS and DSR results.

Table 4: Bitumens Iso-Stiffness Temperature.

Sample	Iso-Stiffness Temperature (°C)
FH64-22 Neat	24.5
FH64-22+Elastomer1	24.9
FH64-22+Elastomer2	24.5
FH64-22+Plastomer1	26.4
FH64-22+Anti-Stripping	24.7
FH64-22+Acid	25.7
CRM58-28 Neat	19.5
CRM58-28+Acid	20.5

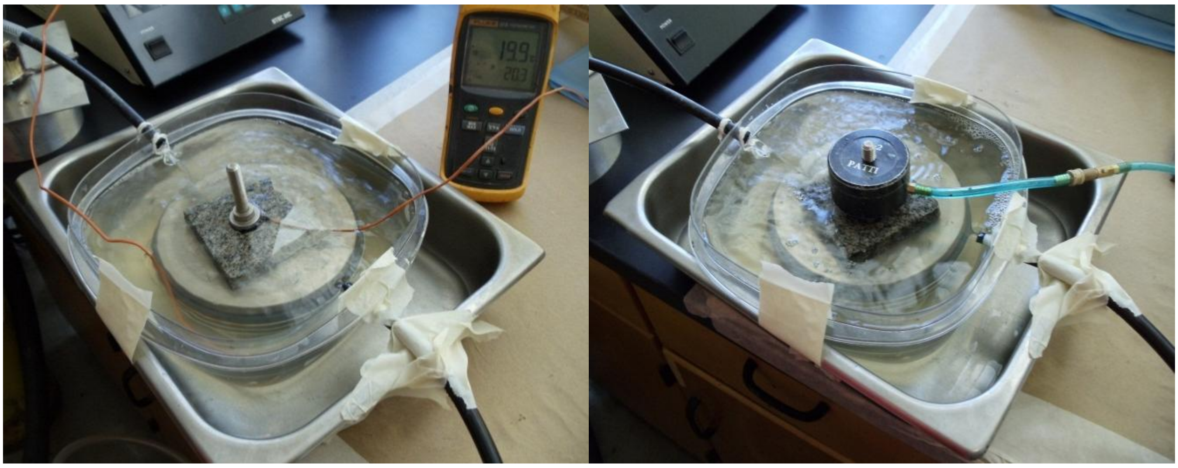

Figure 4: BBS Test With Controlled Temperature.

Table 5: BBS and DSR Results at 25°C and at Iso-Stiffness Temperature.

Sample	Dry Conditioning - 24h		Wet Conditioning - 96h		|G*|	
	POTS at 25°C (MPa)	POTS at Iso-stiffness Temp. (MPa)	POTS at 25°C (MPa)	POTS at Iso-stiffness Temp. (MPa)	|G*| at 25°C (MPa)	|G*| at Iso-stiffness Temp. (MPa)
FH64-22 Neat	2.01	2.33	1.47	1.60	0.897	1
FH64-22+Elastomer1	2.36	2.51	1.36	2.27	0.967	1
FH64-22+Elastomer2	2.15	2.69	1.94	1.84	0.906	1
FH64-22+Plastomer1	2.34	2.11	1.88	1.57	1.271	1
FH64-22+Anti-Stripping	2.32	2.32	1.96	1.86	0.945	1
FH64-22+Acid	2.36	2.47	2.01	1.91	1.127	1
CRM58-28 Neat	1.51	2.33	1.37	1.85	0.332	1
CRM58-28+Acid	1.73	2.29	1.43	1.94	0.438	1

Figure 5 shows the relation between the change of pull-off tensile strength defined as $\mathbf{\Delta POTS = POTS_{Iso\text{-}stiffness\ Temp} - POTS_{25°C}}$, and the change in bitumen stiffness defined as $\mathbf{\Delta G^* = |G^*|_{Iso\text{-}stiffness\ Temp} - |G^*|_{25°C}}$, after dry conditioning. Figure 6 presents same relation after wet conditioning. Note that the BBS results used for the comparison after wet conditioning correspond to bitumens that failure through cohesive mode only.

It is assumed that effects of moisture on the bitumen stiffness are negligible compared to the accuracy of the parameters measured in this test method. This assumption is based on extensive testing of bitumen in the DSR stored under water for more than 7 days. Thus, bitumen stiffness is assumed to be independent of moisture conditioning. On the other hand, the significant effect of moisture conditioning on adhesive strength as measured by the BBS, is well recognized.

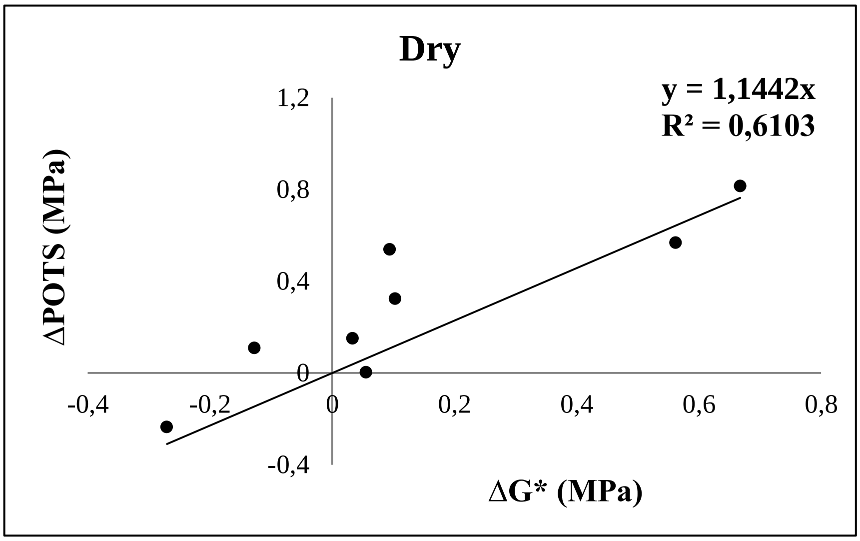

Figure 5: Correlation between change in pull-off tensile strength (ΔPOTS) and change in bitumen stiffness (ΔG*) at dry conditioning.

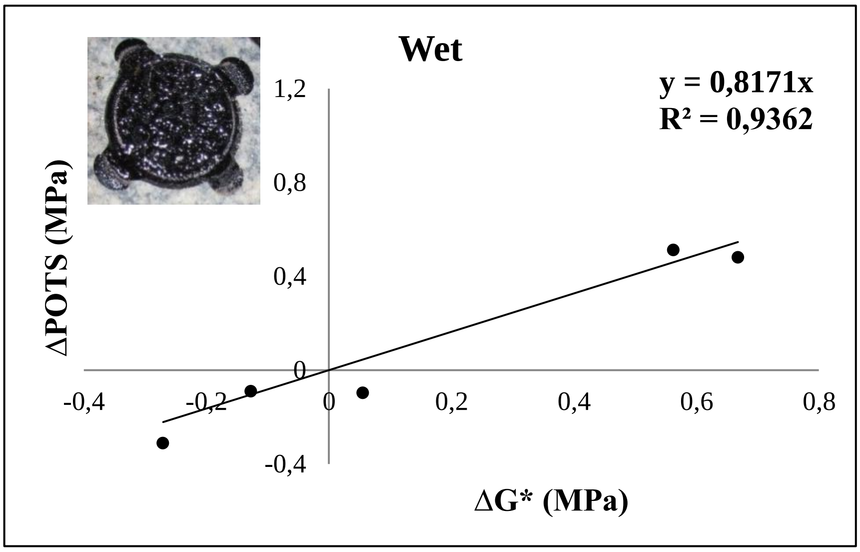

Figure 6: Correlation between change in pull off tensile strength (ΔPOTS) and change in bitumen stiffness (ΔG*) after wet conditioning (for cohesive failures only).

As can be seen, bitumen stiffness has a considerable influence on the value of pull-off tensile strength (POTS). It is important to mention that bitumen stiffness is highly temperature dependent. Therefore, the BBS test should be conducted in a temperature controlled environment, and at a temperature that reflects field conditions, rather than at ambient, room temperature. On the other hand, if one is strictly comparing the moisture sensitivity of different bitumens, it may be more appropriate to test at an iso-stiffness condition to eliminate the effect of stiffness variation on POTS. Once the representative temperature for the project is determined, either testing at the selected temperature is conducted or the following equations can be used to adjust the POTS values. Since the change in G* is required for these equations, the DSR measurements needs to be know.

$$\Delta POTS = 1.14\,\Delta G^* \qquad (2)$$

$$\Delta POTS = 0.82\,\Delta G^* \qquad (3)$$

where, **ΔPOTS = POTS** $_{\textbf{Iso-stiffness Temp}}$ **– POTS** $_{\textbf{Temp}}$, and **ΔG* = |G*|** $_{\textbf{Iso-stiffness Temp}}$ **- |G*|** $_{\textbf{Temp}}$

5. CONCLUSIONS

In this study, a comprehensive experimental test matrix was completed to investigate the effect of bitumen stiffness (|G*|) on the bond strength before and after conditioning in water obtained with the Bitumen Bond Strength (BBS) test.

Experimental results indicate that the bond strength of bitumen-aggregate systems is dependent on stiffness of the bitumen. The following points summarize the main findings of the study.

- The Bitumen Bond Strength (BBS) test can effectively measure the effects of moisture conditioning time and modification on the bond strength of bitumen-aggregate systems.
- In many cases, conditioning of specimens in water causes a change in the failure mode. In absence of water, failure occurs within the bitumen (i.e. cohesive failure). After water conditioning, the failure changes from total cohesive to adhesive failure for many combinations of bitumen and aggregates. The transition in failure mechanism depends on time of conditioning and balance of surface energy. Longer wet conditioning time results in higher loss of adhesion.
- The time dependency is not fully understood. Water can reach interface through the aggregate substrate very rapidly, however there appears to be a time-dependent mechanism for the water to strip (de-bond) the bitumen film from the aggregates. Testing in this study was done under static conditions, in the field dynamic traffic effects could expedite the process. It is proposed that 96 hours should be sufficient to show significant effects in the BBS test.
- It is observed that the bonding between bitumen and aggregate under wet conditions is highly dependent on bitumen modification type and conditioning time.
    - Polymers are found to improve the adhesion between the bitumen and aggregate as well as the cohesion within the bitumen.
    - Poly-Phosphoric Acid (PPA) significantly improves the moisture resistance of bitumen-aggregate systems tested in this study. The effect is especially noticed for granite or acidic aggregates. All samples containing PPA have a cohesive failure, which indicates that the bond at the bitumen-aggregate interface is greater than the cohesive strength of the bitumen.
- The influence of bitumen stiffness on pull-off tensile strength (POTS) results is found to vary between wet and dry conditions. If testing is intended to strictly compare the moisture sensitivity of different bitumens, it is more appropriate to test at an iso-stiffness condition to eliminate the effect of stiffness on POTS. A single linear model is proposed to correct bond strength for dry (Equation 2) and wet (Equation 3) conditions when testing at a single temperature at which stiffness values of binders are different.

6. ACKNOWLEDGEMENTS

This research was sponsored by the Asphalt Research Consortium (ARC), which is managed by FHWA and WRI. This support is gratefully acknowledged. The results and opinions presented are those of the authors and do not necessarily reflect those of the sponsoring agencies.

7. REFERENCES

[1] The Mechanisms of Moisture Damage in Asphalt Pavement by Applying Chemistry Aspects. CHO, D-W.; and KIM, K.. In *KSCE Journal of Civil Engineering*, Vol. 14, n. 3, pp. 333-342, 2010.

[2] Moisture Sensitivity of Modified Asphalt Binders-Factors Influencing Bond Strength. Copeland, A. R.; Youtcheff, J. and Shenoy, A. In Transportation Research Record: *Journal of the Transportation Research Board*, n. 1998, pp. 18-28, 2007.

[3] Chemical and Mechanical Processes of Moisture Damage in Hot-Mix Asphalt Pavements. Little, N. D.; and Jones IV, D. R. In *Moisture Sensitivity of Asphalt Pavements: A National Seminar*, San Diego, California, pp. 37-70, February 4-6, 2003.

[4] Stripping in HMA Mixtures: State-of-the-Art and Critical Review of Test Methods. Kiggundu, B. M.; and Roberts, F. L. In *Report 88-2*. National Center for Asphalt Technology. Auburn University, Auburn, Alabama, 1988.

[5] Role of Adhesion and Thin Film Tackiness of Asphalt Binders in Moisture Damage of HMA. Kanitpong, K.; and Bahia, H. U. In *Asphalt Paving Technology*, Vol. 72, pp. 502-528, 2003.

[6] Adhesive and Cohesive Properties of Asphalt-Aggregate Systems Subjected to Moisture Damage. Canestrari, F.; Cardone, F.; Graziani, A.; Santagata, F.; and Bahia, H. In *Road Materials and Pavement Design*, Vol. 11, pp. 11-32, 2010.

[7] Affinity of Asphalt to Mineral Aggregate: Pull-off Test Evaluation. Meng, J. *MS Thesis*, University of Wisconsin-Madison, Madison, Wisconsin, 2010.

[8] Measuring Effect of Moisture on Asphalt-aggregate Bond With The Bitumen Bond Strength Test. Moraes, R.; Velasquez, R.; and Bahia, H. In Transportation Research Record: *Journal of the Transportation Research Board*, Vol. 2209, pp. 70-81, 2011.

[9] *Handbook of Adhesion.* Packham, D. E. Longman Scientifia & Technical, 1992, pp. 301, 2005.

[10] *Handbook of Adhesives and Sealants.* Petrie, E. M. McGraw-Hill, New York, 1999, pp. 267, 2006.

[11] Surface Free Energy to Identify Moisture Sensitivity of Materials for Asphalt Mixes. Bhasin, A.; Little, D. N.; Vasconcelos, K. L.; and Masad, E. In *Transportation Research Record: Journal of the Transportation Research Board*, n. 2001, pp. 37-45, 2007.

[12] Summary Report on Water Sensitivity. Terrel, R. L.; and Shute, J. W. In *SHRP-A/IR-89-003*, Strategic Highway Program, Washington, D.C, 1989.
[13] Comprehensive Overview of the Stiffness Characterization of Asphalt Concrete. Lytton, R. L. In Modeling of Asphalt Concrete, McGraw-Hill, Chapter 3, pp. 65-87, 2009.
[14] Testing Methods to Determine Aggregate/Asphalt Adhesion Properties and Potential Moisture Damage. Bahia, H. U.; Hanz, A.; Kanitpong, K.; and Wen, H. In *WHRP 07-02*, Wisconsin Highway Research Program, Madison, Wisconsin, 2007.
[15] Rutting Resistance of Rubberized Asphalt Concrete Pavements Containing Reclaimed Asphalt Pavement Mixtures. Xiao, F. P.; Amirkhanian, S. N.; and Juang, C. H. In *Journal of Materials in Civil Engineering*, Vol. 19, pp. 475-483, 2007.
[16] Chemical Properties of Asphalts and Their Effects on Pavement Performance. Robertson, R. E. In *Transportation Research Circular 499*, Transportation Research Board, Washington, DC, 2000.
[17] *The Shell Bitumen Handbook*. Read, J.; and Whiteoak, D. Fifth Edition, Edited by R. Hunter, 2003.
[18] Validation of the Bitumen Bond Strength Test Using Surface Energy Measurements. Moraes, R. *MS Thesis*, University of Wisconsin-Madison, Madison, Wisconsin, 2011.