# MEASURING EFFECT OF MOISTURE ON ASPHALT-AGGREGATE BOND WITH THE BITUMEN BOND STRENGTH TEST

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**ABSTRACT**

Understanding moisture damage mechanisms in asphalt pavements and evaluating the right combination of materials that are resistant to moisture damage is important. Moisture damage can be defined as the loss of strength or stiffness in asphalt mixtures due to a combination of mechanical loading and moisture. A great number of test methods have been developed to evaluate loss of adhesion and cohesion in binders. However, a simple procedure to address moisture damage in the asphalt-aggregate interface is currently not available. The purpose of this paper is to investigate the feasibility of the newly developed Bitumen Bond Strength (BBS) test for moisture damage characterization. An experimental matrix, which included different binders, modifications, and aggregates, to account for different chemical and physical conditions in the aggregate-asphalt interface, was completed. Also, a statistical analysis was performed to verify reproducibility of the BBS test. The results indicate that the bond strength of asphalt-aggregate systems is highly dependent on modification and moisture exposure time. Polymers are found to improve the adhesion between asphalt and aggregate as well as the cohesion within the binder. Moreover, results from this study indicate that the BBS test is repeatable and reproducible. To further validate the effectiveness of the BBS test, a comparison between the BBS test results and the modified Dynamic Shear Rheometer (DSR) strain sweep test was conducted. The comparison shows that the BBS test can rank materials similarly to a more sophisticated and time consuming test.

**INTRODUCTION**

In asphalt mixtures, moisture damage is defined as the loss of stiffness and strength due to moisture exposure under mechanical loading and manifests itself in a phenomenon referred to as stripping. The reduction of the pavement integrity due to moisture damage plays an important role in other types of distresses, such as rutting, fatigue cracking, raveling, and potholes. Moisture can accelerate damage in asphalt mixtures as a result of other types of distress (*1*). The mechanics of the bonding at the aggregate-binder interface, which is highly affected by moisture conditions, influences the response of the asphalt mixture to different distresses.

There are three mechanisms by which moisture degrades an asphalt mixture: (*a*) loss of cohesion within the asphalt mastic, (*b*) failure of the adhesive bond between aggregate and asphalt (i.e., stripping), and (*c*) degradation of the aggregate (*2*). Furthermore, water present in the mixture can affect its performance by flowing between interconnected voids, and by remaining static at the interface and voids (*3*).

Cohesive failure happens due to the rupture of bonds between molecules in the asphalt film. On the other hand, adhesive failure happens due to rupture of bonds between molecules of different phases. The effect of moisture on the performance of the pavement can be the result of the combination of both mechanisms.

Bond strength is a critical parameter in evaluating a binder’s ability to resist moisture damage. Adhesion between asphalt and aggregate is quantified in terms of the adhesive bond energy (*4*). Therefore, a test method performed directly on the asphalt-aggregate system can effectively evaluate the influence of water in both cohesive and adhesive failure types, leading to a better understanding of the moisture sensitivity of asphalt mixtures (*5, 6, 7*).

Canestrari et al. (*5*) suggested a repeatable, reliable, and practical method to investigate the adhesion and cohesion properties of asphalt-aggregate systems based on the Pneumatic Adhesion Tensile Testing Instrument (PATTI). However, a standard procedure to address moisture damage in the asphalt-aggregate interface is currently not available.

This paper evaluates the use of the Bitumen Bond Strength (BBS) test, which is a modification of the PATTI test, for moisture damage characterization of asphalt-aggregate systems. Different base binders, modifications, and aggregate types were used to account for a broad range of chemical and physical conditions of the asphalt-aggregate interface. Also, a statistical analysis was performed to verify the reproducibility of the BBS in testing the influence of moisture conditioning time on the bond strength of asphalt-aggregate systems. A comparison between BBS results and strain sweep tests performed in the Dynamic Shear Rheometer (DSR) was conducted to determine if a test that takes into account the effect of cyclic loading on moisture damage resistance of asphalt-aggregate systems compares reasonable well with the proposed procedure.

Note that moisture damage testing of asphalt mixtures suffer from variability due to air voids, gradation, degree of saturation, and volumetrics. The proposed BBS test measures the bond strength between two materials under very well controlled conditions. Moreover, samples of the aggregate-asphalt system are prepared to a high precision level in comparison to a more variable asphalt mixture sample.

## LITERATURE REVIEW

### Adhesion

Adhesion between two different surfaces is defined as the process in which dissimilar particles/surfaces are held together by valence forces and/or interlocking forces *(8)*. 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 tensile test (e.g., Bitumen Bond Strength Test).

### Asphalt-Aggregate Adhesion Mechanisms

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 asphalt binder and aggregates are: mechanical theory, chemical theory, weak boundary theory, and thermodynamic theory (*6, 12*).

The mechanical theory indicates that bonding of aggregate-binder is affected by physical properties of the aggregate such as porosity, texture, and surface area. The chemical theory suggests that adhesion depends on the pH and the functional groups of both the asphalt binder and aggregate. The weak boundary theory suggests that rupture always occurs at the weakest link of the asphalt-aggregate interface. Finally, the thermodynamic theory studies the attraction between aggregate-asphalt-water due to differences in surface tension.

These theories and associated mechanisms are not exclusively independent and many researchers agree that a combination of mechanisms take place. Also, several factors affect the adhesion of the asphalt binder to the aggregate, including: interfacial tension between the asphalt binder and the aggregate, chemical composition of the asphalt binder and aggregate, binder viscosity, surface texture of the aggregate, aggregate porosity, aggregate cleanliness, aggregate temperature and moisture content at the time of mixing (*13*). Therefore, what has been identified as a major challenge is a system that can effectively measure bond strength and evaluate the effect of moisture.

**Factors Influencing Adhesive Bond Between Asphalt and Aggregate**

*Effect of Asphalt Binder Characteristics*

The asphalt binder characteristics can influence both the adhesion of the asphalt-aggregate system and the cohesion of the mastic. The properties of the asphalt binder that can influence the asphalt-aggregate bond are the chemistry of the asphalt (e.g., polarity and constitution), viscosity, film thickness, and surface energy (*14, 15*). The cohesive strength of the asphalt matrix in the presence of moisture is also influenced by the chemical nature of the binder and processing techniques.

The chemical interaction between the asphalt binder and the aggregate is critical in understanding the capability of compacted bituminous mixtures to resist moisture damage. Robertson (*16*) describes that carboxylic acids in asphalt binders are quite polar and adhere strongly to dry aggregate. However, this chemical group tends to be removed easily from aggregate in the presence of water. One reason for this behavior is the fact that sodium and potassium salts of carboxylic acids in asphalt are essentially surfactants or soaps, which are debonded under the action of traffic in the presence of water (*17*). Note that calcium salts from hydrated lime are much more resistant to the action of water. Robertson (*16*) also suggested that aged asphalts are more prone to moisture damage than unaged asphalts, due to the presence of strongly acidic material in oxidized binders. Petersen *et al.* (*18*) observed that asphalt binders containing ketones and nitrogen are the least susceptibility to moisture damage.

The viscosity of the asphalt binder does play a role in the propensity of the asphalt mixture to strip. It has been reported that asphalts with high viscosity resists displacement by moisture better than those that have low viscosity. Asphalts with high viscosity usually carry high concentration of polar functionalities that provide more resistance to stripping (*14*).

It has also been reported that the bond strength is directly related to film thickness. Samples with thicker asphalt film tend to have cohesive failure after moisture conditioning. On the other hand, specimens with thinner asphalt film have adhesive failure (*6*).

With respect to surface energy, according to the thermodynamic theory of asphalt-aggregate adhesion, low values of this property for the asphalt is preferable to provide better wetting.

*Effect of Aggregate Characteristics*

Aggregate properties have a greater impact on adhesion than some of the binder properties. Size and shape of the aggregate, pore volume and size, surface area, chemical constituents at the surface, acidity and alkalinity, adsorption size surface density, and surface charge or polarity are some of the widely cited aggregate characteristics that can influence moisture damage (*19*).

The chemistry of aggregate affects the asphalt-aggregate adhesion substantially; various mineral components of the aggregates show different affinity for asphaltic material. When an aggregate is being coated with asphalt, the aggregate selectively adsorbs some components of the asphalt. The general trend is that sulfoxides and carboxylic acids have the greatest affinity for aggregates. It is also apparent that aromatic hydrocarbons have much less affinity for aggregate surfaces than the polar groups. Therefore, the type and quantities of the adsorbed components affect the degree of adhesion and various aggregates develop bonds of different strength (*16*).

Aggregates are commonly classified as either hydrophilic (i.e., greater natural affinity for water than for asphalt binder) or hydrophobic (i.e., greater natural affinity for asphalt than for water) (*6, 19, 20*). It is commonly know that acidic aggregates are hydrophobic while basic aggregates are hydrophilic. However, there are notable exceptions and the general conclusion is that few if any aggregates can completely resist the stripping action of water (*19*). For example, limestone is classified as hydrophobic aggregate and granite is considered as hydrophilic, however the level of basic or acidic condition of the limestone and granite aggregates may vary according to their chemical composition.

Rough surfaces and therefore larger contact area are preferred for better adhesive bond. Porosity is another important characteristic of the aggregate that can affect asphalt adsorption. For example, when the asphalt binder coats a rough aggregate surface with fine pores, air is trapped and the asphalt has difficulty penetrating the fine pores (*21*). However, the penetration of asphalt cement into pores is also dependent on the viscosity of the asphalt cement at mixing temperatures.

Moisture and dust can also significantly reduce the bond strength of aggregate-asphalt systems. The presence of dust coatings on the aggregate inhibits complete wetting of the aggregate by the asphalt binder, since the asphalt is adhered to the dust coating and not to the aggregate itself (*22*).

## MATERIALS AND TESTING PROCEDURE

### Materials

Three types of aggregates which are known to have different moisture sensitivity were selected: limestone, granite, and diabase. Two asphalt binders 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, four modified asphalt binders were prepared: FH64-22+Acid (PG 70-22), which was modified with 1% by weight of polyphosphoric acid, FH64-22+Elastomer1 (PG 70-22), modified with 0.7% by weight of Elvaloy and 0.17% of polyphosphoric acid, CRM58-28+Acid (PG 64-28), modified with 1% by weight of polyphosphoric acid, and CRM58-28+Elastomer2 (PG 64-28),modified with 2% by weight of Linear Styrene Butadiene Styrene.

For conditioning media, tap water is used to investigate the effects of conditioning media on the adhesion between asphalt and aggregate.

### Bitumen Bond Strength Test

The challenge to quantitatively evaluate the adhesive bond between asphalt and aggregate is to identify a test which is simple, quick and repeatable for evaluating adhesion properties of asphalt-aggregate systems. Furthermore, no method is included in the Superpave binder specifications to evaluate adhesive characteristics of asphalt binders (*2*).

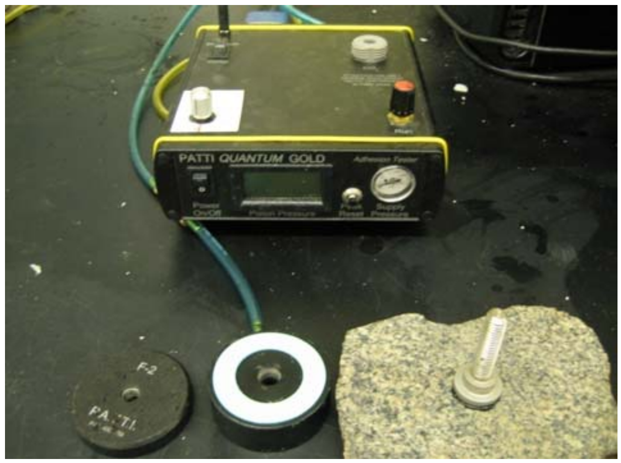
Youtcheff and Aurilio (*7*) used the Pneumatic Adhesion Tensile Testing Instrument (PATTI), originally developed for the coating industry, to measure the moisture susceptibility of asphalt binders. In this study, the Bitumen Bond Strength Test (BBS), which is a significantly modified version of the original PATTI (*21*), was used to evaluate the asphalt-aggregate bond strength.

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. To start the test, the piston is placed over the pull-out stub and the reaction plate is screwed on it. Then, a pressure hose is used to introduce compressed air to the piston. 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:

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

where,

$A_g$ = contact area of gasket with reaction plate ($mm^2$)
BP = burst pressure (kPa)
$A_{ps}$ = area of pull stub ($mm^2$)
C = piston constant



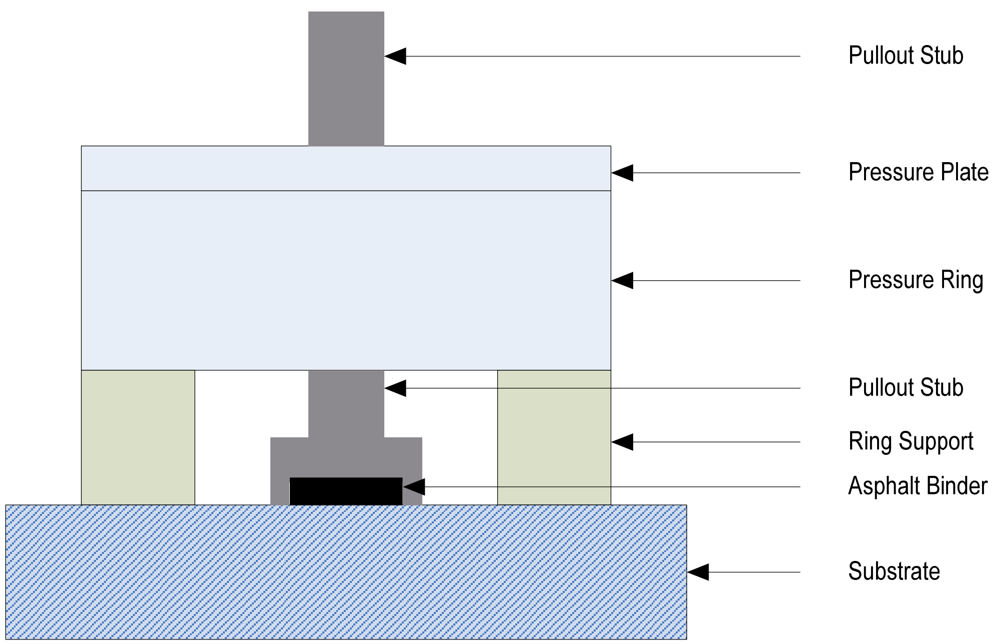




**FIGURE 1 Bitumen Bond Strength Test (BBS).**

The pull-out stub has a rough surface that can prevent asphalt debonding from the stub surface by providing mechanical interlock and larger contact area between the asphalt binder and stub (Figure 2). The pull-out stub in the BBS test has a diameter of 20 mm with a surrounding edge, used to control film thickness. The stub edge has a thickness of 800 μm (Figure 2). This new geometry and surface treatment was developed in two extensive recent studies (*5, 21*) in an effort to improve repeatability of the testing system.

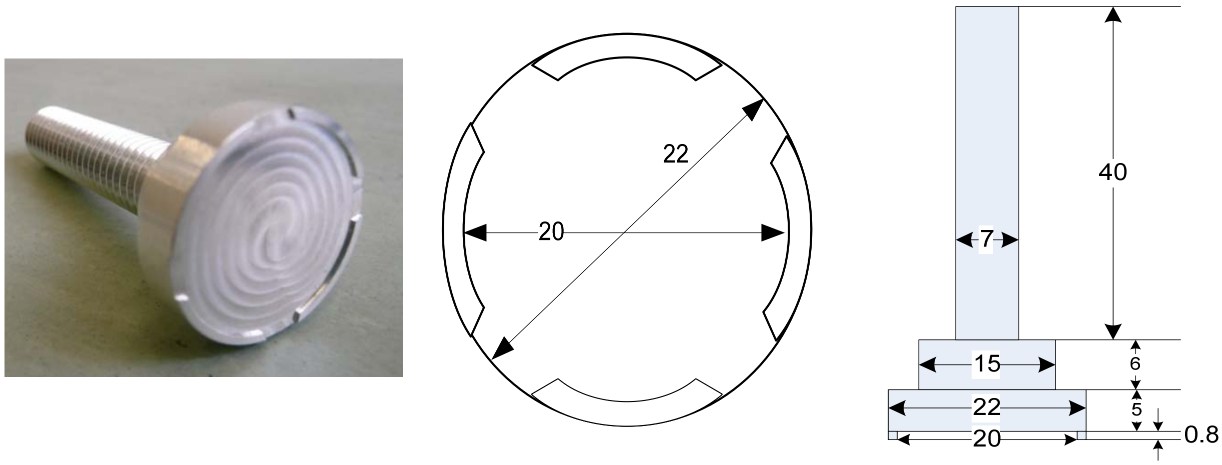



**FIGURE 2 Pull-out stub for the Bitumen Bond Strength Test (BBS).**

*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 any residue from the cutting process and neutralize the surface of aggregate to its original condition. It should be mentioned that the lapping is done to provide a control on the roughness of the surface.

*Asphalt Sample Preparation*

The aggregate surface and pull-out stubs are degreased with acetone to remove moisture and dust which could affect adhesion. After cleaning with acetone, the pull-out stubs and the aggregate plates are heated in the oven at 65°C for a minimum of 30 minutes to remove absorbed water on the aggregate surface and provide a better bond between the asphalt binder and the aggregate. The asphalt binders are heated in oven at 150°C. The stubs are removed from the oven and an asphalt binder 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 asphalt sample is pressed into the aggregate surface firmly until the stub reaches the surface and no excess of asphalt binder is observed to be flowing. The stubs need to be pushed down as straight as possible and twisting needs to be avoided to reduce the formation of trap air bubbles inside the sample and to minimize stresses.

Before testing, dry samples are left at room temperature for 24 hours. For wet conditioning, samples are first left at room temperature for 1 hour to allow for the aggregate-binder-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:

- Before testing, air supply and pressure hose connection should be checked.
- Set the rate of loading to 100 psi/s. Measure sample temperature using a thermometer before starting the test.
- Place circular spacer under the piston to make sure that the pull-off system is straight and that eccentricity of the stub is minimized.
- 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.
- 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; otherwise, it is a cohesive failure.

**Modified Dynamic Shear Rheometer (DSR) Strain Sweep Test**

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 asphalt films adhering to aggregate surfaces in dry and moisture conditions. Cho and co-workers (*22*) modified the DSR strain sweep test procedure to evaluate the rheological properties of the asphalt-aggregate interface before and after water conditioning.

A cored rock disk of 25 mm in diameter and 5 mm thick is used as the substrate for adhering asphalts (Figure 3). The disk and asphalt binder simulate the asphalt-aggregate interface in asphalt mixtures. The rock disk is glued on the DSR base metal plate. In the DSR setup, the parallelism is obtained by aligning the disk using the metal DSR top spindle while the epoxy binder dries. A water cup, fabricated specially for the DSR (Figure 3), is used to allow continuous water access to the interface (*22*). Rheological responses are measured using oscillated loads of 1% to 100% strain sweep with 1.6 Hz frequency ( i.e., 10 rad/s), at 40°C, in both dry and wet (i.e., using tap water) conditions (*22*).

**FIGURE 3 DSR testing apparatus: (a) Sample Preparation (b) Wet-Conditioning (*22*).**

## ANALYSIS OF BBS TEST RESULTS

### Effect of Conditioning Time

In this experiment, samples were conditioned in tap water for 0, 6, 24, 48, and 96 hours. Please note that 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. All the reactions involved in this process have a different and unknown kinetics and therefore the different conditioning times selected are considered appropriate. The effect of conditioning time on the pull-off tensile strength (POTS) for the asphalt-aggregate systems tested using the BBS can be observed in Figure 4.

The average pull-off strength was calculated from four replicates. As shown in the charts, the conditioning of specimens in water caused a significant reduction in strength and, in some cases, a change in failure mode from cohesive to adhesive type (Table 1). 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.

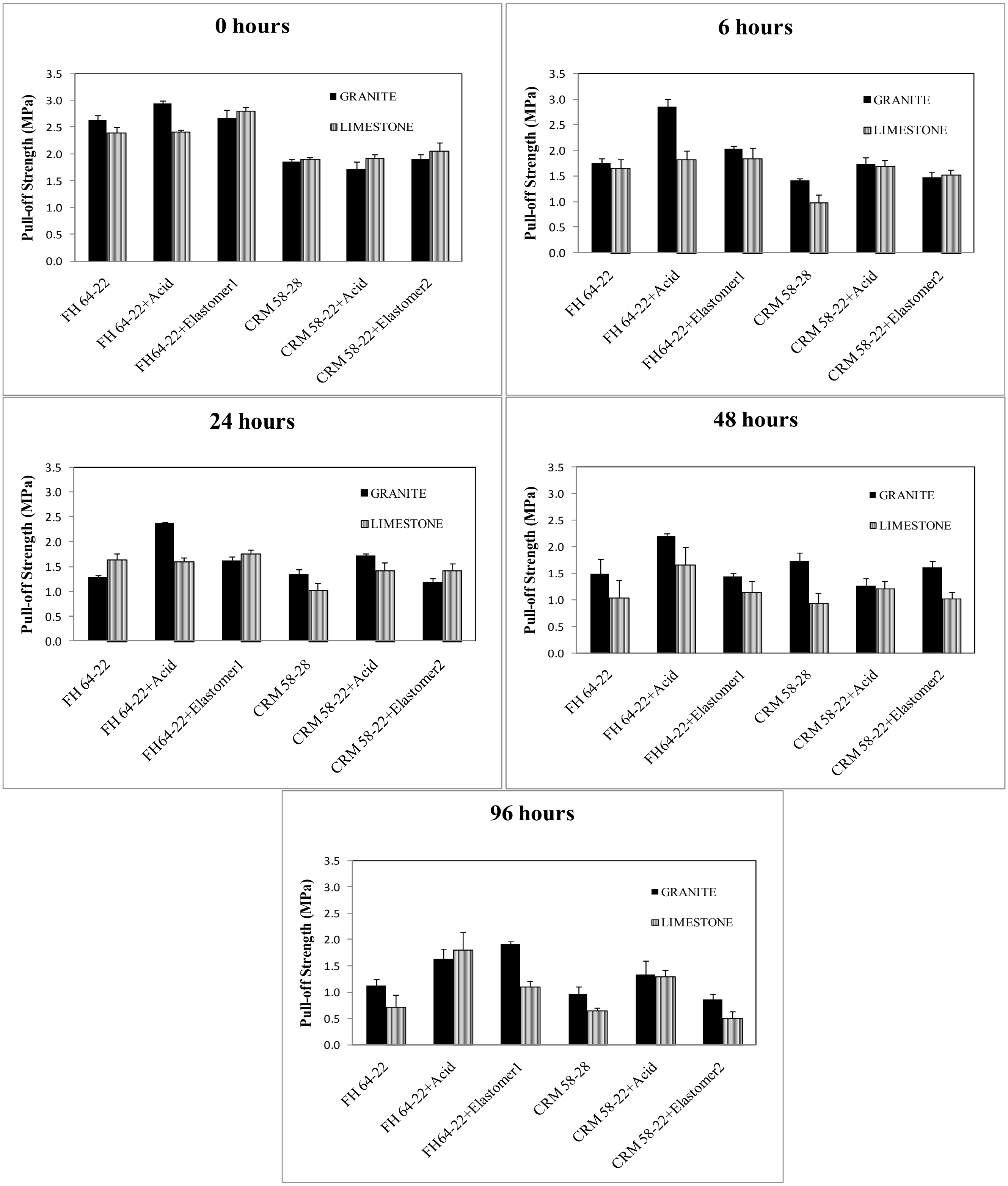



**FIGURE 4 Influence of conditioning time on the pull-off tensile strength (POTS) for different asphalt-aggregate systems.**

**TABLE 1 Failure mode in BBS testing**

| Asphalt Binder Type | *CT (hr) | Failure Type | |
|---|---|---|---|
| | | Granite | Limestone |
| FH64-22 neat | Dry | Cohesion | Cohesion |
| | 6 | Adhesion | Cohesion |
| | 24 | Adhesion | Cohesion |
| | 48 | 50%A -50%C | 50%A -50%C |
| | 96 | Cohesion | Cohesion |
| FH64-22 +Elastomer1 | Dry | Cohesion | Cohesion |
| | 6 | Cohesion | Cohesion |
| | 24 | Adhesion | Cohesion |
| | 48 | Cohesion | 50%A -50%C |
| | 96 | Cohesion | Cohesion |
| FH64-22+Acid | Dry | Cohesion | Cohesion |
| | 6 | Cohesion | Cohesion |
| | 24 | Cohesion | Cohesion |
| | 48 | Cohesion | Cohesion |
| | 96 | Cohesion | Cohesion |
| CRM 58-28 neat | Dry | Cohesion | Cohesion |
| | 6 | Cohesion | Cohesion |
| | 24 | Cohesion | Cohesion |
| | 48 | Adhesion | Cohesion |
| | 96 | Adhesion | Adhesion |
| CRM 58-28 +Elastomer2 | Dry | Cohesion | Cohesion |
| | 6 | Adhesion | Cohesion |
| | 24 | Adhesion | Cohesion |
| | 48 | 50%A -50%C | Adhesion |
| | 96 | Adhesion | Adhesion |
| CRM58-28+Acid | Dry | Cohesion | Cohesion |
| | 6 | Cohesion | Cohesion |
| | 24 | Cohesion | Cohesion |
| | 48 | Cohesion | Cohesion |
| | 96 | Cohesion | Cohesion |

*Conditioning Time (CT)

There are two general trends observed for the effect of conditioning time on the POTS (Figure 5). The first is the continuous reduction of the magnitude of the POTS with conditioning time in water for a number of the systems tested including the following combinations of binder and aggregate show this trend: FH 64-22 Neat – Limestone; FH 64-22+Acid – Granite; CRM 58-28+Elastomer2 – Granite; CRM 58-28+Elastomer2 – Limestone. The second corresponds to a reduction on the POTS up to a specific asymptote. This trends is seen for conditioning times in the 24-48 hours range for the following binder-aggregate systems: FH 64-22 Neat – Granite; FH 64-22+Acid – Limestone; FH 64-22+Elastomer1 – Granite; FH 64-22+Elastomer1 – Limestone; CRM 58-28+Acid – Limestone.

Note that the bond strength for the CRM 58-28+Acid binder and granite did not significantly change with conditioning time (Figure 5). This result indicates that (PPA) may induce effects that reduce the moisture susceptibility of this aggregate-binder interface.

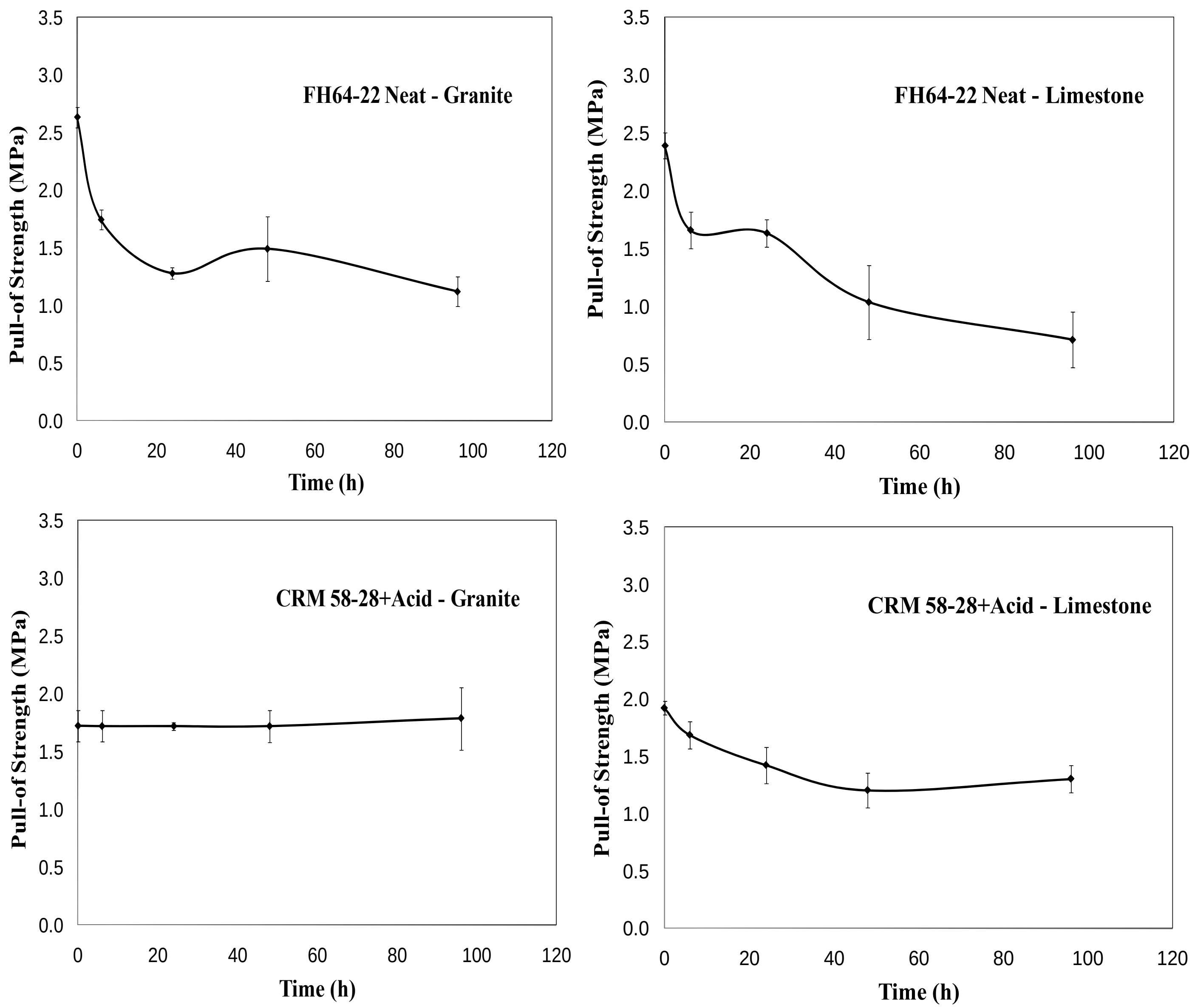



**FIGURE 5 Effect of large conditioning times on the pull-off tensile strength for FH 64-22 Neat and CRM 58-28+Acid.**

**Effect of Asphalt Modification**

The effects of modification of asphalt on the POTS values are clearly detected by the BBS testing results. For example, Figure 4 shows that the modified FH64-22 binders have higher dry average pull-off tensile strength in comparison to the neat binder for both granite and limestone aggregates.

The asphalts modified with PPA show less susceptibility to moisture conditioning in comparison to neat asphalts. Note that the effect of PPA is better in granite than in limestone aggregates, due to the acidic nature of the granite aggregate. Asphalt binder modified with Elvaloy also show moisture resistance improvements for the granite case compared to the neat asphalt. However, for the limestone case, no significant difference between FH64-22 neat and FH64-22+Elastomer1 were observed.

Failure mechanisms are also affected by modification type. Table 1 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 asphalt). On the other hand, adhesive failure (i.e., between aggregate and binder) 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 asphalt changes from adhesive to cohesive when PPA is used as modification. These observations indicate that PPA improves the bond of the interface between the asphalt and granite. All samples containing PPA have cohesive failure, which indicates that the bond at the aggregate-binder interface is greater than the cohesive strength of the binder at the specified testing conditions. Note that these observations cannot be generalized to all combinations of asphalts 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 binder modification.

**Effect of Aggregate Type**

The nature and chemical characteristics of aggregates greatly affect bond strength and failure mechanisms of asphalt-aggregate systems as indicated by Table 1. On both, limestone and granite surfaces, the failure mode changed after moisture exposure, showing that the nature of the aggregate greatly affects adhesion.

It can be seen that for all limestone samples, the failure type was cohesive, which indicates that the adhesive bond in the asphalt-aggregate interface is larger than the cohesive strength of the binders. Also, Figure 4 indicates that limestone aggregates have higher adhesive bond to asphalt than granite aggregates, and thus more resistance to adhesive failure.

The pull-off tensile strength obtained from BBS tests performed is highly influenced by the cleanness of the surface of the aggregate plate. Inconsistent and unexpected results for some of the samples conditioned at 48 and 96 hours were obtained when the aggregate plates used were different than the plates used for the 0, 6, and 24 hours tests. It appears that slight changes of the aggregate surface can greatly affect the magnitude of the pull-off tensile strength. Therefore, it is always important to perform moisture susceptibility experiments using the aggregates from the same source and to be consistent in sample preparation.

**Bitumen Bond Strength Reproducibility**

The effect of conditioning time (0, 6 and 24 hours) on the pull-off strength of the asphalt-aggregate systems tested by different operators can be observed in Figure 6. As can be seen, the values of pull-off strength for each aggregate-binder system were similar for both operators.

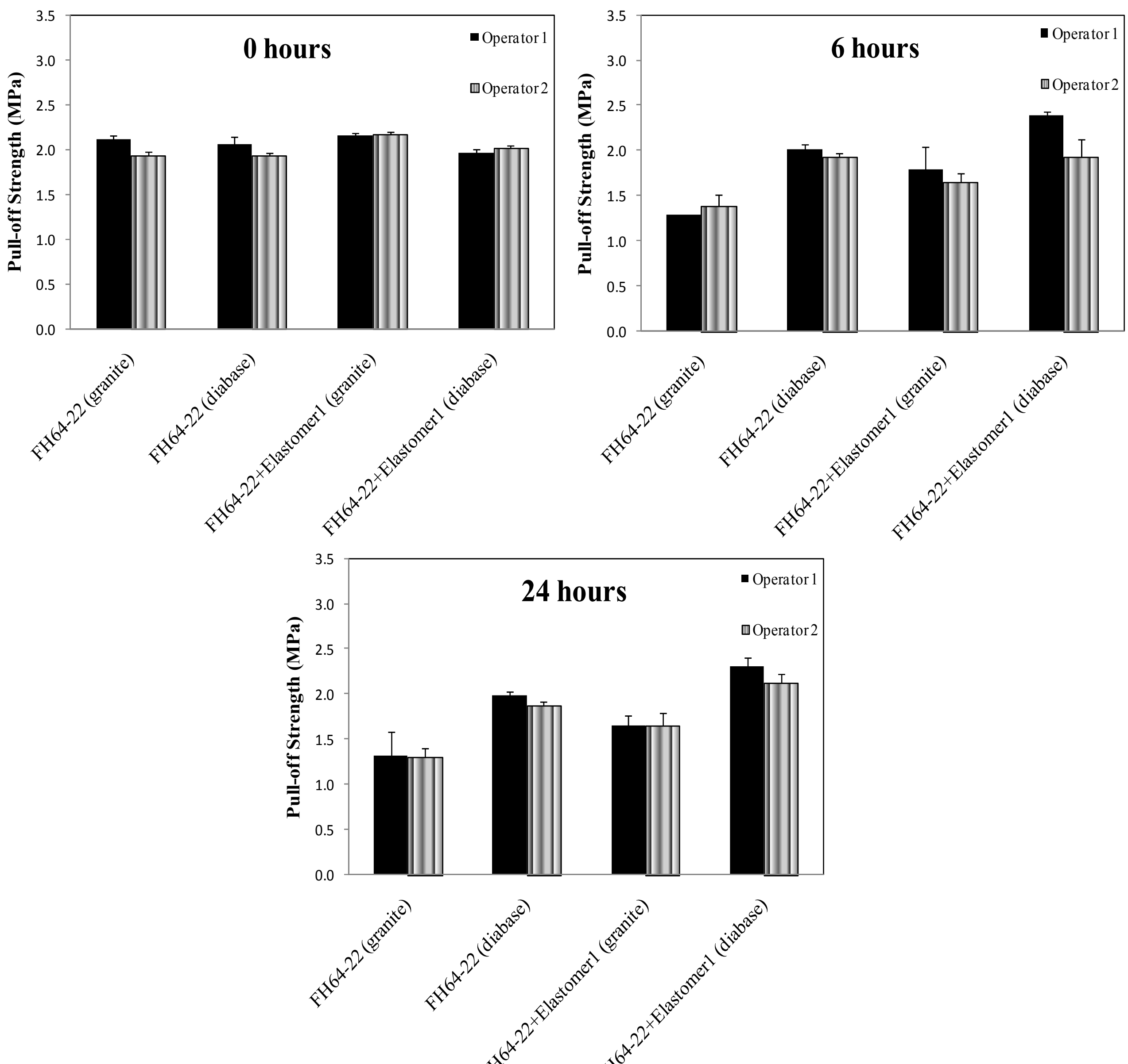



**FIGURE 6 Influence of operators in testing the effect of large conditioning on the pull-off tensile strength.**

*Statistical Analysis*

Statistical analyses were performed to evaluate the reproducibility of the BBS test. Specifically, test of hypotheses were used to determine if there is any statistically significant difference between the means of the pull-off tensile strength obtained with two operators. For the test of hypotheses a two-tailed test was used. The following null and alternative hypotheses were used with α = 0.05 (type I error, reject $H_o$ when $H_o$ is true):

$$H_0 : \mu_1 - \mu_2 = 0$$
$$H_a : \mu_1 - \mu_2 \neq 0 \tag{2}$$

with the test statistic:

$$t = \frac{\bar{X}_1 - \bar{X}_2}{\sqrt{S_p^2\left(\frac{1}{n_1} + \frac{1}{n_2}\right)}} \tag{3}$$

where,

$\bar{X}_1$ = estimation of the population mean of the pull-off tensile strength for operator 1.

$\bar{X}_2$ = estimation of the population mean of the pull-off tensile strength for operator 2.

$n_1$ = number of replicates tested by operator 1 to estimate population mean.
$n_2$ = number of replicates tested by operator 2 to estimate population mean.
$S^2_p$ = variance pooled estimator.

The variance pooled estimator (*23*) can be calculated using:

$$S_p^2 = \frac{(n_D - 1)s_D^2 + (n_S - 1)s_S^2}{n_D + n_S - 2} \tag{4}$$

where,

$s^2_1$ = calculated variance for the pull-off tensile strength of operator 1.
$s^2_2$ = calculated variance for the pull-off tensile strength of operator 2.

The test of hypotheses described above has the following rejection region (values of the t-test statistic for which the null hypotheses is rejected): $t < -t_\alpha$ and $t > t_\alpha$ where $t_\alpha$ are based on $n_1$+ $n_2$-2 degrees of freedom and the selected type I error (α).

Table 2 shows the results of the statistical analysis of the operator variability of the BBS test data for all asphalt-aggregate systems. Note that the average pull-off strength was calculated from three replicates for each operator and that α = 0.05 is used.

Note that generally, the BBS test is not sensitive to the operator performing the test. Only in two conditions the average of the pull-off tensile strength was statistically different between operators: FH 64-22 Granite at 0 hours and FH 64-22+Elastomer1 Diabase at 6 hours of conditioning time. Figure 7(a) shows one of the two cases where the null hypothesis was rejected for $\alpha = 0.05$. On the other hand, Figure 7(b) presents an example of the very similar probability distributions obtained for the BBS test results by different operators.

**TABLE 2 Statistical analysis of the reproducibility of the BBS test data**

| Materials | Operator 1 | | | Operator 2 | | | $Sp^2$ | $t_{statistic}$ | $t_\alpha$ | $-t_\alpha$ | Result |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | $u_1$ | σ | CV (%) | $u_2$ | σ | CV (%) | | | | | |
| FH64-22, Granite (0 h) | 2.110 | 0.040 | 1.90 | 1.937 | 0.040 | 2.07 | 0.00 | -5.297 | | | Reject Ho |
| FH64-22, Diabase (0 h) | 2.058 | 0.080 | 3.89 | 1.932 | 0.030 | 1.55 | 0.00 | -2.554 | | | Accept Ho |
| FH64-22+Elastomer1, Granite (0 h) | 2.150 | 0.030 | 1.40 | 2.164 | 0.030 | 1.39 | 0.00 | 0.572 | | | Accept Ho |
| FH64-22+Elastomer1, Diabase (0 h) | 1.966 | 0.040 | 2.03 | 2.024 | 0.020 | 0.99 | 0.00 | 2.246 | | | Accept Ho |
| FH64-22, Granite (6 h) | 1.284 | 0.010 | 0.78 | 1.388 | 0.120 | 8.65 | 0.01 | 1.496 | | | Accept Ho |
| FH64-22, Diabase (6 h) | 2.017 | 0.050 | 2.48 | 1.925 | 0.050 | 2.60 | 0.00 | -2.254 | | | Accept Ho |
| FH64-22+Elastomer1, Granite (6 h) | 1.787 | 0.260 | 14.55 | 1.650 | 0.100 | 6.06 | 0.04 | -0.852 | 2.776 | -2.776 | Accept Ho |
| FH64-22+Elastomer1, Diabase (6 h) | 2.387 | 0.040 | 1.68 | 1.930 | 0.190 | 9.84 | 0.02 | -4.077 | | | Reject Ho |
| FH64-22, Granite (24 h) | 1.321 | 0.260 | 19.68 | 1.305 | 0.090 | 6.90 | 0.04 | -0.101 | | | Accept Ho |
| FH64-22, Diabase (24 h) | 1.981 | 0.050 | 2.52 | 1.880 | 0.040 | 2.13 | 0.00 | -2.732 | | | Accept Ho |
| FH64-22+Elastomer1, Granite (24 h) | 1.644 | 0.120 | 7.30 | 1.656 | 0.130 | 7.85 | 0.02 | 0.117 | | | Accept Ho |
| FH64-22+Elastomer1, Diabase (24 h) | 2.298 | 0.100 | 4.35 | 2.127 | 0.090 | 4.23 | 0.01 | -2.201 | | | Accept Ho |

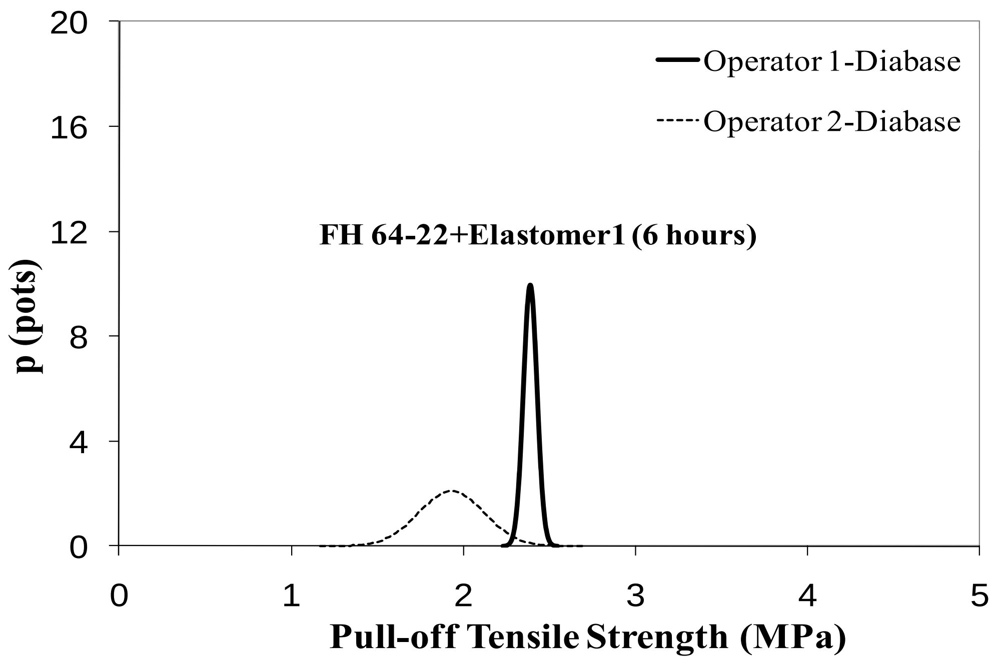



**FIGURE 7 (a) Distributions of the BBS test results from two operators: hypothesis was rejected for α = 0.05.**

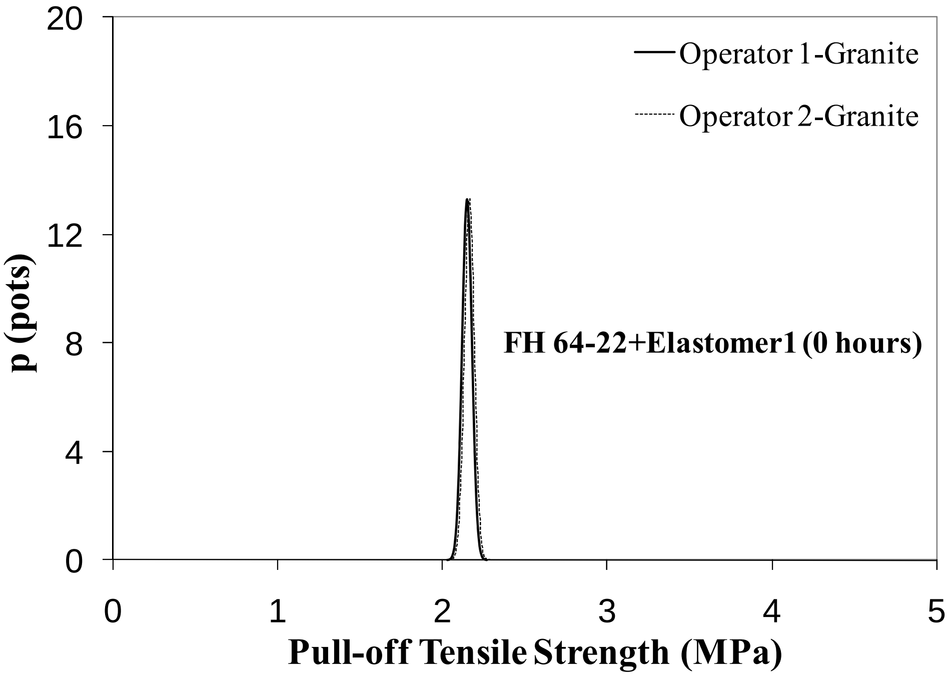



**FIGURE 7 (b) Distributions of the BBS test results from two operators: hypothesis was accepted for α = 0.05.**

## COMPARISON BETWEEN BBS AND MODIFIED DSR STRAIN SWEEP TESTS

A limited number of tests were performed to compare moisture susceptibility measurements obtained from the newly developed BBS test and a more time consuming DSR strain sweep test. Note that the DSR can simulate the cyclic nature of the stresses applied by the pore pressure under moving traffic. This phenomenon can not be simulated by any other device currently available. This traffic-induced pressure is one of the most important factors in moisture damage of asphalt mixtures. Three different asphalt binders CRM 58-28 neat, CRM 58-28+Elastomer2, and FH 64-22+Elastomer1 were tested using granite as aggregate substrate in both the BBS and the DSR. The strain sweep test was performed following the procedure described previously (*22*). Two replicates were tested for each condition and test type.

Figure 8 shows a typical result obtained from the DSR strain sweep procedure. It can be seen that water conditioning significantly affects the rheological properties of asphalt-aggregate systems.

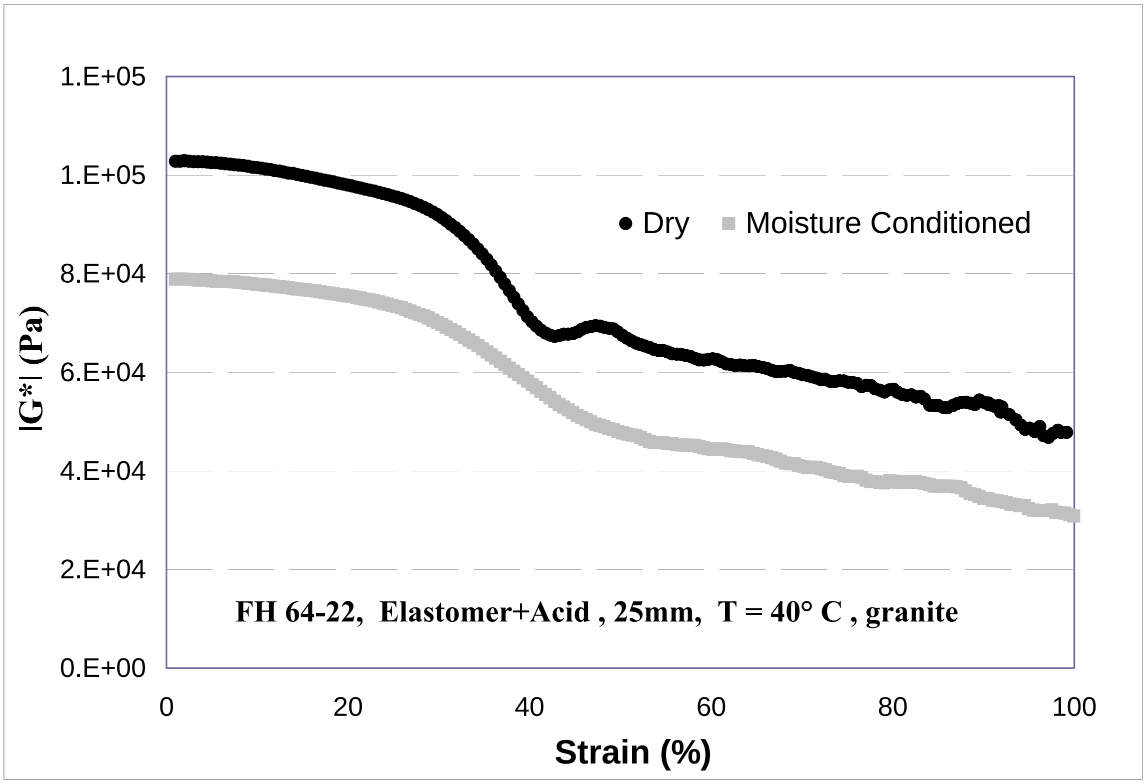



**FIGURE 8 Strain sweep test in DSR for FH 64-22+Acid and granite in dry and wet conditions.**

Comparison of the BBS and DSR procedures involved the calculation of the percent loss of a specific property after water conditioning for 6 hours. In the case of the BBS test the pull of tensile strength (POTS) was used to calculate moisture susceptibility. On the other hand, for the DSR strain sweep test, the complex modulus |G*| at a strain of 1% was selected as the parameter. Note that similar results were obtained when selecting the complex modulus at higher strain levels (i.e., γ=100%). The following equation was used to compute moisture damage in the BBS test:

$$\%Loss\_After\_Moisture\_BBS = \left(1 - \frac{POTS_{WET}}{POTS_{DRY}}\right) \times 100 \tag{5}$$

where, $POTS_{DRY}$ and $POTS_{WET}$ are the pull of tensile strength from BBS test in dry and moisture conditioning after 6 hours, respectively. To calculate the moisture damage in the strain sweep test, the following equation was used:

$$\%Loss\_After\_Moisture\_DSR = \left(1 - \frac{\left|G^*\right|_{\gamma=1\%,\_WET}}{\left|G^*\right|_{\gamma=1\%,\_DRY}}\right) \times 100 \tag{6}$$

where, $\left|G^*\right|_{\gamma=1\%,\_WET}$ and $\left|G^*\right|_{\gamma=1\%,\_DRY}$ are the complex modulus at a shear strain of 1% from DSR testing in dry and moisture conditioning after 6 hours, respectively.

Table 3 shows the results for the three asphalt-aggregate systems tested in the BBS and DSR. It can be seen that the moisture susceptibility ranking from the BBS test and the DSR strain sweep test are the same.

**TABLE 3 Ranking moisture susceptibility of three different asphalt-aggregate systems with BBS and DSR testing**

| Asphalt-Aggregate System Description | *%Loss_DSR* | *%Loss_BBS* | Ranking DSR | Ranking BBS |
|---|---|---|---|---|
| CRM 58-28 neat Granite | 10% | 24% | 2 | 2 |
| CRM 58-28+Elastomer2 Granite | 8% | 22% | 1 | 1 |
| FH 64-22+Elastomer1 Granite | 23% | 26% | 3 | 3 |

## SUMMARY AND CONCLUSIONS

In this paper, a comprehensive experimental test matrix was tested to investigate the feasibility of the Bitumen Bond Strength (BBS) test for moisture damage characterization. Different base binders, modifications, and aggregate types were used to account for a broad range of chemical and physical conditions of the asphalt-aggregate interface. Based on the results and analyses, the following conclusion can be drawn:

- The Bitumen Bond Strength (BBS) test can effectively measure the effects of moisture conditioning time and modification on the bond strength of asphalt-aggregate systems.
- The pull-off tensile strength (POTS) value decreases when samples are conditioned in water, regardless of the selected asphalt binder or aggregate type. In general, POTS measurements for the dry samples have lower coefficient of variation than for the samples tested after water conditioning.
- In some cases, conditioning of specimens in water causes not only loss of pull-off tensile strength, but also a change in the failure mechanism. In absence of water, failure usually happens within the asphalt (i.e. cohesive failure). After water conditioning, the failure changes from total cohesive to adhesive failure.
- It is observed that the bonding between asphalt and aggregate under wet conditions is highly dependent on binder modification type and conditioning time.
- Polymers are found to improve the adhesion between the asphalt and aggregate as well as the cohesion within the binder.

- Polyphosphoric Acid (PPA) significantly improves the moisture resistance of asphalt-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 aggregate-binder interface is greater than the cohesive strength of the binder.
- Statistical analysis indicates that the BBS test is repeatable and reproducible. No significant differences between the results obtained by different operators were observed. Therefore, the BBS test can be used as a practical method to measure bond strength between aggregate and binders in dry and moisture conditions.
- Limited results on the validation/verification of the BBS test procedure with the modified Dynamic Shear Rheometer (DSR) strain sweep test indicates that the BBS test can rank the asphalt-aggregate systems with respect to moisture damage similarly to tests that can simulate the cyclic nature of the traffic-induced stresses. Note that results are preliminary and a more extensive test matrix needs to be performed for such comparison. It is clear that BBS test is a simpler and more practical test. The comparison is needed only for validation of results in terms of ranking of aggregate-binder systems.

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