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# Experimental Evaluation of Anti-stripping Additives in Bituminous Mixtures through Multiple Scale Laboratory Test Results

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## Abstract

This paper presents performance changes and material characteristics associated with moisture damage due to anti-stripping additives in asphalt mixtures through various laboratory tests. Two additives (hydrated lime and fly ash) are investigated by adding them into two types of mixes where different asphalt binders and aggregates are used. Two widely used asphalt concrete mixture performance tests (the AASHTO T-283 and the asphalt pavement analyzer under water) and two mixture constituent tests (the boiling water test and the pull-off tensile strength test) are conducted to characterize the effects of anti-stripping additives on the binder-aggregate bonding potential in mixtures. Results from laboratory tests indicate that the mixes, where high-quality aggregates and polymer-modified binder are used, are fairly self-resistant to moisture damage without treating any anti-stripping additive and do not show any visible sensitivity between additives, whereas the effects of additives and their sensitivity are significant in the mixes that use the unmodified binder and low-quality aggregates. With the limited amount of test data, both hydrated lime and fly ash contribute to reducing moisture damage, which implies potential significant cost savings by the use of fly ash as an alternative additive.

**Keywords:** hot-mix asphalt, pavement, moisture damage, hydrated lime, fly ash

## 1. Introduction

Moisture damage is a major problem in asphalt pavements, and shows itself in various forms with multiple mechanisms, such as adhesion failure between asphalt and aggregate, moisture-induced cohesion failure within the asphalt binder, cohesion failures within the aggregate, emulsification of the asphalt, and freezing of entrapped water. Among those, the reduction of adhesion between asphalt and aggregates in the presence of water and the deterioration of asphalt due to cohesive failure within the asphalt binder itself have been known as two primary driving mechanisms of moisture damage since the 1920s [1]. In 2002, Aschenbrener [2] conducted a survey on moisture damage of hot-mix asphalt (HMA) pavements in the United States and found that a total of 44 states have experienced severe moisture damage in their pavements. To reduce moisture damage, 82 percent of the nation's state highway agencies require some sort of anti-strip treatment. Of those agencies that treat, 56% use liquids, 15% use liquid or lime, and 29% treat with lime only.

Due to the great number of pavements under severe moisture damage, attempts have been made to identify the moisture-damage mechanisms [3–9] and to develop test procedures that can estimate the moisture susceptibility of asphalt mixtures. Recently, fundamental material properties and mechanisms to assess moisture susceptibility of asphalt mixtures have been actively pursued in order to overcome shortcomings of traditional test methods that are mostly empirical. Many studies [5,9,10–16] proposed new concepts associated with key material properties, such as fracture parameters, surface energy, diffusion coefficients, and adhesion characteristics, to better identify and understand moisture-damage characteristics of asphalt mixtures. Furthermore, many different types of additives have been applied to the asphalt mixtures to minimize moisture-related damage. Numerous studies [6,17–22] indicate that anti-stripping additives can positively affect the binder–aggregate bonding characteristics and overall mixture performance by reducing mixtures' moisture susceptibility.

One well-known anti-stripping additive is hydrated lime. Hydrated lime provides better adhesive compatibility between aggregate and asphalt mastic. Thus, the use of hydrated lime may increase bonding characteristics between aggregate and asphalt. Furthermore, it has also been demonstrated that hydrated lime significantly changes rheological properties of asphalt systems. Many experimental results have shown that adding hydrated lime to asphalt mixtures significantly improves moisture-damage resistance, especially when subjected to the wetting-drying treatment [19,21]. Therefore, many state highway agencies employ and/or require the use of hydrated lime in HMA pavements. 1.0% hydrated lime by weight of total dry aggregates in a mix is typically applied to HMA used in US pavements. Sufficient literature strongly supports the use of hydrated lime to control moisture sensitivity of asphalt mixtures and also to induce other benefits due to lime addition, such as stiffening the asphalt binder and HMA, improvements in the resistance to fracture growth at low temperatures, and favorable oxidation kinetics and interactions with products of oxidation to reduce deleterious effects by aging [20,21,23].

Recently, the use of alternative additives such as fly ash has driven significant attention to the asphalt materials/pavement community, because fly ash is much more economical and convenient to access than hydrated lime in certain states such as Nebraska, where a large amount of fly ash is produced daily, which requires landfills for disposal and related costly operations. Its application in asphalt mixtures can potentially bring benefits to the environment and reduce the amount of disposed material. A survey conducted by the American Coal Ash Association (ACAA) provides information about production and application of fly ash from 170 power plants in the United States. In 2007, approximately 72 million tons of fly ash was produced in the United States and only 32 million tons (44.4% of total) were consumed. The remaining material has been deposited in landfill sites. The cost of disposing the unused fly ash varies from \$12 to \$15 per ton; sometimes it can reach \$34 per ton. Considering the amount of abandoned fly ash in 2007, a significant amount of cost was spent in the disposal process, not to mention the environmental issues that this by-product can cause. This situation has driven highway engineers and researchers to investigate the use of fly ash for various engineering purposes, such as the application of fly ash in asphalt pavements.

Several previous studies have shown that the addition of fly ash can improve HMA performance. Rosner et al. [24] presented that the addition of 3–6% of fly ash in asphalt mixtures had comparable results for moisture-damage resistance compared to other anti-stripping additives. The improvement of moisture-damage resistance by adding fly ash to the asphalt mixture was also found by Henning [25] and Dougan [26]. Henning also reported that fly ash works as a stiffening and void-filling agent for the mixture. Ali et al. [27] stated that fly ash added in the amount of 2% of total weight of aggregates as mineral filler improves not only the stiffness characteristics, but also mixture strength and stripping resistance. However, it is not clearly understood how fly ash contributes to moisture damage-resisting mechanisms and how much effective fly ash is compared to the widely used additive, hydrated lime. If fly ash is sufficiently effective to mitigate moisture damage, it can bring significant cost savings to certain states such as Nebraska where hydrated lime must be transported from other states, while abundant fly ash is available. In 2010, Nebraska spent approximately \$1.4 M to import around 8900 tons of hydrated lime.

## 2. Research objectives

The overall objective of this research is to investigate the effects of two anti-stripping additives (hydrated lime as an additive that has been popularly used in many places and fly ash as an alternative, supplemental material) on moisture-damage resistance. More specifically, this study is to:

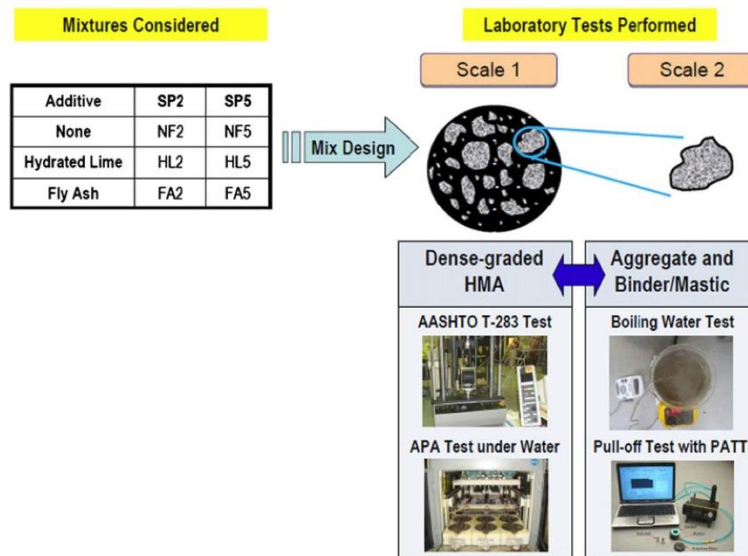
- evaluate mechanical behavior of those two additives in different asphalt mixes, where different mixture components (binder and aggregate) are involved, by an integrated evaluation of various laboratory tests in two different testing scales: mixture scale and component scale;
- provide useful insights to understand the impact of aggregate surface modification through crushing and binder modification with polymers on moisture-induced

damage characteristics such as adhesive bonding potential between aggregate and asphalt binder incorporated with anti-stripping agents in the mix; and

- identify the effect of fly ash as a potential anti-stripping agent. Compared to hydrated lime, it is not clear how much effective fly ash is to mitigating moisture damage in asphaltic mixtures. Some states such as Nebraska can be benefited by the alternative material which can bring significant cost savings.

### 3. Research method

Figure 1 briefly illustrates the process of the research method employed for this study. Two Superpave mixes (i.e., SP2 and SP5) used in Nebraska were selected for this study to draw more comprehensive and general conclusions on the material-specific effects of additives based on results from diverse mixes. The SP5 mix consists of better-quality (e.g., more crushed) aggregates and polymer-modified asphalt binder PG 70-28, while the SP2 mix is usually produced with less-angular aggregates and unmodified asphalt binder PG 64-22.



**Figure 1.** Research method employed for this study.

As mentioned, this research pursued an integrated evaluation through two different testing scales. Laboratory tests of asphalt concrete mixtures are composed of volumetric mixture design of various SP2 and SP5 mixes treated without and with the two different anti-stripping agents (i.e., hydrated lime and fly ash), and fabrication of compacted asphalt concrete samples and mechanical testing of the asphalt concrete samples using traditional performance evaluation techniques such as AASHTO T-283 [28] and asphalt pavement analyzer (APA) test under water. Furthermore, the bonding between aggregate and binder at a local-scale (component) level was investigated following the boiling water test (ASTM

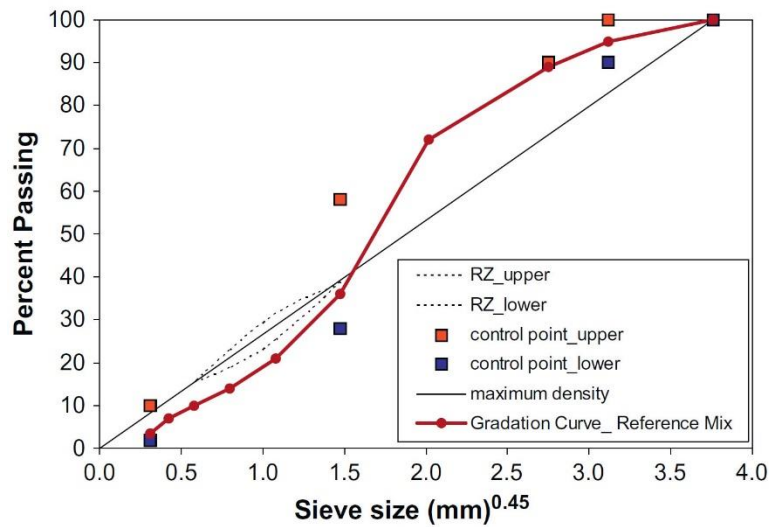
D 3625) [29] and the pull-off test using a Pneumatic Adhesion Tensile Testing Instrument (PATTI) procedure (ASTM D 4541) [30]. The PATTI has gained attention in the scientific community because it contributes to a better understanding of the local-scale debonding characteristics between aggregate and binder in the presence of water, which leads to a better evaluation of material-specific moisture susceptibility. Test results between the two scales (global and local) were then compared and related so that measured characteristics of each mix component can be related to performance testing results of asphalt concrete samples.

#### **4. Materials, mixture design, and volumetric results**

This section describes materials used in this research (aggregates, asphalt binders, and two anti-stripping additives—hydrated lime and fly ash). It also illustrates mix design results of six Superpave mixes (three SP2 mixes: NF2 (without additive), HL2 (with hydrated lime), and FA2 (with fly ash); and three SP5 mixes: NF5 (without additive), HL5 (with hydrated lime), and FA5 (with fly ash)).

A total of six local aggregates (three limestone types and three gravel types) that have been widely used in Nebraska pavements were used in this study. All six mixes designed were targeted to be blended with 45% limestone type and 55% from gravel type but with different level of aggregate crushing for each mix type (SP2 and SP5) so that SP2 mixes are similar to SP5 mixes in the mineralogical characteristics, while presenting different aggregate surface characteristics: angularities. Two asphalt binders were used in this study. To fabricate SP5 mixes and samples, the Superpave performance-graded polymer-modified binder PG 70-28 was used. For the SP2 mixes and samples, the unmodified binder PG 64-22 was used. Hydrated lime evaluated in this study was a typical one with its median particle size of 2  $\mu\text{m}$ , 98% of  $\text{Ca}(\text{OH})_2$ , and specific gravity of 2.343. Fly ash estimated in this study was Class C with specific gravity of 2.650 and 26.9% of  $\text{CaO}$ .

Individual mixtures were designed with the same blend of aggregates to avoid variability due to physical and mineralogical characteristics of the aggregates. Variables differentiate mixtures are the mix type (SP2 or SP5) and the existence and type of additive (NF, HL, or FA). The two NF mixtures (NF2 and NF5) are reference mixtures where no additive was added. Figure 2 presents an overall gradation of below restricted zone (RZ) and contains 3.5% of mineral filler, aggregates passing the No. 200 sieve (0.075 mm mesh size).



**Figure 2.** Aggregates gradation curve of the mix NF (reference mix).

For the treated mixtures with the anti-stripping agent, 3% of water by total weight of aggregates was first added into the blend of aggregates (presented in fig. 2) and subsequently mixed so as to wet all of the particles. After mixing the aggregates with water, for the hydrated lime-treated mixtures (HL2 and HL5), 1% hydrated lime (by total weight of dry aggregates) was added to the wet aggregates and mixed to cover all of the aggregates. The treated aggregates were then oven-dried for 2 h to eliminate all water before the addition of asphalt binder. In order to ensure the equivalent volumetric application of each additive in the mixture, the total weight of hydrated lime in the mixtures was converted to its volume with given specific gravity, and the same volume was targeted to estimate the gravimetric amount of fly ash, which resulted in 1.13% fly ash by total weight of dry aggregates. In other words, the other mixtures with different additives were designed such that the volume would be a constant among all the studied mixtures and the weight of each one would vary according to their specific gravity value.

Optimum asphalt content was found until all volumetric parameters of individual mixtures met the required Nebraska Superpave specifications. Volumetric mix design parameters of each mixture and the required specifications for each mix type (i.e., SP2 and SP5) are shown in table 1.

**Table 1.** Volumetric mix properties, aggregate properties, and specification values

Parameters	SP2 mixtures and specifications				SP5 mixtures and specifications			
	NF2	HL2	FA2	Required	NF5	HL5	FA5	Required
V <sub>a</sub> <sup>a</sup> (%)	4.5	4.2	4.3	4.0 ± 1.0	4.8	4.0	4.6	4.0 ± 1.0
VMA <sup>b</sup> (%)	15.4	14.4	14.6	> 14	15.4	14.4	14.7	> 14
VFA <sup>c</sup> (%)	70.8	70.8	70.5	65–78	68.8	72.2	68.7	65–75
P <sub>b</sub> <sup>d</sup> (%)	5.82	5.40	5.50	N/A	5.80	5.50	5.40	N/A
D/B <sup>e</sup>	1.08	1.26	1.10	0.7–1.7	0.83	1.34	1.05	0.7–1.7
CAA <sup>f</sup> (%)	76	76	76	> 65	96/96	96/96	96/96	> 95/90
FAA <sup>g</sup> (%)	43.3	43.3	43.3	> 43	45.2	45.2	45.2	> 45
SE <sup>h</sup> (%)	73	73	73	> 40	83	83	83	> 45
F&E <sup>i</sup> (%)	1.0	1.0	1.0	< 10	4.0	4.0	4.0	< 10

**Note:**

- a. V<sub>a</sub> (air voids)
- b. VMA (voids in mineral aggregates)
- c. VFA (voids filled with asphalt)
- d. P<sub>b</sub> (binder content)
- e. D/B (dust/binder ratio)
- f. CAA (coarse aggregate angularity)
- g. FAA (fine aggregate angularity)
- h. SE (sand equivalency)
- i. F&E (flat and elongated aggregates)

## 5. Laboratory tests and results

The two most popular performance tests associated with evaluation of HMA moisture damage and susceptibility were conducted in this study: AASHTO T-283 (Resistance of Compacted Bituminous Mixture to Moisture-Induced Damage) and APA testing of compacted asphalt concrete samples under water. The two HMA tests were to evaluate macroscopic moisture-related sensitivity of mixtures.

As a parallel approach to the HMA mixture tests, this study evaluated the bonding-debonding characteristics at the aggregate-binder interface by performing two local-scale mixture constituent tests: the boiling water test (ASTM D 3625) and the pull-off test using a PATTI device. These tests can characterize directly and/or indirectly the bonding potential between aggregate and binder with the different treatments of anti-stripping additives. Test results between the two scales (HMA and component) were then compared and related so that measured characteristics of mixture components can be related to performance testing results of asphalt concrete samples.

### 5.1. AASHTO T-283 test

A Superpave gyratory compactor was used to produce testing specimens, 150 mm in diameter and 95 ± 5 mm height with 7% ± 0.5 air voids. Three subsets of specimens were fabricated and tested, with two subsets subject to partial vacuum saturation (around 75%), followed by one freeze-thaw (F-T) cycle and six F-T cycles, respectively, prior to being tested. In the field, asphalt mixtures may experience many F-T cycles during their service



lives, which was simulated by introducing the multiple F–T cycling, although it is not required in the standard testing procedure. The third subset is tested without the conditioning process. All specimens were tested to determine their indirect tensile strengths. A compressive load was applied to a cylindrical specimen through two diametrically opposed rigid platens to induce tensile stress along the diametral vertical axis of the test specimen. A series of splitting tensile strength tests were conducted at a constant strain rate of 50-mm per minute vertically until vertical cracks appeared and the sample failed. A peak compressive load was recorded to obtain tensile strength of the sample. A tensile strength ratio (TSR) which is the ratio of the average tensile strength of the conditioned specimens (1 F–T and 6 F–T) to the average tensile strength of the unconditioned specimens was then calculated. The TSR represents a reduction in the mixture integrity due to moisture damage. A minimum of 80% TSR has been typically used as a failure criterion [28]. Averaged TSR values of individual mixtures except FA2 are plotted in figure 3. AASHTO T-283 test was conducted in this study for all mixtures except the FA2 mixture.

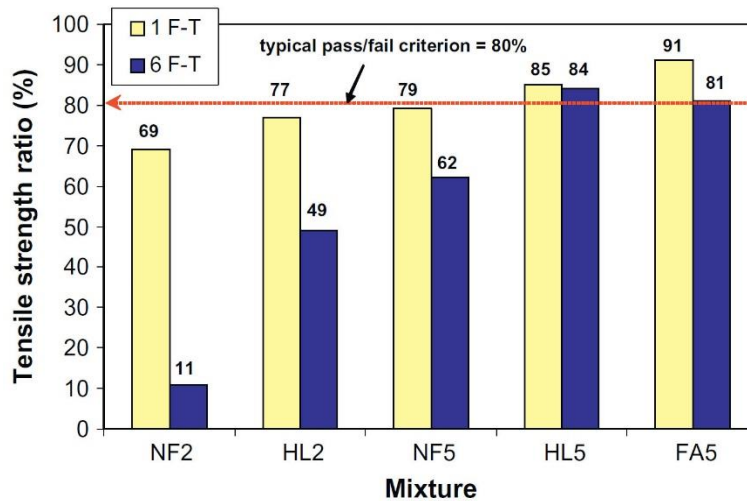


Figure 3. TSR results of each mixture.

In case of the low-volume pavement mixture SP2, where low aggregate angularities and the unmodified asphalt binder PG 64-22 are necessary, the values of TSR from the SP2 mixes were 69% and 77% after one F–T cycle, and 11% and 49% after six F–T cycles, for the untreated mixture (NF2) and hydrated lime–treated mixture (HL2), respectively. The effect of hydrated lime was significant and even more impressive when the mixtures were subjected to multiple F–T cycling. In case of SP5 mixtures, the addition of anti-stripping agents in the mixtures generally demonstrated positive effects particularly with six F–T cycles. The reference mixture (NF5) exhibited a TSR value close to the required limit when the mixture was subjected to only one F–T cycle; however, with six F–T cycles, the TSR value was close to 60%, representing failure by moisture damage. The TSR values from HL and FA were very similar for both conditioning levels. All treated mixtures passed the mini-

imum required TSR value even after severe conditioning processes, and the untreated mixture performed fine with one F–T cycle. Test results imply that the SP5 mixtures, where high-quality aggregates and polymer-modified binder are used, are fairly self-resistant to moisture damage without being treated with any anti-stripping additive, but the use of anti-stripping additives in the mixture can still improve moisture-damage resistance, although any visible sensitivity among additives evaluated in this study has not been observed from the TSR estimation. Clearly, the effects of binder and aggregate quality on the overall mixtures' resistance to moisture damage can be captured from the figure. NF2 mixture experienced severe damage with multiple F–T cycles, which is not true of the SP5 mixtures, as shown in figure 3.

### 5.2. APA test under water

The APA testing was conducted on pairs (up to three) at a time using gyratory-compacted asphalt concrete specimens of 75 mm high with  $4\% \pm 0.5$  air voids. Testing was conducted at  $64^\circ\text{C}$ . In order to evaluate moisture susceptibility, the test was conducted under water. The water temperature was also set at  $64^\circ\text{C}$ . The APA specimens were preheated in the APA chamber for 16 h before testing. The hose pressure and wheel load were 690 kPa and 445 N (100 psi and 100 lb), respectively.

Figure 4 presents APA performance-testing results of all six mixtures. As shown, in case of SP5 mixtures, the rut depth values after 8000 cycles did not differ from mixture to mixture. All mixtures presented a satisfactory performance according to the typical 12-mm failure criterion. High-quality mixture constituents (angular aggregates and polymer-modified binder) in the SP5 mixtures resulted in good rutting performance with no significant sensitivity among mixtures, which was also observed from AASHTO T-283. APA testing could not capture the effect of the anti-stripping agent in the mixtures.

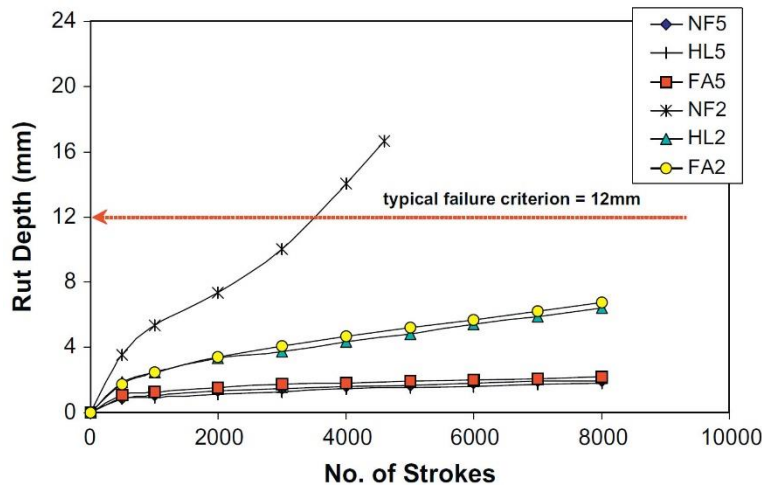


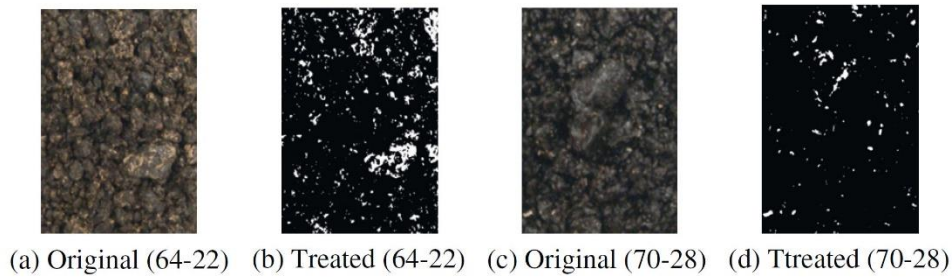
Figure 4. Combined APA test results from SP2 and SP5 mixtures.

Contrary to the SP5 mixtures performance, in case of SP2 mixtures, the untreated control mixture reached a 12-mm rut depth after 3500 strokes, indicating premature failure. Mixtures treated with hydrated lime passed the failure criterion with a rut depth of approximately 5–6 mm after 8000 strokes, implying that the addition of hydrated lime improved the resistance of mixtures to the moisture damage. Mixtures treated with fly ash also performed very well. By comparing the APA performance from the untreated SP2 mixtures to the untreated SP5 mixtures, the mechanical contribution of the polymer-modified binder and higher-angularity aggregates to the rutting-related moisture-damage resistance could again be verified. Anti-stripping effects were positive and similar, while no dramatic impact was presented when they were added in the high-quality mixtures.

### **5.3. Boiling water test (ASTM D 3625)**

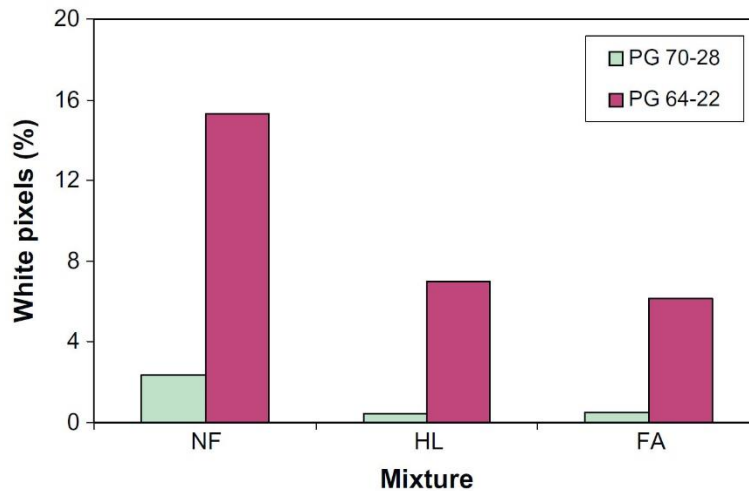
The boiling water test is extremely simple to perform, but appears to have the potential to evaluate the effect of anti-stripping additives in the mixture to minimize the loss of adhesion between aggregate and asphalt binder. Furthermore, this test has also presented a good correlation between laboratory results and field performance [31]. The boiling water test is a visual rating of the degree of stripping after boiling the loose HMA mixture for 10 min. Approximately 500 ml of water was placed in a 1000 ml beaker and was heated to boil; 250 g of loose HMA mixture was then heated at a maximum temperature of 100°C, but not lower than 80°C, and immersed in the boiling water for 10 min. Once finished, the beaker was removed from the heat source and a paper was used to skim off the bitumen on the water surface to prevent recoating. After cooling it to room temperature, the water was removed, and the mixture was placed onto a white paper towel to be visually analyzed. The criterion of failure is by visual identification of stripped (uncoated) aggregates. The percentage of asphalt coating remaining from the initial reference condition (before testing) was visually estimated by investigators to quantify the level of degradation due to moisture damage.

In an attempt to estimate the test in a more objective manner than the subjective visual rating by the investigators, a digital image analysis of photographs taken for each mixture using a digital camera was conducted. Each picture was cropped to a consistent size and then transformed to a black-and-white image by applying the same level of threshold. The black area represents the aggregates covered with asphalt binder, while the white portion represents aggregates or spots in the aggregates with stripping. Using an image analysis software, each portion was quantified by counting the number of pixels corresponding to each color and provides the percentage of black and white pixels. As an example, figure 5 shows the cropped original images and their transformed images in black and white for the reference (NF) mixtures with two different binders: PG 64-22 and PG 70-28. Clearly, a larger portion of white pixels is observed from the mixture with PG 64-22 than the mixture with polymer-modified binder, PG 70-28.



**Figure 5.** Digital image analysis of the boiling water test: reference mixture (NF).

Analysis results are plotted in figure 6. Before making any conclusions from the figure, it should be noted that the values presented in the figure are influenced by several factors related to image processing, such as the level of threshold applied. In other words, one cannot affirm that the percentage of white portion is a real value of stripping. Factors can change the results of image analysis; however, a relative ranking among mixtures can still be made in an objective manner because the identical factors are applied to all mixtures compared.



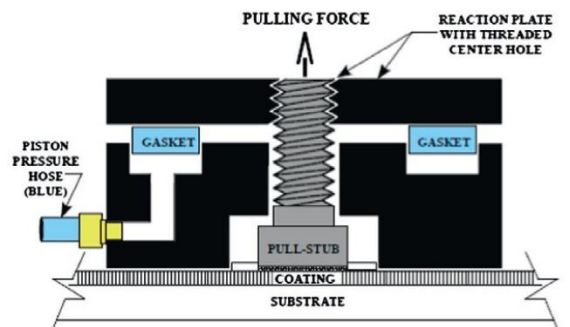
**Figure 6.** Digital image analysis results from the boiling water test.

Results from the digital image analysis are in good agreement with the results from HMA mixture performance tests in that asphalt binder PG 64-22 was much less resistant to moisture damage than binder PG 70-28, and the effect of additives was more visible from the mixtures with binder PG 64-22 than the mixtures with PG 70-28. There was no significant difference between hydrated lime and fly ash.

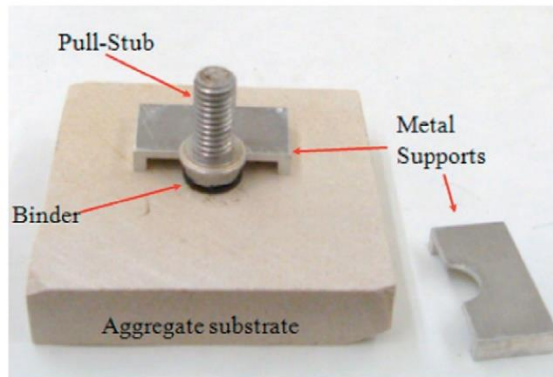
#### **5.4. Pull-off test using the PATTI**

The bond strength between asphalt film and aggregate can be compromised in the presence of water. Thus, the understanding of this process is important to predict and to prevent the moisture-damage process. Until now, a method to accurately determine mechanical bond strength between these two materials has not been fully established. However, a pull-off test method as specified in the ASTM D 4541, "Pull-off Strength of Coatings Using Portable Adhesion Testers," has been employed by several researchers, such as Kanitpong and Bahia [5], Copeland [15], and Cho and Bahia [32], as a promising approach for characterizing the adhesive bonding potential of asphalt materials. Youtcheff and Aurilio [10] used this method to evaluate the adhesive bond between aggregate and asphalt film in the presence of water.

The equipment used to perform the pull-off test is the Pneumatic Adhesion Tensile Testing Instrument (PATTI), which was developed by the National Institute of Standards and Technology (NIST). Figure 7 illustrates a cross-section schematic view of the piston attached to a pull-stub. The PATTI measures the maximum tensile pressure necessary to separate the binder from the aggregate substrate. The thickness of the binder must be controlled precisely and identically in all cases. A similar manner developed by Kanitpong and Bahia [5], where the binder film thickness could be controlled by placing two metal supports under the pull-stub, as also shown in figure 7, was employed in this study. The binder film thickness is the space between the pull-stub and the aggregate surface, which is targeted to be 0.4 mm.



(a) Cross-section view of piston attached to pull-stub



(b) Prepared sample with metal supports

**Figure 7.** Schematic view of PATTI and testing specimen.

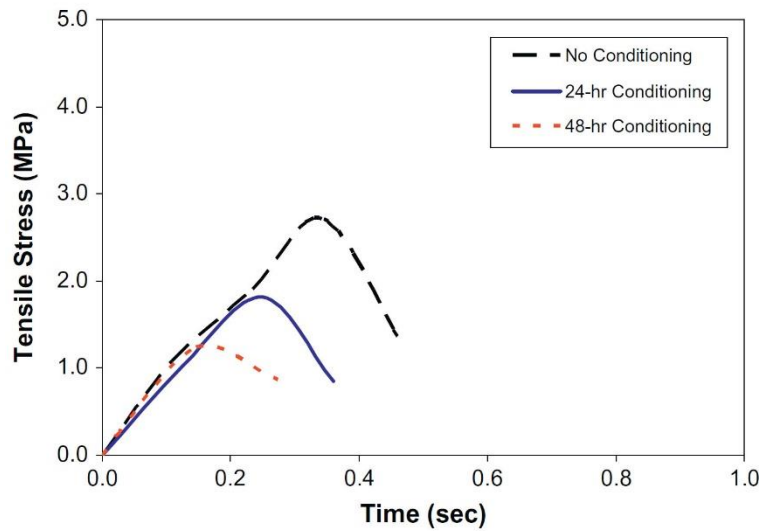
In order to evaluate the effect of anti-stripping additives on the bonding between binder and aggregate, treatments were applied to the aggregate substrate, which simulates asphalt mixtures treated with anti-stripping agents. This treatment was performed in such a way to approximate, as closely as possible, the amount of anti-stripping additive that was actually treated in the HMA mixture. For this process, total surface area of aggregates in the HMA mixture was first estimated based on the procedure described in Kandhal et al. [33]. The total aggregate surface area was then used to calculate the surface area per gram of each anti-stripping additive, followed by a required mass of the anti-stripping additive to be treated on the aggregate substrate with the known surface area of the aggregate substrate. For a more uniform and an efficient treatment of the additive on the aggregate plate, a solution of 2 ml water and the required amount of additive was prepared and applied to the surface of the substrate. A detailed procedure describing the treatment of additive on the aggregate plate and the placement of the pull-stub with 0.4-mm thick binder film can be found in Pinto et al. [34].

To perform the pull-off test using the PATTI, the piston is placed over the pull-stub and attached in the reaction plate by the threads of the pull-stub. Air pressure is transmitted to the piston through the pressure hose. A constant rate of pulling pressure, which is set in the PATTI pressure control panel, is applied to the sample, and test results in a form of

tensile pressure vs. testing time are recorded by a data acquisition system. The PATTI allows the sample to be conditioned in water. Therefore, moisture damage to the materials and their interface can be investigated and compared using different substrates, binders, and additives. A typical set of test results at different moisture conditioning levels (0, 24, and 48 h) is presented in figure 8. If the tensile pressure exceeds the bond strength between the pull stub and a substrate, failure occurs in the sample. The pressure at failure is captured and transmitted to its pull-off tensile strength, as expressed in the following equation:

$$POTS = \frac{(BP \cdot A_g) - C}{A_{ps}} \quad (1)$$

where  $POTS$  = pull-off tensile strength,  $BP$  = burst pressure,  $A_g$  = contact area of gasket with relation plate,  $C$  = piston constant, and  $A_{ps}$  = area of pull-stub.



**Figure 8.** A typical set of test results from the pull-off PATTI test.

In this study, two binders (PG 64-22 and 70-28) were glued to a sandstone substrate with a total of three interface treatment strategies: treatment with hydrated lime and fly ash, and without treatment. Each case was tested at three moisture-conditioning steps: 0-h, 24-h, and 48-h conditioning in a water bath at 25°C. Unconditioned samples (i.e., 0-h conditioning) were kept inside a dry chamber at the same temperature, 25°C, applied to the conditioned cases, to maintain equal testing conditions. For each case, at least three samples were tested at a constant pressure rate. Tensile strength data were then used to calculate the tensile strength ratios (hereafter it is called PO-TSR: pull-off tensile strength ratio, to be distinguished from the TSR value of AASHTO T-283 testing) at the two different levels of moisture conditioning (24-h and 48-h). Table 2 summarizes the ratios.

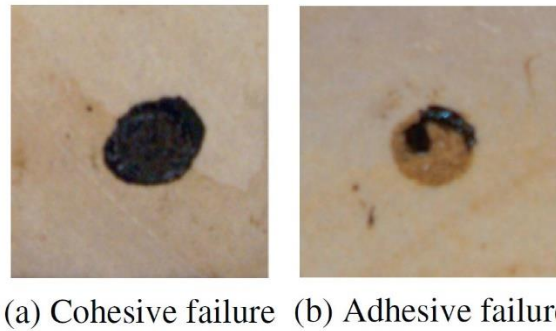
**Table 2.** PO-TSR values obtained from the PATTI pull-off test

Binder	Conditioning time (h)	PO-TSR (%)		
		NF	HL	FA
PG 70-28	24	75	83	83
	48	68	78	74
PG 64-22	24	63	84	80
	48	37	76	65

As expected, all cases suffered from damage due to the moisture conditioning, and the level of damage increased as the conditioning time increased. The table clearly demonstrates that the polymer-modified binder contributed to an increase in moisture-damage resistance, which has been identically observed in other tests. The effect of binders was even more impressive when the samples were subjected to longer moisture conditioning. The PO-TSR values from the reference mixture (NF) after 48-h conditioning were 68% from the sample with the PG 70-28 binder, but reduced to 37% when the unmodified binder was used. One more interesting thing that can be seen from the table is that additives in the mixtures play an important role in reducing stripping potential, which can be captured from the fact that PO-TSR values were not quite dependent on the type of binder when the samples were treated with additives. Even if it may not be conclusive with the limited data, comparing only cases with treatment, hydrated lime seems to perform similar to or slightly better than fly ash without any remarkable difference between two additives. The first author and his colleagues [35] have attempted an integrated experimental-numerical approach by incorporating the PATTI test with its numerical modeling to estimate the material-specific moisture damage characteristics of binder-aggregate interfaces. For the simulation, a sequentially coupled moisture diffusion-mechanical analysis was implemented into a finite element technique to model the bond strength and progressive interfacial degradation due to moisture diffusion followed by mechanical pulling pressure. The integrated approach could successfully identify material-specific damage mechanisms and damage resistance potential by resulting in a degradation function that characterizes interfacial damage due to moisture uptake with two model parameters representing the remaining bond strength and the degradation trend. Clearly, the two anti-stripping additives (hydrated lime and fly ash) contributed to increased resistance to moisture damage when they are associated with PG 64-22 binder, and the contribution between hydrated lime and fly ash was not significantly different.

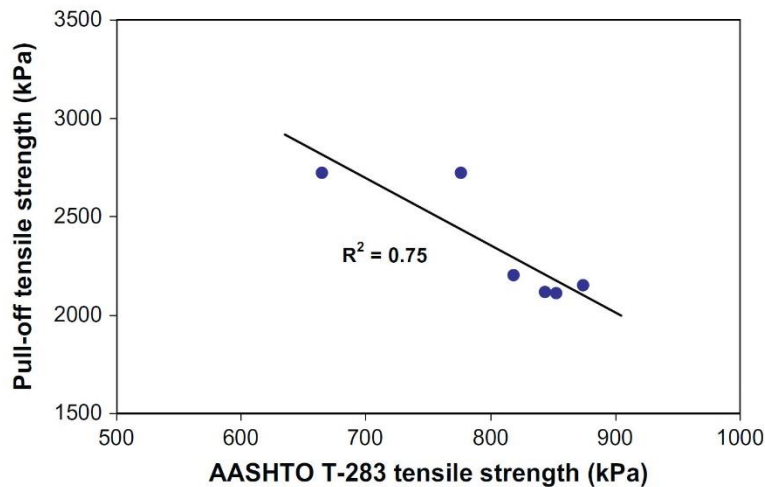
The pull-off test can also identify the type of failure, either adhesive or cohesive. According to a study by Kanitpong and Bahia [36], when more than 50% of the aggregate is exposed from the debonding process between aggregate plate and binder film, the failure can be categorized as adhesive failure; otherwise, it is considered cohesive failure. As exemplified in figure 9, unconditioned samples typically presented cohesive failure in most cases, while adhesive fracture (fig. 9b) was more frequent from samples with 48-h conditioning, which clearly implies that the presence of water caused a reduction in the bond strength between aggregate and binder.





**Figure 9.** Two different types of failure from the PATTI test with moisture damage.

Overall, performance test results of HMA scale samples appeared to be strongly linked to small-scale mixture component characteristics. This can be further validated by figure 10 where the local-scale pull-off test results and global-scale (HMA scale) test results from the AASHTO T-283 exhibited a close correlation on the tensile strength values among mixtures. The figure presents a good linear relationship between two data sets with a  $R^2$ -value of 0.75. Only test data from unconditioned samples were included in the figure at this point, since the moisture-conditioning method for the AASHTO T-283 was not identical to the conditioning used for the pull-off testing.



**Figure 10.** Relationship between two scale test results.

The strong relationship between two scales was also found by Kim et al. [8]. They conducted various performance tests of HMA samples induced by moisture damage and measured several fundamental properties (stiffness, toughness, and bonding energy) of mixture components. Properties and damage characteristics of mixture components were closely related to macroscopic performance behavior of HMA samples, as confirmed by this study.

Evaluation of component characteristics, such as the adhesive fracture potential between binder and aggregate, aids to identify moisture-damage mechanisms and their impacts on pavement performance in a more fundamental manner. Use of component properties and characteristics can be significantly beneficial, since testing of mixture components are much more economical and efficient than testing of asphalt concrete samples, and also component information can be simply used to judge (or potentially predict) HMA performance based on the strong relationship.

## 6. Summary and conclusions

Performance changes and fundamental material characteristics associated with moisture damage due to anti-stripping additives in HMA mixtures were studied through various experimental approaches. Two additives (i.e., one reference additive: hydrated lime and an alternative additive: Class C fly ash) were investigated by adding them into two types of mixes (SP2 for low-traffic-volume roadways and SP5 for high-traffic-volume roadways) where two different asphalt binders (i.e., PG 64-22 for the SP2 mix and polymer-modified binder PG 70-28 for the SP5) and aggregates with different levels of angularity are used. Two HMA mixture scale performance tests, the AASHTO T-283 and the APA under water, and two local-scale mixture constituent tests, the boiling water test (ASTM D 3625) and the PATTI pull-off test, were conducted to characterize the effects of binder-specific anti-stripping additives on the binder–aggregate bonding potential in mixtures. Based on the test results, the following conclusions can be drawn:

- All tests identically demonstrated that the mixtures, where high-quality aggregates and polymer-modified binder are used, are fairly self-resistant to moisture damage without being treated with any anti-stripping additive, and did not show any visible sensitivity between additives, whereas the effects of additives and their sensitivity were significant in the mixtures that use the unmodified binder and low-quality aggregates.
- The effect of the binder was even more significant when the samples were subjected to longer and/or severe moisture conditioning.
- Even if it may not be completely conclusive at this moment with the limited test data, Class C fly ash seems to perform similar to hydrated lime. There was no remarkable difference between the two additives.
- The local-scale test results and global-scale test results exhibited a close correlation. This implies that the evaluation of component characteristics can help identify moisture-damage mechanisms and their impacts on pavement performance. Testing of component characteristics is beneficial, since it is generally more economical and fundamental than testing global-scale asphalt concrete samples.

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