Evaluation of Adhesion Properties of Costa Rican Asphalt Mixtures using the Bitumen Bond Strength (BBS) and Contact Angle Measurement Tests

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ABSTRACT

Because of the geographic location of Costa Rica, the country is subjected to one of the highest levels of precipitation in the world. As such, it is to be expected that moisture damage is the most common type of pavement failure in the country. However, despite the previous fact, little research has been performed in quantifying the affinity of the asphalt binder and aggregates that are used.

Consequently, the present study consists of an effort to characterize the strength in the bond between the asphalt binder that is used locally (PG64-22) and several types of aggregates from different parts of the country (1 limestone and 4 distinct river gravels from several locations). Additionally, the neat asphalt binder was also modified with a commercial SBR, a modifier commonly used in Costa Rica since it is supposed to promote adhesion. To evaluate the strength of the bond between the asphalt binder and the various aggregate combinations, the Bitumen Bond Strength (BBS) test was used. The results were checked by means of a goniometer that measures the contact angle between the asphalt binder and the aggregate surface, which corresponds to a measure of wettability. Finally, a subset of the analyzed asphalt binder and aggregate combinations were used to prepare an HMA mixture and evaluate it under the Hamburg Wheel Tracking Device (HWTD).

The BBS results showed differences in behavior due to the effect of moisture on bond strength when changing the aggregate source. Additionally, depending on the aggregate type, different types of failure were observed: cohesive versus adhesive. A decrease was identified in the bond strength when the SBR was used. However, when using the modifier, the effect of moisture on bond strength was reduced. The BBS results were consistent with the contact angle measurements and with the HWTD results, showing that the test can eventually be implemented as a screening tool.

INTRODUCTION

Moisture damage has been reported as one of the main cause of deterioration of asphalt pavement structures in Costa Rica. Moisture damage, which is associated with a reduction in the adhesion between the asphalt binder and aggregate surface, or a cohesive failure of the binder mastic structure when subjected to moisture, is dependent on several variables that include: type of asphalt mixture, properties of the asphalt binder and aggregate, environmental and traffic characteristics, construction techniques, and the use of modifying additives or agents *(1,2)*. However, the presence of moisture in the water-accessible pores of the aggregates and/or at the asphalt binder and aggregate interface is the most common factor in stripping related problems.

In order to ensure a proper resistance to moisture damage, the Costa Rican road and highway specifications require a retained tensile strength, according to AASHTO T283, above 85% for all hot mix asphalt (HMA) mixtures *(3,4)*. Most HMA mixtures in Costa Rica tend to display retained tensile strengths considerably above the required specification. However, once the HMA is placed in the field the deterioration rates due to moisture damage are fairly high. Pavement failures just months after construction were observed in many cases. This has led to into mandating the use of lime or some other types of anti-stripping additives on some projects. Moreover, other moisture sensitivity tests such as the Hamburg wheel tracking device has been examined as an alternative or companion test to the current AASHTO T283 test.

Consequently, it becomes evident the need to better understand the adhesion characteristics between the commonly used aggregates and asphalt binders in Costa Rica. To this end, a study was initiated at LarammeUCR to assess moisture damage of asphalt mixtures with local material in Costa Rica. The study included a PG64-22 asphalt binder mixed with five different aggregate sources: one limestone from the central part of the country and four river gravels from several other locations. The study focused on the cohesion and adhesion properties of the asphalt binder with the various aggregate sources by measuring the Bitumen Bond Strength (BBS) test, the contact angle between the asphalt binder and the aggregate using a goniometer, and the Hamburg Wheel Tracking Device (HWTD) test.

BACKGROUND

Moisture damage can occur at the interface between the mastic (mixture of asphalt binder and mineral filler) and aggregate surface (adhesive failure) or within the mastic structure itself (cohesive failure). The type of failure that may occur mainly depends on the properties of the mastic itself. However, several other factors would also have an effect on the moisture susceptibility such as the addition of a binder modifier, liquid anti-strip agent, or hydrated lime *(6)*. It has also been reported that an increase in the pH of the water at the asphalt binder and aggregate surface interface has an important effect on the weakening of the adhesion bond between the two materials *(7)*.

A literature review by Tarrer and Wagh *(1)* showed that at least five different mechanisms of failure are associated to moisture damage and stripping, and might occur individually or simultaneously: detachment, displacement, spontaneous emulsification, pore pressure, and hydraulic scouring. Detachment occurs when a thin layer of water displaces the complete asphalt film from the aggregate surface. This is a result of lower free surface energy of water as compared to the asphalt binder, resulting in a higher wettability of the aggregate *(1,8)*.

Displacement differs from detachment because water penetrates the aggregate surface by a break in the asphalt binder film caused by inadequate coating or asphalt film rupture *(1,7,9)*. Spontaneous emulsification results when water and asphalt binder combine to form an emulsion, phenomenon that is amplified by the presence of emulsifiers such as some mineral clays and asphalt binder additives *(1,7,9)*. Pore pressure can also generate moisture damage in asphalt mixtures with high air void contents, typically open graded mixtures where water can circulate through the interconnected voids. The problem worsens if water becomes trapped in the impermeable voids *(2,10)*. Hydraulic scouring occurs only at the pavement surface and is a result of the effect of vehicle tires on wet pavement surfaces which generate high water pressures ahead of the tire and suction behind the tire *(1,10)*.

There are several methods available in the literature for characterizing the moisture susceptibility of asphalt mixtures. Most of the tests are empirical in the sense that they are intended to characterize the resistance of the mixture to moisture damage in general without any ability to differentiate between the various aforementioned modes of moisture damage. Examples of moisture susceptibility tests are the boiling test (ASTM D3625), Texas boiling test (Tex-530-C), static-immersion test (AASHTO T 182), Lottman test, modified Lottman (AASHTO T283), Tunnicliff and Root Conditioning test *(11)*, immersion-compression test (AASHTO T 165), Texas freeze thaw pedestal test, Hamburg wheel tracking device (HWTD) test (AASHTO T 324), and the Superpave simple performance tests (static creep, repeated load permanent deformation, and dynamic modulus) with an environmental conditioning system (ECS).

In addition to the previous tests, thermodynamics approaches to quantify the affinity of aggregate and asphalt binder have also been employed. This type of analysis evaluates the micro-mechanisms associated with adhesive or cohesive failures and requires the measurement of surface free energy of aggregates and asphalt binder. Surface free energy corresponds to the amount of increase of free energy (work) required to create a unit area of surface of any given material. The surface free energy can be classified based on the source of the intermolecular forces that generate it into: γ^{+} (monopolar acidic), γ^{-} (monopolar basic), and γ^{LW} (apolar or Lifshitz-van der Waals) *(12,13,14)*. The total surface free energy is a combination of these components and can be used to calculate the work of adhesion if the components are known for both aggregate and asphalt binder. This type of analysis generally involves the use of a Universal Sorption Device (USD) for measurement of the surface free energy of the aggregates and the Wilhelmy Plate for measuring the surface free energy of the asphalt binder. This consists of a limitation since some of the equipment, such as the USD, is not readily available and need to be manufactured for this purpose.

However very recently, a test based on a modification of the Pneumatic Adhesion Tensile Testing Instrument (PATTI) test was proposed by researchers at the University of Wisconsin–Madison: Bitumen Bond Strength (BBS) test *(15)*. This type of analysis is very useful in identifying whether the type of failure that is likely to occur is due to the adhesive interface between the aggregate and the asphalt binder or due to the cohesive strength or the durability of the asphalt binder and the mastic itself *(6)*. Additionally, the test has been reported as repeatable and capable of capturing the differences associated with use of additives and exposure to moisture.

OBJECTIVE

The main objectives of this study are to 1) investigate the affinity of the different types of aggregate sources to the asphalt binder that is used in Costa Rica, and 2) to characterize the effect of incorporating additives to the asphalt binder on the moisture susceptibility of the HMA mixture. The BBS test was used to evaluate the asphalt binder and aggregate adhesion as well as the asphalt binder cohesion. Contact angle measurements were also performed on all the combinations of asphalt binder and aggregate samples by means of contact angle goniometer. Additionally, HWTD testing was performed on a subset of the asphalt binder and aggregates, while considering changes in the testing temperature and the effect on the incorporation of lime and liquid anti-stripping additive. The results were used to quantify the strength of the bond between the asphalt binder and the different aggregate sources.

MATERIALS USED IN THE STUDY

The different materials that were used in this study are summarized in Table 1. Only one asphalt binder source was selected for the study since the Costa Rican National Petroleum Refinery (RECOPE) produces only one type of asphalt. The asphalt is classified at the national level as an AC-30 which corresponds to a PG64-22. The asphalt binder was also modified with Styrene-Butadiene-Rubber (SBR) and used in this study. The SBR modified asphalt binder has been recently used and advertised in some projects in Costa Rica as an enhancer for asphalt adhesion. The SBR was introduced to the asphalt binder by means of a low shear mixer at a temperature of 150°C. The resulting performance grade of the modified binder was PG70-22.

The selected aggregate sources are some of the most widespread aggregate sources used in Costa Rica. One of the aggregate sources corresponds to a limestone material. The remaining aggregate sources correspond to river gravels of complex mineralogy from different geographical locations in Costa Rica. However, all of them can be classified as siliceous materials from igneous formations that have been subjected to some sedimentary processes. The Central Caribbean material has historically performed well with regards to moisture damage. The materials from the Pacific Coast have been known to result in stripping problems.

TABLE 1 Summary of Materials Selection.

Factor	Levels	Description
Asphalt Binder	2	PG64-22
		PG64-22 + 2.5% SBR (PG70-22)
Aggregate Source	5	Limestone – Central Valley
		River Gravel 1 – Central Caribbean
		River Gravel 2 – Central Pacific
		River Gravel 3 – South Pacific
		River Gravel 4 – South Pacific
Anti-stripping Agent (*)	2	Lime (1.5% by wt. of aggregate)
		Liquid Anti-Strip (1.0% by wt. of aggregate)

(*) The use of these agents was included only for the performance evaluation by means of HWTD.

The moisture resistance of selected HMA mixtures was assessed in the HWTD using hydrated lime and Ultrapave liquid anti-additive. Ultrapave (Ultracote UP-5000) was introduced following the vendors specifications. The additive was introduced to the aggregate immediately before mixing at a concentration of 1.0% by total weight of aggregate. Only the aggregates identified as River Gravel 1 and River Gravel 2 and the original binder (PG64-22) were used. All of the mixtures were designed following Superpave specifications for N_{des} of 100 gyrations. Typical gradations were used for each of the evaluated aggregate sources. All the gradations had a nominal maximum aggregate size (NMAS) of 12.5 mm. The design asphalt binder content was 6.2 and 6.1% for the HMA mix with River Gravel 1 aggregate and River Gravel 2 aggregate, respectively.

DESCRIPTION OF TEST METHODS

The first part of the study consisted of characterizing the bond strength between the asphalt binder and the different aggregate sources using the BBS test. Testing was performed in accordance with AASHTO TP-91 *(16)*. The BBS test is performed by means of the PATTI apparatus *(17)* which is typically used by the coating and paint industry (Figure 2). Aggregate samples are initially lapped using a silicon carbide material and cleaned in an ultrasonic cleaner prior to binder application so that there is no mechanical interlock between the surfaces. Then a sample of asphalt binder (0.4g ± 0.05g) is initially placed on metal stubs of known diameter (20 mm). The stubs with the asphalt binder sample are then pressed against the aggregate surface.

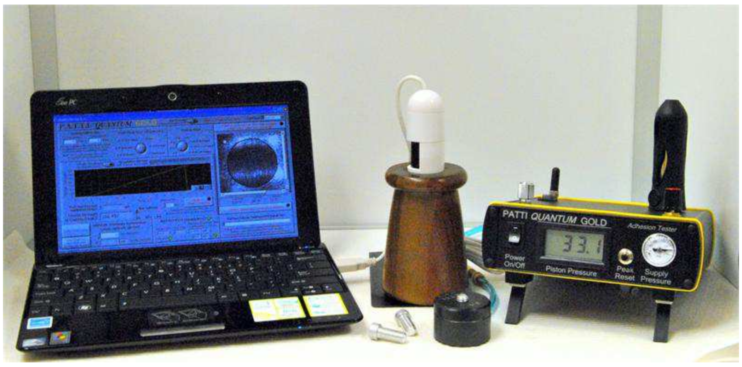


FIGURE 1 PATTI Testing Equipment (Source: http://www.semicro.org)

The pull off tensile strength (POTS) under two types of conditioning, 24 hours dry and 96 hours wet, is determined using the BBS test. Four replicates were used for each of the material combination. Additionally, the percent loss in bond strength and the bond strength ratio are calculated as [$POTS_{Dry}$–$POTS_{Wet}$]/$POTS_{Dry}$ and $POTS_{Wet}$/$POTS_{Dry}$, respectively. All BBS testing were conducted at the Modified Asphalt Research Center (MARC) in Madison, Wisconsin.

In order to characterize the wettability of the aggregate surface by the asphalt binder, contact angle measurements were also performed. The testing was performed with the purpose of quantifying how strongly the asphalt binder and aggregate molecules interact with each other, relative to how strongly each interacts with its own kind. Contact angle measurements were performed using a contact angle goniometer at 25 °C. The goniometer used in this study is shown in Figure 2.

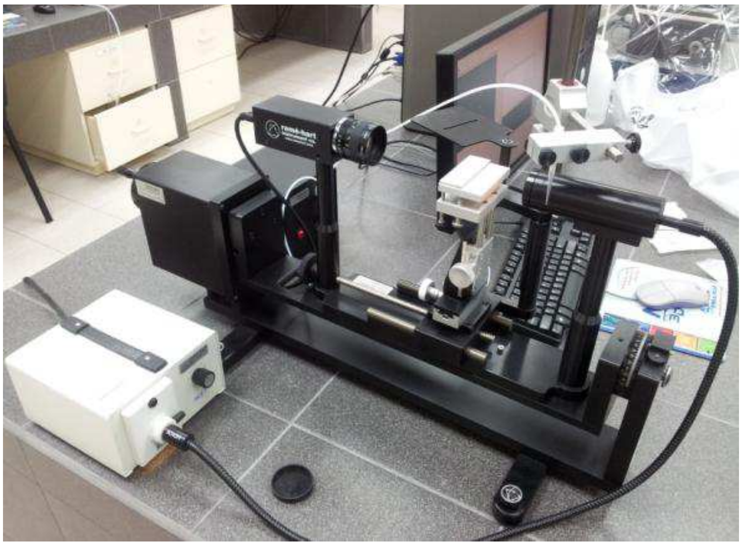
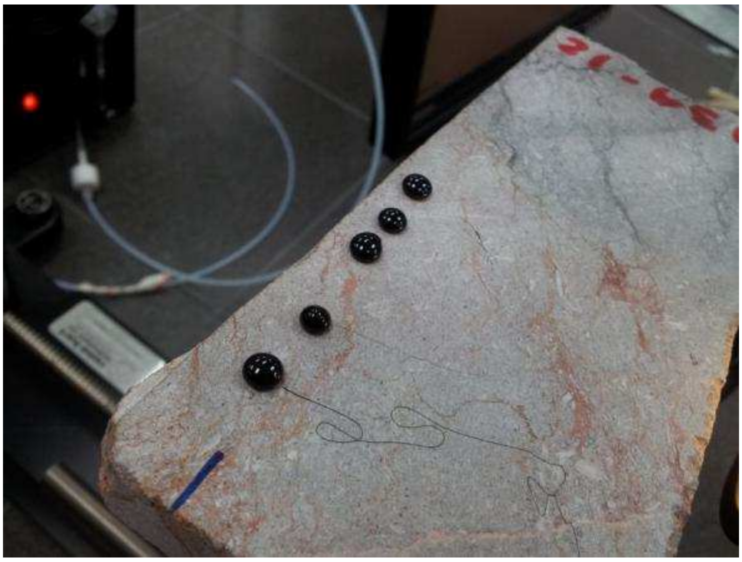
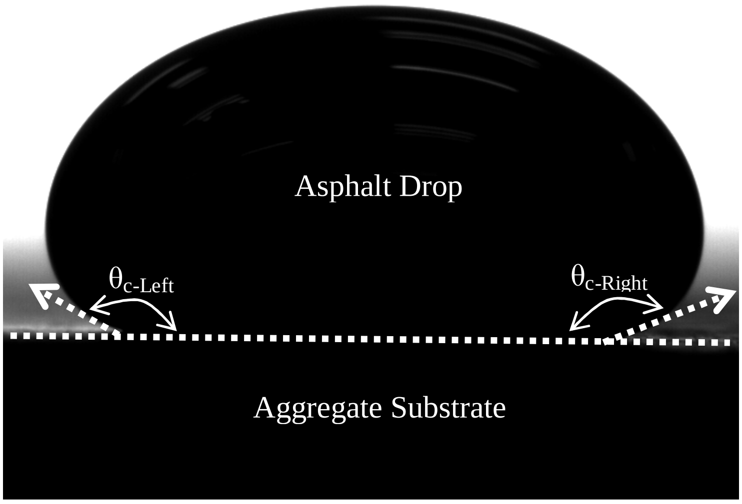


FIGURE 2 Goniometer used in Contact Angle Measurements

The goniometer consists of an optical equipment capable of capturing the profile of a liquid (asphalt binder) over a solid substrate (aggregate), and is based on the sessile drop method *(18)*. Basically, the angle that is formed between the liquid/solid interface and the liquid/vapor interface is the contact angle (θ_c). The equipment uses a high resolution camera and software to capture and analyze the contact angle. The samples are prepared very similarly to those for BBS but differ in that the controlled asphalt binder drop is applied directly over the aggregate surface (Figure 3). Four repetitions for each material combination were used for estimating the contact angle.



(a)



(b)

FIGURE 3 (a) Asphalt Binder Drop Samples for Contact Angle Measurement and (b) Contact Angle Images Used in Measurements

Finally, HWTD testing was performed on HMA samples. HWTD testing was performed at two different testing temperatures: 40°C and 50°C. Testing was performed according to AASHTO T-324 specifications, for a total number of 20,000 wheel loading cycles *(19)*. Six replicate samples of HMA were prepared for each analysis condition in the HWTD for a total of 72 test specimens (2 aggregate sources x 2 asphalt binder types x 3 anti-striping agent conditions x 6 repetitions). All sample specimens were compacted using the SGC to 7.0% ± 1.0% air voids.

TESTING RESULTS AND DATA ANALYSIS

Bitumen Bond Strength Test

The parameter that is directly measured by the BBS tests is the pull off tensile strength (POTS). Figure 4 shows the results for both the neat (Control) and the SBR-modified (Modified) asphalt binders under two conditioning states (The error bars represent one standard deviation). The results indicated that under dry conditions, the combination of neat binder and limestone aggregate required the lowest force to pull off the binder from the aggregate. Note also that the standard deviation for this aggregate was higher than those of the other aggregate samples. This was due to failure in the rock itself: during the BBS test, some of the rock was removed with the asphalt binder. However, when using the SBR-modified binder, the effect of the aggregates on POTS was reduced. Specifically under dry condition, all of the aggregate and SBR-modified binder combinations exhibited similar bond strength. Furthermore, it was observed that generally the POTS value of the neat asphalt binder was consistently higher than the asphalt binder modified with SBR. This observation was not expected, but it is believed to be associated with the binder stiffness for each condition because the original binder might be slightly aged during the incorporation of the SBR, affecting the bonding strength between the binder and the aggregate. Additionally, it is believed that SBR particles within the asphalt binder matrix might result on small areas where the bond strength might be slightly lower since the styrene has very high rigidity and less adhesive to the asphalt binder.

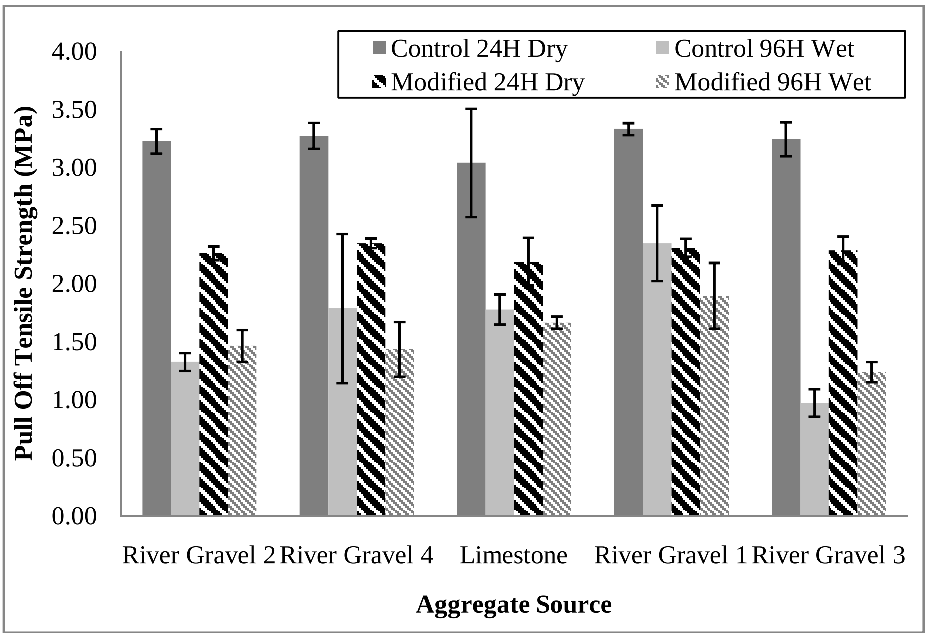


FIGURE 4 Pull Off Tensile Strength (POTS)

In order to better understand the significance of the different parameters and their interactions on POTS, regression analysis was conducted on the data. The results are presented in Table 2. The data indicate that most of the independent variables (aggregate source, asphalt binder, and conditioning state) have a significant effect on the POTS at any given level of confidence (p-value < 0.001). Furthermore, the joint significance of all the independent parameters and their interactions is very high (p-value < 0.001). This indicates that even though some of the individual factors might not classify as significant at a given level of confidence (e.g. 90%), the joint significance of this parameters with other factors in the model is high. This is the case of the Limestone aggregate source which by itself might appear to be statistically equivalent to the River Gravel 4 aggregate. However, when evaluated jointly with other factors such as conditioning state it becomes significant and therefore should not be dropped from the overall model.

It is important to note that overall the analysis confirms the superior performance of the River Gravel 1 aggregate under most of the analysis conditions. Inversely, River Gravel 3 shows the poorest performance results in POTS. Additionally, the analysis indicates that on average, performing the test in dry condition resulted in POTS values approximately 580 kPa higher than if the test is performed in wet condition (for the analyzed set of asphalt binders and aggregate sources). Similarly, it can be quantified that modifying the neat asphalt binder with SBR resulted in a decrease in POTS of approximately 260 kPa.

TABLE 2 Summary Statistics of Regression Analysis.

Parameter	Estimate	t-stat	p-value
Intercept	2.179	82.67	< 0.001
Limestone	-0.003	-0.06	0.950
River Gravel 1	0.300	5.72	< 0.001
River Gravel 2	-0.102	-1.94	0.057
River Gravel 3	-0.235	-4.48	< 0.001
Dry	0.580	22.10	< 0.001
Limestone*Dry	-0.133	-2.53	0.014
River Gravel 1*Dry	0.231	-4.40	< 0.001
River Gravel 2*Dry	0.094	1.80	0.077
River Gravel 3*Dry	.0245	4.76	< 0.001
PG64-22	0.261	9.96	< 0.001
Limestone*PG64-22	-0.021	-0.39	0.695
River Gravel 1*PG64-22	0.107	2.04	0.046
River Gravel 2*PG64-22	-0.055	-1.04	0.300
River Gravel 3*PG64-22	-0.089	-1.70	0.095
Dry*PG64-22	0.210	8.01	< 0.001
Adjusted R^2			0.902

It is also important to highlight the type of failure observed during the BBS testing. In general, under dry condition, a cohesive type of failure was observed for all evaluated cases. This was also the case for most materials under wet condition, with the exception of River Gravel 2 and River Gravel 3 which exhibited an adhesive failure between the asphalt binder and the aggregate surface. Figure 5 shows selected examples for the failed samples after testing in BBS. From these type of figures, a conclusion can be made as to the type of failure that occurred: if more than 50% of the aggregate area is exposed, the failure is defined as adhesive; otherwise, the most likely failure mode is due to cohesion of the asphalt binder.

(a) (b)

FIGURE 5 BBS Specimens After Testing Under Wet Conditions for Unmodified Asphalt Binder with (a) River Gravel 1 and (b) River Gravel 3

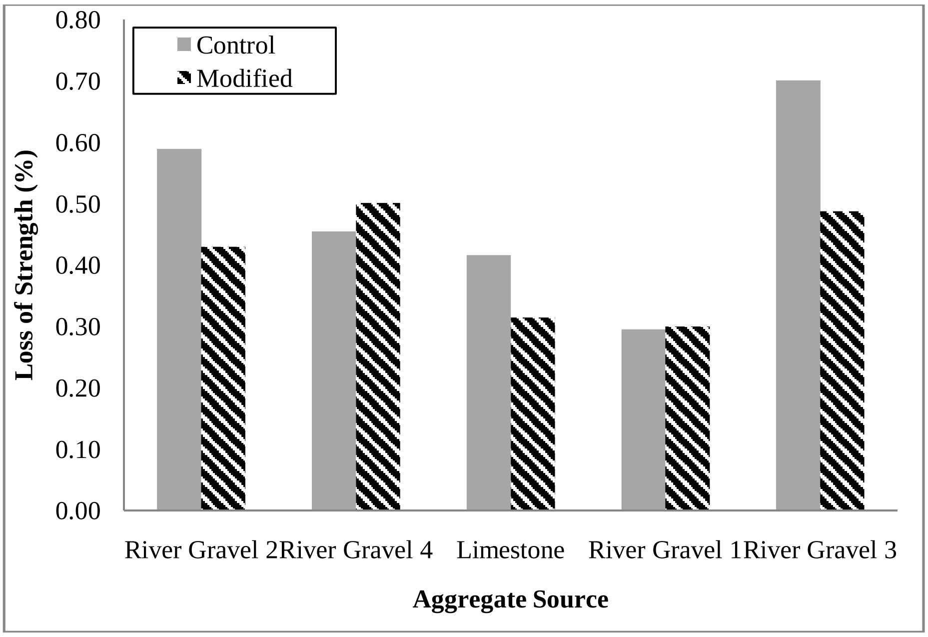


FIGURE 6 POTS Loss Bond Strength (%)

The results of the BBS test can also be interpreted in terms of the percent loss in bond strength between the POTS values in dry and wet conditions (Figure 6). The data confirms that the effect of moisture on POTS is significant, and that POTS is able to discern between the different aggregate sizes. This can be in part explained by the difference in affinity that is exhibited between the CaO and the SiO_2 molecules in the aggregates with the asphalt binder composition.

Furthermore, the effect of the additive on bond strength differs between the different asphalt binder and aggregate combinations. In the case of the River Gravel 1, the effect of adding SBR to the asphalt binder was negligible on the loss in the bond strength. For all the remaining asphalt binder and aggregate combinations, a reduction in the loss of bond strength was observed between the POTS in dry conditions and the POTS in wet conditions, with the exception of the River Gravel 4 aggregate which actually showed an increase in loss of the bond strength with the SBR-modified asphalt binder..

The previous results can also be confirmed when comparing the ratio between the POTS in dry condition to the POTS in wet condition (Figure 7). The figure shows that in general all aggregate and binder combinations show a reduction in POTS ratio when modifying the asphalt binder with SBR. As observed before, the River Gravel 1 and the Limestone aggregates show the lowest ratios, and in fact, the bond strength ratio in both cases is very similar when using the modified binder.

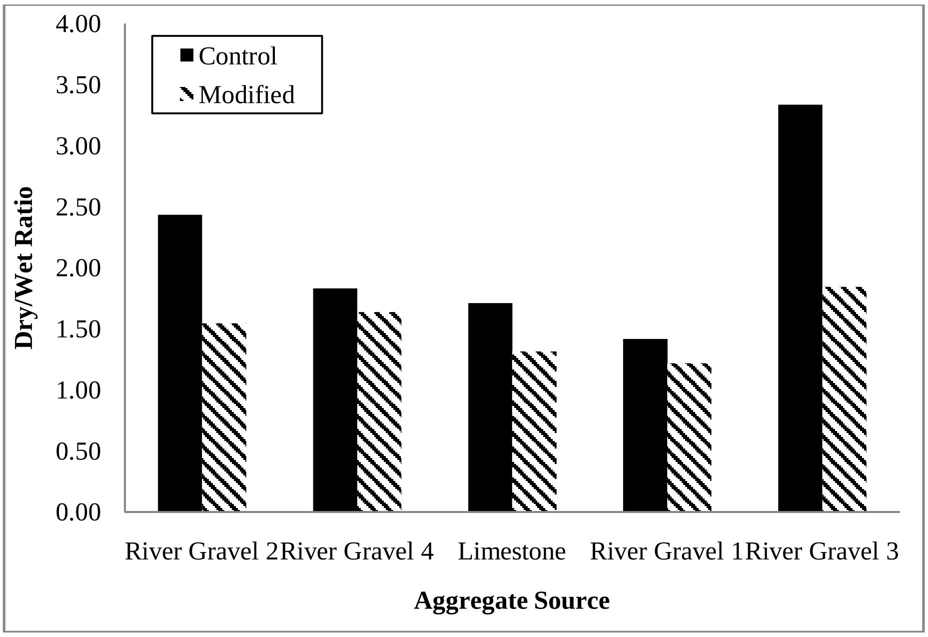


FIGURE 7 POTS Dry/Wet Ratio

Contact Angle Measurements

The contact angle measurements were obtained to determine the wettability of the different asphalt binder aggregate source combinations, and to evaluate how well this value correlate to the BBS test results. The contact angle was measured on a drop of asphalt binder placed on the aggregate surface, 1 minute after placement and at room temperature. Each drop was measured 10 times at 1 second intervals. Four drops of each asphalt binder were measured for each aggregate surface. The results are shown in Figure 8. It is very interesting to note that the contact angle between the asphalt binder and the aggregate surface increases in some of the cases when the asphalt binder was modified (River Gravel 2 and River Gravel 4). Although this might be contrary to what is expected, it is consistent with the reduction in POTS that was observed when modifying the asphalt binder. It seems to indicate that the SBR modification is reducing the wettability of the asphalt binder on the aggregate surface. Furthermore, the cases where an increase in contact angle was observed due to modification of the asphalt binder are consistent with the material combinations that exhibited worse resistance to moisture as measure by POTS loss in bond strength and POTS Ratio. The remaining materials showed a decrease in the contact angle when the asphalt binder was modified. This can be translated into enhanced wettability of the aggregate surface by the asphalt binder and an improvement in moisture resistance as observed in previous results.

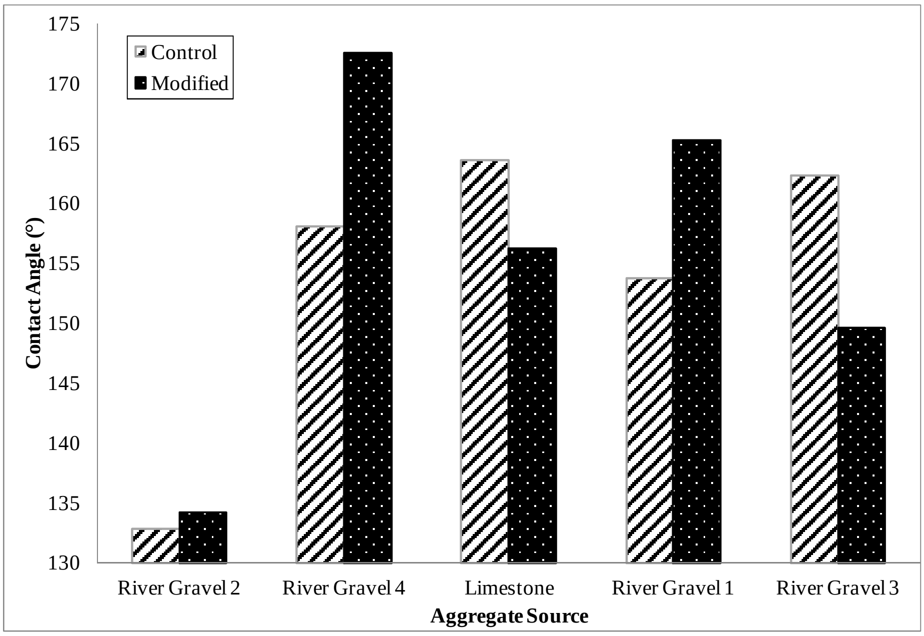


FIGURE 8 Contact Angle Results

It is important to note that the use of the goniometer as a means to measure the contact angle between the asphalt binder and aggregate surface is relatively new. Therefore, there is still no specification as to standardize the conditions under which the asphalt drop is placed on the aggregate surface and measured. In this study, the asphalt binder was heated to 150°C and placed over the aggregate surface at room temperature which results in a significant thermal differential between the asphalt binder droplet and the aggregate surface. This results in a considerable effect on the magnitude of the contact angle. To test this effect, the analysis was repeated at several temperatures and changes in the contact angles were observed. However, the general trends remained the same (effect of different aggregates and asphalt binder) and therefore it is the order of the factors and not necessarily the magnitudes that should be observed.

Hamburg Wheel Tracking Device Testing

In order to correlate the POTS to a performance measure, HWTD testing was performed using the neat binder and two of the aggregate sources: River Gravel 1 and River Gravel 2. These were selected since the bond strength and bond properties that were exhibited in each case were different. Furthermore, the type of failures in the BBS test also differed (adhesive versus cohesive) by material combinations. In order to comply with local specifications, the effect of anti-stripping additives (hydrated lime and liquid anti-strip) was also evaluated. The performance results are shown in Figure 9.

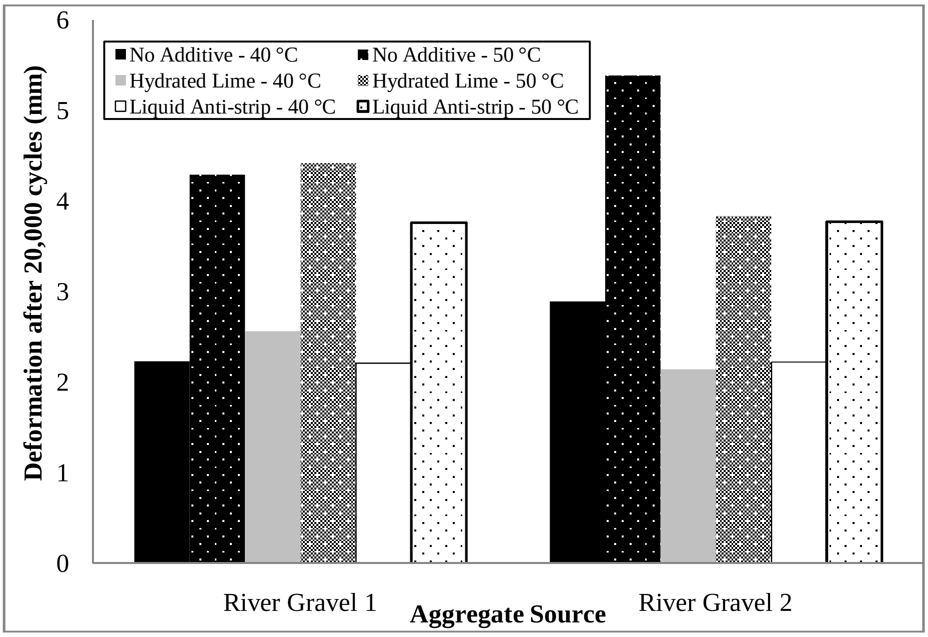


FIGURE 9 HWTD Test Results

The data show that when no anti-strip additives are used, the difference in performance exhibited by both aggregates was larger and consistent with what was observed in the BBS and contact angle tests. However, despite those differences, all of the rut deformations were relatively low and met the maximum 12.5 mm specification requirement. Additionally, the measured rut deformations were reduced when hydrated lime or liquid anti-strip additive were used. The difference in the effect of the aggregate when adding lime or liquid anti-strip decreased and in general the rut deformations were similar. Furthermore, it is important to note that none of the samples showed tertiary profile during the test, indicating that rutting resistance and stripping resistance should be adequate.

SUMMARY OF FINDINGS AND CONCLUSIONS

Testing based on the Bitumen Bond Strength test has confirmed, for the evaluated material, that the test results differs significantly between aggregate sources, asphalt binders, and moisture conditions. It was observed that even in cases where the mineralogy and formation process of the aggregate is relatively similar, considerable differences in bond strength with asphalt binder can occur.

In general, it was observed that modification of the asphalt binder with SBR resulted in an overall decrease in the strength required to separate the asphalt binder from the aggregate surface. The cause of reduction in the bond strength is believed to be related to two factors: 1) stiffening of the asphalt binder during the modification process, and 2) intrinsic properties of the SBR. The styrene is very stiff and rubber is not an adhesive material, but in general SBR has high resistance to tearing and moisture. However, regardless of the previous reduction, the effect of moisture on the bond strength decreased when the additive was used. This trend was also observed in the contact angle measurements between the asphalt binder (neat and modified conditions) and the different aggregate materials.

The findings the bond strength between the asphalt binder and aggregate surface correlated well with the HMA testing based on the HWTD for the subset of mixtures evaluated. However, the differences in evaluated mixtures were reduced when anti-stripping additives were used.

Finally, even though significant differences were identified in the bond between the asphalt binder and the different aggregate sources, in general the bond between the two materials was adequate by exhibiting a ratio between the pull off tensile strength in dry and wet conditions below 0.70 as recommended in the literature *(20)*. Consequently, it is suggested that the aggregate sources be further expanded to identify a wider range of bond strengths with the asphalt binder, and to calibrate a threshold value that can be used to screen different asphalt binder plus aggregate source combinations in Costa Rica. Additionally, the study should be complemented with aggregates from existing pavements which have and have not exhibited moisture damage problems to further establish a threshold value for bond strength.

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