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Screening of South Dakota Asphalt Mixes for Moisture Damage Using Conventional and Innovative Approaches

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SCREENING OF SOUTH DAKOTA ASPHALT MIXES FOR MOISTURE DAMAGE USING CONVENTIONAL AND INNOVATIVE APPROACHES

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ABSTRACT

Moisture-induced damage (stripping) is a major distress in asphalt pavements. This study was undertaken to evaluate the effects of chemical Warm Mix Asphalt (WMA) additives, Reclaimed Asphalt Pavement (RAP), Anti-Stripping Agent (ASA), and hydrated lime on moisture-induced damage potential of asphalt mixes. For this purpose, plant-produced asphalt mixes containing foregoing additives and asphalt binder-aggregate systems consisting of different combinations of different binder grades, aggregates, and additives were tested. Effects of moisture and freeze-thaw cycles on resistance of mixes to stripping were evaluated by determining different fracture energy parameters obtained from Indirect Tension (IDT) and Semicircular Bend (SCB) tests. Also, the effect of moisture and freeze-thaw on adhesion of different combinations of four binder blends of various grades, additives, and aggregates were investigated by conducting Binder Bond Strength (BBS) tests. Fracture-energy-based parameters determined based on IDT and SCB tests showed potential for being applied for screening of mixes with respect to their propensity to moisture-induced damage. Also, the BBS test, as a quick, direct, inexpensive, and effective method, indicated the combinations of the aggregates, additives, and binders, which produce mixes with the maximum resistance to moisture-induced damage and successfully singled out binder-aggregate combinations with a high stripping potential.

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EXECUTIVE SUMMARY

Moisture-induced damage is a major distress in asphalt pavements. The loss of strength and durability in asphalt mixes due to loss of adhesion between aggregate and binder in the presence of moisture is called moisture-induced damage. The South Dakota Department of Transportation (SDDOT) and other DOTs in Region 8 spend millions of dollars annually to combat this problem. With increased use of warm mix asphalt (WMA), reclaimed asphalt pavement (RAP), polymer-modified asphalt (PMA), and anti-stripping agent (ASA), the evaluation of stripping of asphalt mixes has become particularly important. For example, there are concerns over moisture-induced damage potential of WMA mixes and those containing RAP. Also, some aggregates, upon their incorporation in an asphalt pavement containing some binder sources or WMA additives, may lead to a higher moisture-induced damage potential. Therefore, there is a need for evaluation of the effects of different additives and asphalt binders and aggregate sources on pavements' moisture-induced damage potential. As a response to this need, the present study was undertaken to evaluate the moisture-induced damage potential of asphalt mixes used in South Dakota. This report presents the findings of a study conducted on asphalt mixes to evaluate their moisture-induced damage potential through testing of the plant-produced asphalt mixes in South Dakota using local aggregates and commonly used asphalt binders. The moisture-induced damage potentials of the asphalt mixes were evaluated by conducting tensile strength ratio (TSR) and Semicircular Bend (SCB) tests. The effect of moisture on asphalt binder-aggregate adhesion was evaluated by conducting binder bond strength (BBS) test on binder-aggregate systems. The asphalt mixes tested in this study included a hot mix asphalt (HMA) containing hydrated lime (1% by the weight of aggregates), asphalt mix containing an amine-based WMA additive (0.5% by the weight of mix), and asphalt mix containing RAP (20% by the weight of aggregates). Asphalt binder-aggregate adhesion evaluation plan comprised of testing 16 types of asphalt binder blends, namely PG 64-34, PG 64-22, PG 58-28, and PG 70-28, blended with simulated RAP binder, an amine-based ASA, and an amine-based WMA additive. The BBS tests were conducted on combinations of the binder blends with three types of aggregates: Quartzite, Granite-I, and Granite-II. Forty eight combinations of asphalt binder-aggregate systems were tested. The tensile strength ratio obtained from a TSR test, critical strain energy release rate, and energy release ratio (ERR) obtained from SCB test, and pull-off strength obtained from BBS test for unconditioned and moisture-conditioned samples were used to evaluate the moisture-induced damage. The indirect tension (IDT) test results were used to perform a fracture energy analysis of the TSR samples in dry and moisture-condidtioned states to explore the feasibility of applying this method for evaluating the moisture-induced damage utlizing parameters such as toughness index, toughness index ratio (TIR), fatigue index and fatigue index ratio (FIR). The result showed that the asphalt mixes tested in this study met the minimum TSR requirement set by the Superpave® mix design method. The critical strain energy release rate of HMA for dry and moisture-conditioned samples were lower than the range recommended by the ASTM D8044-16 standard (ASTM, 2016). For the asphalt mix containing RAP and the asphalt mix containing WMA additive, the critical strain energy release rate values of dry and moisture-conditioned samples met the minimum values recommended by the ASTM D8044-16 standard (ASTM, 2016). The ERR and FIR values calculated for all mixes were greater than one, indicating no decrease in their resistance to cracking after moisture-conditioning. The TIR values calculated for the mixes were less than one for HMA mixes but greater than one for the mix containing RAP and the mix containing WMA additive. The pull-off strength ratio (PSR) obtained from BBS tests showed that the PG 58-28 binder containing 20% RAP by the weight of the binder with Granite-I had a higher moisture-induced damage potential compared to other asphalt binder-aggregate systems tested in the study. The PG 64-34 binder containing 0.5% ASA with Granite-I and the PG 58-28 binder containing 0.5% WMA additive with Granite-II had higher PSRs than the other asphalt binder-aggregate combinations tested in the current study. The findings of this study are expected to help engineers and the asphalt industry professionals select asphalt binders and aggregates that are more compatible to minimize moisture-induced damage potential.

1. INTRODUCTION

1.1 General Background

Moisture-induced damage is known as degradation of the strength and durability of the asphalt mix in the presence of the water (LaCroix et al., 2016). Moisture-induced damage, described as the loss of bond between binder and aggregate or within asphalt binder/mastic interface itself (Huang et al., 2010), has been considered as one of the commonly occurring distresses in the asphalt pavements (Kim et al., 2008). Field testing of the asphalt mixes to evaluate their moisture-induced damage can take a long time with an uncertainty of obtaining consistent results (Kim et al., 2012). Recent developments have enabled the asphalt industry to use various laboratory equipment and test methods for evaluating the performance of asphalt mixes in the laboratory (e.g., Hossain et al., 2014; Ozer et al., 2016; Yang et al., 2016).

The current industry practice used for screening of asphalt mixes for their moisture-induced damage potential is to conduct tests that are not necessarily mechanistic and may not represent field conditions and damage mechanisms (e.g., Ahmad et al., 2014; Tarefder et al., 2017). Therefore, in many cases, these tests underestimate or overestimate resistance of the asphalt mixes to moisture-induced damage, when compared to field observations (Tarefder et al., 2015; Wen et al., 2016). Different techniques, including digital imaging, surface wave techniques and developing finite element models, are applied to analyze and simulate the moisture-induced damage phenomenon in the asphalt mixes (Barnes et al., 2010; Kim, 2011; Lee et al., 2013). Therefore, the major challenge is to develop methods for evaluating the moisture-induced damage potential in asphalt mixes that are more mechanistic and can better correlate with the field conditions an asphalt pavement may experience during its service life. During the last two decades and with the introduction of different asphalt technologies, new materials and methods for producing asphalt mixes have become available, and they are economically efficient and environmentally sustainable (e.g. Ghabchi et al., 2015; Ghabchi et al., 2016). Among them, warm mix asphalt (WMA), asphalt mixes containing reclaimed asphalt pavement (RAP), and asphalt mixes containing antistripping agents (ASA) have gained popularity across the pavement industry (Mogawer et al., 2013). However, methods used for evaluation of the moisture-induced damage in asphalt mixes are developed and verified for the traditional HMA mixes. Therefore, evaluation of the moisture-induced damage potential of the WMA mixes and HMA mixes containing RAP and ASA are of significant importance.

In view of the significance and importance of the moisture-induced damage as a costly distress, further research is needed to assess the moisture-induced damage potential of the asphalt mixes by using methods that have a mechanistic base and can represent the failure mechanisms in the field.

1.2 Research Objectives

Specific objectives of this study are to:

1. Characterize moisture-induced damage potential of asphalt mixes used in South Dakota and Upper Midwest region.
2. Evaluate the effect of using warm-mix asphalt (WMA), anti-stripping agent (ASA), and reclaimed asphalt pavement (RAP) on moisture-induced damage potential of mixes.
3. Evaluate the moisture-induced damage potential of the asphalt binder-aggregate systems using mechanistic method.
4. Study the feasibility of applying innovate test methods in assessing moisture-induced damage potential of the asphalt mixes.

1.3 Study Tasks

Specific tasks carried out in the study are to:

1. Collect three types of plant-produced asphalt mixes, including an HMA mix containing a PG 64-34 asphalt binder and 1% hydrated lime with a nominal maximum aggregate size (NMAS) of 12.5 mm, an asphalt mix containing a PG 58-28 asphalt binder and 20% RAP (NMAS = 12.5 mm), and an asphalt mix containing a PG 64-34 asphalt binder and 0.5% of a chemical WMA additive (NMAS = 12.5 mm). These mixes are commonly used in South Dakota and elsewhere in Upper Midwest region.
2. Compact asphalt mixes, prepare test specimens and conduct TSR tests in accordance with (AASHTO, 2010) on unconditioned and moisture-conditioned specimens.
3. Compact asphalt mixes, prepare test specimens and conduct SCB tests in accordance with (AASHTO, 2013a) on unconditioned and moisture-conditioned specimens.
4. Collect four types of asphalt binders, namely PG 58-28, PG 64-22, PG 64-34, PG 70-28, three types of aggregates, namely Granite-I, Quartzite, Granite-II, and asphalt additives, namely an amine based WMA additive, an amine-based ASA, and a PAV-aged PG 58-28 asphalt binder (simulated RAP binder).
5. Conduct binder bond strength (BBS) tests in accordance with AASHTO TP-XX-11 (AASHTO, 2011) using a pneumatic adhesion tensile testing instrument (PATTI) on unconditioned and moisture-conditioned asphalt binder-aggregate samples.
6. Compare the result of the TSR, SCB, and IDT tests (using fracture energy approach).
7. Evaluate the effect of asphalt binder type, aggregate type, and additive type on adhesion of the asphalt binder with aggregates in moisture-conditioned and unconditioned states.
8. Evaluate the effectiveness of the applied test methods for assessing the moisture-induced damage potential of the aggregates-binder systems and mixes in presence of different additives.

2. LITERATURE REVIEW

2.1 Moisture-induced Damage in Asphalt Mixes

Moisture-induced damage in an asphalt mix occurs as a result of loss of adhesion between asphalt binder and aggregate or loss of cohesion in asphalt binder in the presence of water (Caro et al., 2008). The air voids and other discontinuities in the asphalt mix allow water to penetrate in the pavement (Lu et al., 2007). Often the term stripping is used for moisture-induced damage governed by material properties, such as nature of the asphalt and aggregates, the proportion of the asphalt and aggregate, and environmental factors, namely freeze-thaw action, precipitation, and humidity and construction factors such as air voids and weather condition during the construction and traffic loads (Cho et al., 2010). Also, other forms of distresses — namely fatigue cracking, potholes, and rutting — are accelerated as a result of moisture-induced damage (Huang et al., 2010).

2.2 Moisture-induced Damage Mechanisms

To describe the mechanism of the moisture-induced damage, different approaches such as contact angle, pore water pressure, surface energy, spontaneous emulsification, and chemical and mechanical reaction have been suggested and studied by several researchers (e.g. Caro et al., 2008; Cho et al., 2010; Varveri et al., 2015). Moisture-induced damage process is known to be accelerated due to pore water pressure buildup under the wheel load repetitions in combination with environmental factors and interaction of clay minerals in aggregate with water (Cho et al., 2010). Aggregates, due to high surface energy, have higher tendency to absorb water than the asphalt binder leading to an adhesive failure of the asphalt binder-aggregate bond in presence of the water (Cho et al., 2010). Adhesion failure is observed if the contact angle of aggregate-water interface is less than that for asphalt-water interface (Bhasin et al., 2006). Varveri et al. (2015) explained the separation of the aggregates from the binder with mechanisms such as detachment, displacement, spontaneous emulsification, pore pressure development, and hydraulic scouring. According to Varveri et al. (2015), moisture enters the asphalt binder-aggregate interface by molecular diffusion. Also, detachment occurs by separation of the uncracked binder film from aggregate in the presence of water. Furthermore, displacement occurs by disruption of the asphalt film in presence of water. Moreover, spontaneous emulsification occurs without thermal and mechanical energy exchange. Hydraulic scouring occurs by action of the tire in the saturated pavement leading to abrasion of the asphalt binder from the aggregate, losing the contact and dislodging from the pavement (Varveri et al., 2015).

Mineral additives like hydrated lime contain calcium, which reacts with aluminates and silicates of the aggregates forming a strong bond in presence of the water (Varveri et al., 2015). Liquid additives like amine group additives act as a Lewis base that acquires some protons from an acidic group of the asphalt binders, which is suitable for reducing the surface tension of the asphalt binders. Adhesion at asphalt binder-aggregate interface depends on pH and chemical reaction between the functional group of the aggregates and asphalt binder (Varveri et al., 2015).

2.3 Evaluation of Moisture-induced Damage in Asphalt Mixes

Several studies have been carried out to characterize the moisture-induced damage potential of the asphalt mixes by conducting dynamic modulus test (e.g., Chen et al., 2008; Jahromi, 2009; Barnes et al., 2010; Huang et al., 2010; Weldegiorgis et al., 2015). The dynamic moduli of the moisture-conditioned HMA samples were lower than those measured for unconditioned samples. In other studies, various researchers (e.g. Tarefder et al., 2012; Ahmad et al., 2014; Amelian et al., 2014; Kakar et al., 2015; Kim et al., 2015; Varveri et al., 2015; Weldegiorgis et al., 2015) have evaluated moisture-induced damage of HMA mixes by conducting TSR test in accordance with the conditioning method described in AASHTO T 283 (AASHTO, 2010) test method. The tensile strength ratio obtained from TSR test was less than one. Moisture-induced damage decreased the tensile strength of the asphalt mixes.

The HMA samples subjected to long-term conditioning showed further decrease in the tensile strength (e.g., Chen et al., 2008; Varveri et al., 2016). Tarefder et al. (2015) found that a fair correlation exists between tensile strength ratio obtained from TSR tests conducted in accordance with AASHTO T 283 method (AASHTO, 2010) in the laboratory and permeability of pavements when measured in the field. Additionally, a moisture-induced stress tester (MIST) has been used for moisture conditioning of the TSR samples (Ahmad et al., 2017). However, no correlation was found to exist between the permeability of pavements measured in the field and the tensile strength ratio obtained from MIST-conditioned samples (Tarefder et al., 2015).

A digital imaging technique was applied by Amelian et al. (2014) to evaluate the moisture-induced damage potential of the asphalt mixes by a boiling water test. The percentage of the stripping in HMA samples obtained from image analysis is linearly related to the tensile strength ratio obtained from TSR test. Behiry (2013), after conducting Marshall Stability test on HMA samples, found that resilient modulus decreased after moisture conditioning. Some researchers have conducted dynamic shear rheometer tests on dry and moisture-conditioned HMA samples and found that the debonding potential of the asphalt mixes increased after moisture conditioning (e.g., Hossain et al., 2014; Ahmad et al., 2017).

Several researchers have conducted the Hamburg wheel tracking test (HWT) test to evaluate moisture-induced damage potential of the asphalt mixes (e.g., Mogawer et al., 2011; Cui et al., 2015; Ghabchi et al., 2015; Kim et al., 2015; Wen et al., 2016). They found that, after attaining the stripping inflection point, the moisture-induced damage potential of the HMA samples increased as the creep slope of the line obtained by plotting rut depth and number of wheel passes decreases.

A number of laboratory and field studies have been carried out to evaluate the fracture resistance of the asphalt mixes (e.g., Mohammad et al., 2012; Kim et al., 2015; Lopez-Montero et al., 2016; Saha et al., 2016a; Saha et al., 2016b). However, few researchers (e.g., Gong et al., 2012; Yang et al., 2016) have analyzed the moisture-induced damage potential of mixes using fracture energy methods. They found that fracture energy of the hot mix asphalt decreased after moisture conditioning. The SCB test was the most reliable test method for determining fracture energy of the asphalt mixes (e.g., Gong et al., 2012; Saha et al., 2016a). Kim (2011) found that SCB test is the most accurate laboratory test method for characterizing the fracture energy of the asphalt mixes. An increase in the strain energy release rate of HMA samples in SCB test was found to result in a reduction in the fatigue cracking rate in the field (Mohammad et al., 2012). Huang et al. (2013) after conducting SCB samples, found that different types of asphalt binders have different fracture resistant behavior in the HMA. Asphalt binders with higher performance grades were found to show higher fracture resistance. Ozer et al. (2016) found that fracture resistance increases with an increase in the temperature and applied load.

A number of studies have been conducted by researchers to simulate the moisture-induced damage of the asphalt mixes using laboratory data and finite element modeling methods (e.g. Kringos et al., 2007; Kringos et al., 2008a; Kringos et al., 2008b; Caro et al., 2010; Kim, 2011; Das et al., 2015). Kringos et al. (2007) simulated the molecular diffusion of moisture in the asphalt mixes and separation of the mastic from the aggregate created by pumping action of the traffic loads in asphalt pavements. It was found that the physical-mechanical processes such as pumping action facilitates diffusion of the moisture and accelerates the moisture-induced damage. In an another study, Kringos et al. (2008a) applied finite element modeling and concluded that the non-moisture-induced damages like settlements, cracks, and aging can occur before the moisture-induced damage. In a similar study, Kringos et al. (2008b) found that mastic weakening is due to moisture diffusion and erosion of the mastic caused by higher pressure gradients finally causes cohesive failure. Aggregate-mastic bond weakening was observed due to continuous moisture diffusion leading to adhesive failure (Kringos et al., 2008c).

Caro et al. (2010) incorporated the moisture diffusion and mechanical loading in a micromechanical finite element model and found that asphalt samples with higher moisture content have higher deformations, longer cracks, and lower load carrying capacity. Cohesive failure developed at the dry condition and adhesive failure due to the effect of moisture conditioning. Kim (2011) found that rate-dependency and temperature-sensitivity of the asphalt binder in a mix can be incorporated in finite element models. The combined effect of the moisture-induced damage and oxidative damage in the asphalt mixes was evaluated by Das et al. (2015) using finite element modeling. Moisture diffusion and oxidation were modeled, and their effects on adhesion and cohesion bonding were evaluated. It was found that aging may result in a higher moisture-induced damage potential.

2.3.1 Asphalt Mixes Containing WMA Additives

A high variability in moisture-induced damage potential of asphalt mixes containing different types of WMA additives has been reported in literature (e.g., Xiao et al., 2009; Bennert et al., 2011; Mogawer et al., 2011; Gong et al., 2012; Kim et al., 2012; Lee et al., 2013). Xiao et al. (2009) evaluated the moisture-induced damage potential of the asphalt mixes containing WMA additives, namely Asphamin and Sasobit using ITS and TSR tests. It was found that indirect tensile strength and tensile strength ratio values were not significantly affected by addition of the WMA additives. In a similar study by Kim et al. (2012), after conducting SCB and TSR tests, it was reported that HMA has higher resistance to moisture-induced damage than the asphalt mix containing WMA additives. The fracture energy and tensile strength were higher for HMA mixes than those for mixes containing WMA additives. Also, the field performance of the asphalt mixes containing WMA additives were poorer than that of the HMA with regard to moisture-induced damage.

In another study, Mogawer et al. (2011) evaluated the moisture-induced damage potential of asphalt mixes containing WMA additives — Evotherm, Sasobit, and Sonne — by conducting HWT tests. The moisture-induced damage potentials of the asphalt mixes were not found to be significantly affected by the addition of the WMA additives. Sasobit increased the moisture-induced damage potential of the asphalt mixes. In a study conducted by Wasiuddin et al. (2008), it was found that addition of aspha-min reduced the moisture-induced damage potential of the asphalt mixes. Ghabchi et al. (2015) after conducting Hamburg wheel tracking test reported that asphalt mixes containing Evotherm WMA additive were resistant to moisture-induced damage. Wen et al. (2016), in a similar study, found that rutting resistance of HMA is the same as that of asphalt mixes containing WMA additives. Xiao et al. (2009) reported that the dry and wet ITS values were not affected by the addition of the WMA additives.

2.3.2 Asphalt Mixes Containing RAP

A number of studies conducted to evaluate the moisture-induced damage potential of the asphalt mixes containing RAP showed that the results can vary depending on the test methods, RAP source, aggregate type, binder source, and other factors. (e.g., Ghabchi et al., 2014; Cong et al., 2016; Ghabchi et al., 2016; Fakhri et al., 2017a; Fakhri et al., 2017b; Singh et al., 2017).

Mogawer et al. (2013) evaluated the moisture-induced damage potential of asphalt mixes containing RAP by conducting SCB tests and found that asphalt mixes without RAP have a higher fracture resistance than mixes containing RAP. Yang et al. (2016), after conducting SCB tests, found that fracture resistance of the asphalt mixes containing RAP decreased after moisture conditioning. Ozer et al. (2016) and Singh et al. (2017) conducted SCB tests on asphalt mixes and found an increase in fracture resistance and a decrease in moisture-induced damage potential of asphalt mixes after addition of RAP. In another study, Ghabchi et al. (2016) evaluated the moisture-induced damage potential of asphalt mixes containing RAP by TSR and HWT tests. The TSR test results showed that the addition of RAP increased the moisture-induced damage potential in the asphalt mixes. However, from HWT test results, it was found that moisture-induced damage decreased with an increase in the RAP content. In a study conducted by Cong et al. (2016), it was found that moisture-induced damage potential and rutting resistance of the asphalt mixes increased as a result of addition of RAP to mixes. Fakhri et al. (2017b),after conducting wheel tracking tests on the asphalt mixes, found that moisture-induced damage potential decreased with addition of RAP in aged and unaged asphalt mixes.

2.3.3 Asphalt Mixes Containing ASA

Asphalt mixes containing liquid antistripping agents, hydrated lime, and fly ash have been studied by several researchers in the past (e.g., Chen et al., 2008; Kim et al., 2008; Jahromi, 2009; Huang et al., 2010; Mogawer et al., 2011; Behiry, 2013; Abuawad et al., 2015; Zhang et al., 2017).

Mallick et al. (2005) conducted indirect tensile strength tests on the asphalt mixes containing hydrated lime and found that the addition of the hydrated lime decreased the moisture-induced damage potential of the mixes. In a similar study, LaCroix et al. (2016) found that the addition of ASA to asphalt mixes provided a higher resistance to moisture-induced damage than the HMA without any ASA. However, hydrated lime was less effective in reducing moisture-induced damage potential than the liquid ASA. Similar findings were obtained after conducting boiling water tests by Nazirizad et al. (2015) on the asphalt mixes containing hydrated lime and liquid ASA.

Chen et al. (2008) studied the effect of adding an amine-based ASA on moisture-induced damage by conducting a dynamic modulus test, Superpave® IDT creep test, and resilient modulus test. It was found that addition of an amine-based ASA to HMA reduced the moisture-induced damage potential of the asphalt mixes. In another study, Behiry (2013) evaluated the moisture-induced damage potential of asphalt mixes containing hydrated lime and Portland cement. Addition of the hydrated lime and Portland cement decreased the moisture-induced damage potential of the mixes. However, hydrated lime was found to be more effective in increasing the resistance of the mix to moisture-induced damage than Portland cement. Kim et al. (2008) found that the effect of lime used in the form of dry powder or slurry on moisture-induced damage of the mix is different. After conducting TSR, HWT, and APA tests on the asphalt mixes, it was found that for an increased number of freeze-thaw cycles, the lime slurry has a better anti-stripping effect that dry lime when added to a mix.

In another study conducted by Jahromi (2009), it was found that adding hydrated lime to mix increased the dynamic modulus value of the HMA. Huang et al. (2010) in a similar study, found that the dynamic modulus and tensile strength of HMA increased after addition of the fly ash kiln dust and lime to the HMA. Amelian et al. (2014) evaluated the moisture-induced damage potential of the asphalt mixes based on digital image analysis and found that the ASA in an asphalt mix effectively reduced the moisture-induced damage potential of the HMA.

2.4 Moisture-induced Damage Evaluation in Binder-Aggregate Systems

A number of researchers have evaluated moisture-induced damage potential of asphalt binder-aggregate systems (e.g., Copeland et al., 2007; Moraes et al., 2011; Apeagyei et al., 2015; Lu et al., 2017). Apeagyei et al. (2015) evaluated moisture-induced damage potential of asphalt binder-aggregate systems by conducting a BBS test on four different aggregates — granite, limestone, basalt, and greywacke with asphalt mastics prepared by a 40/60penetration grade asphalt binder. It was found that moisture-induced damage potential is higher in granite than the limestone due to higher absorption and higher diffusion in the granite-mastic sample. Adhesive failure was observed after moisture-conditioning. In a similar study, Copeland et al. (2007) evaluated moisture-induced damage potential of the PG 52-34, PG 64-28, and PG 70-22 asphalt binders with and without binder modifications and found that adhesive strength of the asphalt binders decreases after moisture conditioning. Use of modified binders was not found to necessarily decrease the moisture-induced damage potential.

In an another study, Moraes et al. (2011) conducted BBS tests on granite and limestone aggregates with modified asphalt binders and found that pull-off tensile strength (POTS) is higher in unconditioned samples and it decreases after moisture conditioning. The failure mode changed from the cohesive to adhesive due to the moisture-induced damage. The POTS values were higher in the modified binders with increased adhesion with the aggregate and cohesion within binder. In a atomistic simulation study conducted by Lu et al. (2017) to evaluate the nanoscale effect of the moisture on asphalt binder-aggregate bond, it was found that chemical properties of the aggregates are more dominant parameters in the separation of the binder and aggregates than chemical properties of the asphalt binder. Limestone was a more effective aggregate in reducing moisture-induced damage potential than the quartzite due to a less polar surface in the limestone and highly polar silica in the quartz.

2.4.1 Adhesion of Asphalt Binders Containing RAP Binders with Aggregates

Few studies have been conducted in the past to evaluate the moisture-induced damage potential systems of the binder containing RAP and aggregate. Canestrari et al. (2014) conducted BBS tests on an artificial RAP substrate in wet and dry conditions. Basalt and limestone aggregates were tested with binders, including base, soft, medium, and hard. The percentage reduction in the pull-off strength was higher to lower in the basalt, limestone, coated basalt, and coated limestone in a decreasing order. Addition of RAP to the binders decreased the moisture-induced damage potential. The pull-off strength was observed to be higher in basalt at dry condition and higher in limestone in wet condition. In an another study, Ghabchi et al. (2014) applied surface free energy (SFE) approach to evaluate the moisture-induced damage potential of the asphalt binders containing RAP. Two asphalt binders — PG 64-22 (non-polymer modified) and PG 76-28 (polymer-modified) — were tested with limestone, rhyolite, sandstone, granite, gravel, and basalt aggregates. The RAP binder with a concentration of 0%, 10%, 25% and 40% by the weight of asphalt mix was mixed with neat binders. Addition of the RAP increased the non-polar SFE component and base SFE component and decreased the acid SFE component. Work of adhesion was found to increase with an increase in the RAP content. The debonding potential of the aggregate in the presence of water was found to reduce with an increase in the RAP content.

2.4.2 Adhesion of Asphalt Binders Containing WMA Additives with Aggregates

Wasiuddin et al. (2008) evaluated the moisture-induced damage potential of asphalt mixes containing WMA additives, including Sasobit, Aspha-min, and paraffin wax by determining the adhesion and wettability of the asphalt binder-aggregate systems by applying the SFE method. Amounts of the additives were different for different samples. The PG 64-22, and PG 70-28 binders containing WMA additives were tested with limestone and sandstone aggregates. Sasobit reduced the adhesion force between the aggregate and binder with increased wettability. Aspha-min additive decreased the wettability of the asphalt binder-aggregate systems. The moisture-induced damage potential of the PG 70-28 binder was higher than PG 64-22 containing Sasobit. However, addition of Aspha-min decreased the moisture-induced damage potential of the PG 70-28 binder with aggregates.

In another study, Wasiuddin et al. (2011) found that PG 64-22 binder containing Sasobit produced a mixed mode of failure without a significant change in strength. However, PG 76-22 binder (polymer-modified binder) exhibited adhesive failure. Alavi et al. (2012) conducted a binder bond strength test to evaluate the moisture-induced damage in the granite and rhyolite aggregates with PG 64-22 and PG 76-22 binders blended with WMA additives. The binder containing the WMA additive had a higher moisture-induced damage potential than the neat binder. The reduction in temperature was the primary reason for moisture-induced damage in WMA. Use of rhyolite aggregate resulted in a higher moisture-induced damage potential than that of the granite with non-modified binders.

Recently, Cucalon et al. (2017) evaluated the mastic phase of the HMA and WMA using a surface-free energy approach. Unaged and PAV-aged samples of PG 64-22 and PG 76-22 binders with and without WMA additives — Sasobit, Evotherm, and Rediset — were tested with gabbro and limestone aggregates. It was found that moisture-induced damage potential decreased with the aging of the WMA. Limestone aggregate had a higher resistance to moisture-induced damage than gabbro aggregate. However, in the dry condition, PG 64-22 binder had a higher bond strength than PG 76-22 binder with gabbro and limestone aggregates.

2.4.3 Adhesion of Asphalt Binders Containing an ASA with Aggregates

Kanitpong et al. (2005) conducted BBS tests on the asphalt binder-aggregate systems consisting of a PG 58-28 binder with and without ASA with granite and limestone aggregates. The polymers used for modification were styrene-butadiene (SB), styrene-butadiene-styrene (SBS), and elvaloy. The pull-off strengths of the asphalt binder-aggregate samples decreased after moisture-conditioning. The modified binders had a higher pull-off strength than the base binder. Also, modified binders showed a higher bond strength than the binders containing ASA. The pull of strength of the binders containing ASA was nearly the same under dry and wet conditions, indicating an improvement in adhesion with addition of ASA. In a different study, Wasiuddin et al. (2010) applied a surface energy approach to test the asphalt binders and aggregates with and without styrene-butadiene rubber (SBR) using universal sorption device. Sandstone and limestone aggregates were used in the test. Unconditioned and moisture-conditioned samples were evaluated. Addition of the SBR increased the moisture-induced damage potential. However, due to the acidic nature of the sandstone, adhesion energy was found to increase with addition of SBR, providing a better adhesion than samples prepared using limestone aggregate.

3. MATERIALS AND METHODS

3.1 Materials

This section presents an overview of the materials collected, prepared, and tested in the present study.

3.1.1 Aggregates

Due to their availability and desirable physical, chemical, mechanical and mineralogical properties, aggregates are being used in asphalt mixes for road construction. However, differences in the sources and other properties of the aggregates lead to a difference in their quality, durability, strength, and applicability in an asphalt mix. In this study, Granite-I, Quartzite and Granite-II aggregates with an approximately 300 mm diameter were collected and cut to flat pieces of smaller sizes (Table 3.1) and used for preparing samples for BBS test. The Granite-I had a reddish brown color and Granite-II was bluish brown. Granite-I and Granite-II consisted of quartz mineral bonded with alumina and silica. Quartzite had a red appearance and consisted of the quartz minerals bonded with silica.

Table 3.1 Types and sources of the aggregates collected for BBS test

Aggregate	Geological Origin	Quarry Location	Visual Appearance
Granite-I	Igneous, intrusive	Brookings, SD	Reddish-brown
Quartzite	Metamorphic	Sioux Falls, SD	Red
Granite-II	Igneous, intrusive	Brookings, SD	Bluish brown

3.1.2 Asphalt Binders

Four different types of asphalt binders — PG 58-28, PG 64-22, PG 64-34, and PG 70-28 — were collected from a local material supplier in South Dakota and were used for preparing the specimens for conducting BBS tests.

3.1.3 Warm Mix Asphalt (WMA) Additives

The WMA additives are added to the asphalt mix to increase its workability at low production and compaction temperatures, compared to those of the HMA. One type of an amine-based chemical WMA additive was collected from its supplier and used in this study (Table 3.2). According to its manufacturer, the collected WMA additive is designed to lower the emissions, thermal segregations, reduce binder content, enable the mix to incorporate higher amount of RAP and RAS and allows reduction in mixing and compaction temperatures compared to HMA mixes.

Table 3.2 Types of the WMA additive collected for BBS test

WMA additive	Type	Form
Amine-based	Chemical	Liquid

3.1.4 Simulated RAP Binder (S-RAP)

The S-RAP binder used in this study was produced by conducting the short-term and long-term aging procedures on a PG 58-28 asphalt binder in the laboratory in accordance with AASHTO T 240 standard method and AASHTO R 28 standard practice, respectively (AASHTO, 2013). Aging of an asphalt binder using this method represents a simulation of the asphalt binder aged in a pavement's service life that may be extracted from RAP. The pressure aging vessel (PAV) simulates the in-service aging of 7 to 10 years of an asphalt binder through exposing it to heat and air pressure.

3.1.5 Liquid Antistripping Agent (ASA)

Liquid antistripping agent (ASA) is a chemical additive used in the asphalt mixes to increase their resistance to moisture-induced damage by improving the adhesion of asphalt binder to aggregate. Liquid and mineral form of the additives are used as an ASA. Hydrated lime is the most commonly used mineral antistripping agent. The liquid ASA used in the current study is an amine-based chemical collected from a local material supplier (Table 3.3).

Table 3.3 Type of the ASA collected for preparing samples for BBS test

Antistripping agent	Type	Form
Amine-based	Chemical	Liquid

3.1.6 Asphalt Mixes

Asphalt mixes evaluated in the current study were produced in asphalt plants and collected from different construction projects. The collected mixes were transported to an asphalt laboratory at South Dakota State University (SDSU), then reheated in an oven, compacted and tested. Three types of asphalt mixes were collected for this study: (1) an HMA mix containing a PG 64-34 asphalt binder, mainly Quartzite aggregate and 1% hydrated lime (HMA-Lime); (2) an HMA mix containing a PG 58-28 asphalt binder, mainly Quartzite and Granite-II aggregates, and 20% RAP (HMA-RAP); and (3) a WMA mix containing a PG 64-34 asphalt binder, mainly Granite-I and Granite-II aggregates, and 0.5% of an amine-based chemical WMA additive (C-WMA). All mixes had a nominal maximum aggregate size (NMAS) of 12.5 mm. Details of the collected mixes are presented in Table 3.4. The HMA-Lime was collected in August 2017 from an asphalt overlay project at I-90 near Brandon, South Dakota (Figure 3.1). The HMA-RAP mix was collected in September 2017 from a parking lot construction project in SDSU campus in Brookings, South Dakota (Figure 3.2). The C-WMA mix was collected in October 2017 from an asphalt plant located in western Minnesota produced for a runway reconstruction project in Webster, South Dakota (Figure 3.3).

Figure 3.1 Collection of HMA-Lime Mix From an Overlay Project on I-90 near Brandon, SD

Figure 3.2 Collection of HMA-RAP Mix From Construction Project on SDSU campus in Brookings, SD

Figure 3.3 Collection of C-WMA Mix from an Asphalt Plant Located in Western Minnesota

Table 3.4 Sources and Types of the Collected Asphalt Mixes

Asphalt Mix Name	**Asphalt Mix Type**	**Binder Grade**	**NMAS* (mm)**	**Location**
HMA-Lime	HMA+ 1% Hydrated Lime	PG 64-34	12.5 mm	Brandon, South Dakota
HMA-RAP	HMA+ 20% RAP	PG 58-28	12.5 mm	Brookings, South Dakota
C-WMA	HMA+ 0.5% amine-based WMA additive	PG 64-34	12.5 mm	Webster, South Dakota

*NMAS = Nominal Maximum Aggregate Size

3.2 Sample Preparation

This section describes the procedures and standards followed for preparing the samples for TSR, SCB, and BBS tests. The letters and numbers used for labeling of the prepared samples are shown in Table 3.5.

Table 3.5 Protocol Used for Labeling Samples

Letter Code	Number	Description
B	1	Source1 (I-90 project)
	2	Source2 (Parking lot project)
	3	Source3 (Runway reconstruction project)
M	1	HMA without any additive
	2	HMA containing 20% RAP
	3	HMA containing 0.5% WMA additive
T	1	SCB test
	2	TSR test
	3	BBS test
U		Unconditioned
C		Moisture-conditioned
S	1, 2, 3, …	Specimen replicate number

3.2.1 Tensile Strength Ratio (TSR) and Indirect Tension Test (IDT) Samples

Plant-produced asphalt mixes collected from different projects were reheated in the laboratory and used for preparing TSR/IDT test samples. Trial samples were prepared for each asphalt mix to determine the weight required to obtain desired air voids ranging from of 7% ± 0.5% for the test samples. Sample preparation procedure was similar for the trial samples and test samples, whereas preparation of test samples needed pre-determined weights. Four trial samples, four test specimens for testing without moisture conditioning, and four test specimens for testing after moisture-conditioning were prepared for each type of asphalt mix.

The compaction and testing procedures were followed in accordance with AASHTO T 283 standard (AASHTO, 2010). The TSR/IDT sample preparation consisted of the following steps:

1. Flat-head scoop, trays, material handling chute, Superpave® gyratory compactor (SGC) mold, and the lid of compaction mold were heated in the oven at a temperature of 165°C for 30 minutes.
2. The weight required to prepare four cylindrical specimens of TSR/IDT test was multiplied by the factor of 1.1 to consider the material loss during handling.
3. Asphalt mix was taken out from the paper bag and required weight was transferred to the metal tray (Figure 3.4).
4. Asphalt mix in the tray was heated in an oven at a temperature of 165°C for at least one hour and hand-mixed every 15 minutes (Figure 3.5).
5. The desired weight of the asphalt mix was transferred to the material handling chute and kept in the oven for another five minutes.

6. Heated SGC mold having an inner diameter of 150 mm was weighed and a circular paper disc was placed inside the mold.
7. The hot mix in the material handling chute was removed from the oven and remixed.
8. Asphalt mix of required weight was transferred into the mold from the material handling chute.
9. Asphalt mix in the mold was covered with another circular paper disc, and the metal lid was place on top.
10. The mold was placed inside a Superpave® gyratory compactor. The compaction mode was set to height. Specimen height was set to 95 mm using the digital control on SGC (Figure 3.6).
11. The compacted sample was partially extruded and kept for cooling by fan for approximately 30 minutes before complete extrusion and transferring it onto a flat surface (Figure 3.7).
12. A similar procedure was repeated for preparation of all the TSR/IDT samples.
13. Samples were labeled and kept in in the room temperature for 24 hours before testing.
14. Dry samples were placed inside an environmental chamber and kept at 25°C.

Figure 3.4 Asphalt Mix in Oven Ready for Reheating

Figure 3.5 Hand-Mixing of Asphalt Mix

Figure 3.6 Compaction of Asphalt Mix in a Superpave® Gyratory Compactor (SGC)

Figure 3.7 Sample Extraction from SGC Mold

Moisture conditioning consisted of the following steps:

1. The vacuum saturation was carried out on TSR/IDT specimens by applying the vacuum pressure of 254-660 mm Hg to a sample submerged in the water in a saturation chamber (Figure 3.8).
2. The specimen was weighed to ensure a saturation between 70% and 80%.
3. After obtaining the desired saturation, the specimen was wrapped in the plastic and kept in an air-tight plastic bag after adding 10 ml of water to the bag.
4. Samples was transferred to a freezer maintaining a temperature of -18°C.
5. After 16 hours of keeping the specimens at -18°C, they were placed inside water bath at a temperature of 60±1˚C for 24 hours (Figure 3.9).
6. The specimens were removed from the water bath and placed inside water at 25°C for two hours before testing.

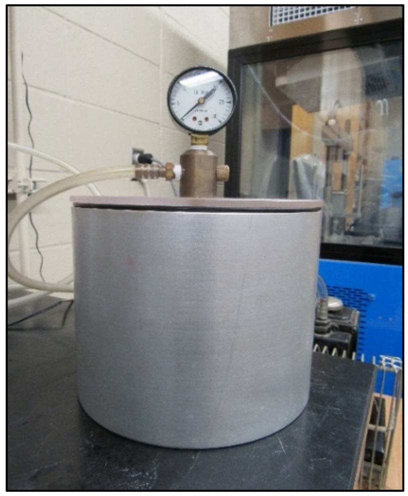


Figure 3.8 Vacuum Saturation Chamber

Figure 3.9 Water Bath

3.2.2 Semicircular Bend (SCB) Samples

The plant-produced asphalt mixes collected from different projects were used to prepare SCB test specimens in the laboratory. Sample preparation and conditioning were carried out in accordance with ASTM D8044 (ASTM, 2016) and AASHTO T 283 (AASHTO, 2010) standard test methods, respectively. For this purpose, the cylindrical samples were compacted in an SGC with a height of 120 mm and a diameter of 150 mm. Then, the semicircular specimens of 57 mm thickness were prepared by wet cutting of the cylindrical samples using a rock saw with a blade of 458 mm diameter and 3 mm thickness (Figure 3.10). Then, notches with a depth of 25.4 mm, 31.75 mm, and 38.1 mm were saw-cut in the mid span of the semicircular samples using a tile saw having a thinner blade (Figure 3.11). The same sample preparation procedure was used for all mixes. Trial semicircular samples with different weights were prepared for each asphalt mix to determine the weight of asphalt mix required to obtain test specimens with air voids of 7.0% ± 0.5%. For each type of asphalt mixes, nine semicircular specimens for testing in dry condition and nine semicircular specimens for testing after moisture conditioning, were prepared (Figure 3.12).

Figure 3.10 Rock Saw Used for Preparing SCB Specimens

Figure 3.11 Tile Saw used for Cutting Notch in SCB Specimens

Figure 3.12 Final SCB Specimens

3.2.3 Binder Bond Strength (BBS) Samples

The large stone samples with different mineralogies (Granite-I, Quartzite and Granite-II) were cut into flat pieces of the aggregates using a rock saw (Figure 3.13). The flat surfaces of the specimens were polished to provide a smooth contact area and were cleaned with distilled water to avoid dust and other contaminants. For surface polishing, an electric grinder operated at an angular velocity of 10,000 rpm was used (Figure 3.14).

The BBS sample preparation was carried out as follows:

1. The aggregate sample cut from the collected rock with parallel surfaces was immersed in the distilled water for 30 minutes. A brush was used for removing the surface dust three times: immediately after submerging, 15 minutes after submerging, and 30 minutes after submerging the specimen in the distilled water. The aggregates sample was removed from water and after 30 minutes resting in room temperature, its surface was cleaned with acetone, and then kept at room temperature for 10 minutes before heating (Figure 3.15).
2. The pull stub and aggregate samples were heated at 60°C for one hour to remove the moisture.
3. The asphalt binder was heated in an oven at 165°C for one hour and mixed every 15 minutes to consistency.
4. The surface of the pull stub heated at 60°C was dipped in asphalt binder and pushed and attached onto an aggregate surface, providing an asphalt binder thickness of 0.8 mm.
5. The excess asphalt binder was carefully removed using a heated utility blade to obtain a clean pull stub attached to aggregate surface.
6. The pull stub attached to the surface of the aggregate was kept for 24 hours at a temperature of 25°C.
7. The dry samples were kept inside an environmental chamber at 25°C for two hours before testing.

Figure 3.13 Preparation of Flat Samples from the Collected Rocks

Figure 3.14 Surface Preparation of BBS Aggregate Samples

Figure 3.15 Cleaning of Aggregate Surface

Moisture conditioning of the BBS samples consisted of the steps as follows:

1. The samples were kept at room temperature of 25°C for two hours after preparation.
2. The samples were submerged in water at a temperature of 25°C for 48 hours.
3. The samples were removed and kept inside a freezer at -18°C for 16 hours.
4. The samples were removed from the freezer and kept in water at 25°C for four hours before testing.

3.3 Laboratory Testing

3.3.1 Theoretical Maximum Specific Gravity (Gmm)

Theoretical maximum specific gravity (G_{mm}) tests were conducted on the loose asphalt mixes in accordance with AASHTO T 209 standard method (AASHTO, 2013b). The G_{mm} values for each mix are needed for calculation of the air voids in the compacted asphalt samples. The test was carried out for all mixes as follows:

1. A Pycnometer was calibrated in accordance with AASHTO T 209 (AASHTO, 2013b) and set aside (Figure 3.16a).
2. Hot and loose asphalt mix was cooled and mixed during cooling to maintain a granular consistency. Then, three samples of cool and loose mix with a mass of at least 1500 g each (for NMAS of 12.5 mm) were placed in trays (Figure 3.16b).
3. The calibrated glass pycnometer was filled with approximately 2000 ml of water at a temperature between 24°C and 25.5°C and placed on a scale and tared.
4. The loose asphalt mix was placed in the pycnometer using a funnel, and its weight was recorded (Figure 3.16c).
5. The pycnometer with the asphalt mix was shaken such that there is about 25 mm of water above the mix.
6. The vacuum pump setup was connected to the pycnometer, and de-airing of the loose mix was carried out by vibrating the sample and pycnometer using a mechanical vibrator while the vacuum pressure of between 25 mm Hg to 30 mm Hg was applied for 13 to 15 minutes.
7. After de-airing procedure was complete, the vacuum pressure was released and the pycnometer with the asphalt mix was filled with water at a temperature between 24°C and 25.5°C and covered with a glass slide.

8. It was ensured that no bubbles were trapped inside the water, when sliding the glass cover on top of the pycnometer. Then, pycnometer and glass slide were carefully dried using a piece of paper towel, and its total weight was recorded.
9. The G_{mm} value was calculated by the method of mass determination in the air as per as AASHTO T 209 (AASHTO, 2013b) from Equation 1.

$$G_{mm} = A / (A+D-E) \quad (1)$$

where,

G_{mm} = theoretical maximum specific gravity;
A = mass of oven dry sample in air (g);
D = mass of container filled with water (g); and
E = mass of container filled with sample and water (g).

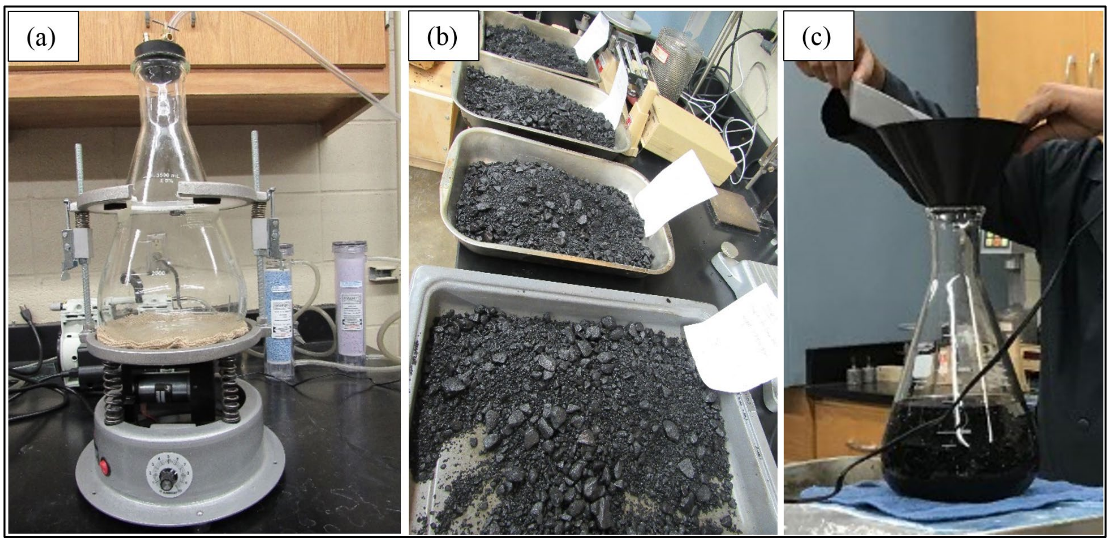


Figure 3.16 Theoretical Maximum Specific Gravity Test (a) Test Setup; (b) Preparing Loose Mix Samples; (c) Placing the Loose Mix in the Pycnometer

3.3.2 Bulk Specific Gravity (Gmb) of Compacted Asphalt Samples

Bulk specific gravity on compacted asphalt samples was conducted in accordance with AASHTO T 166 (AASHTO, 2016). The bulk specific gravity (G_{mb}) value of each sample was determined to calculate their air voids. The G_{mb} test was carried as follows:

1. The dry weight of the sample in the air was recorded.
2. The submerged weight of the sample was recorded after submerging it in the water tank for four minutes (Figure 3.17).
3. The sample was removed from water, and within 30 seconds its surface was saturated surface-dried (SSD) using a wet towel its SSD weight in the air was recorded.
4. The bulk specific gravity (G_{mb}) value was calculated using Equation 2.

$$G_{mb} = A / (B - C) \quad (2)$$

where,

A = mass of the dry specimen in the air (g);
B = mass of the saturated surface-dry specimen in the air (g); and
C = mass of the specimen in water, g.

Percentage air voids (AV%) for each specimen was calculated from Equation 3.

$$AV\ (\%) = (G_{mm} - G_{mb}) \times 100 / G_{mm} \quad (3)$$

Figure 3.17 Volumetric Bench Setup

3.3.3 Tensile Strength Ratio (TSR) Test

The TSR tests were conducted on the compacted asphalt samples in accordance with the AASHTO T 283 (AASHTO, 2010) standard method using an MTS loading frame (Figure 3.18). The test specimens had a diameter of 150 mm and a height of 95 mm with air voids of 7.0% ± 0.5%. The test was carried out at room temperature (25ºC) by applying a monotonical load with a rate of 50 mm/min. The load was applied along the diameter of the specimen using an indirect tension jig mounted in the loading frame. Loading was continued until sample's failure where the load starts to decline (Figure 3.19). The failure surfaces were photographed for visual rating of the unconditioned and moisture-conditioned samples. The tensile strengths of the moisture-conditioned samples and those of unconditioned samples obtained after testing were used to calculate the tensile strength ratio. Calculation of the tensile strength of the samples is discussed in section 3.3.5.

Figure 3.18 Conducting the TSR Test Using MTS Loading Frame

Figure 3.19 TSR Sample after Failure

3.3.4 Indirect Tension Strength

The IDT test was conducted on the TSR samples and the tensile strength of each sample was measured. Tensile strength of each specimen was calculated after measuring the peak load at failure using Equation 4, as specified in AASHTO T 283 standard method (AASHTO, 2010).

$$S_t = (2000\,P)/(\pi\,t\,D) \quad (4)$$

where,

S_t = tensile stress (kPa);
P = maximum load at failure (N);
t = specimen thickness (mm); and
D = specimen diameter (mm).

Additionally, the axial force with axial displacement obtained from the IDT test was plotted and used to calculate the strain energy at failure, toughness index, and fatigue index to analyze the fracture properties of the asphalt mixes (Barman et al., 2018). The indirect tensile stress values were normalized by dividing them to indirect tensile strength (ITS) value, and deformation values were normalized by dividing them to diameter of the specimen (Figure 3.20). The difference in area up to normalized tensile strength with area at terminal strain of 3% was divided by the corresponding difference in the strains to obtain toughness index (Barman et al., 2018). Fatigue index was calculated by dividing the strain energy at failure by the slope of the line connecting the various toughness values at corresponding strains of 3%, 6%, 9%, and 12% (Barman et al., 2018) (Figure 3.20).

Strain energy was determined by calculating the area under the load-deformation plot obtained from IDT test data. Strain energy represents the energy absorbed by the material before the peak load. The toughness index represents the behavior after attaining the peak load. According to Barman et al. (2018) fatigue index represents property of the asphalt mixes before and after peak load, representing both strain energy and toughness index.

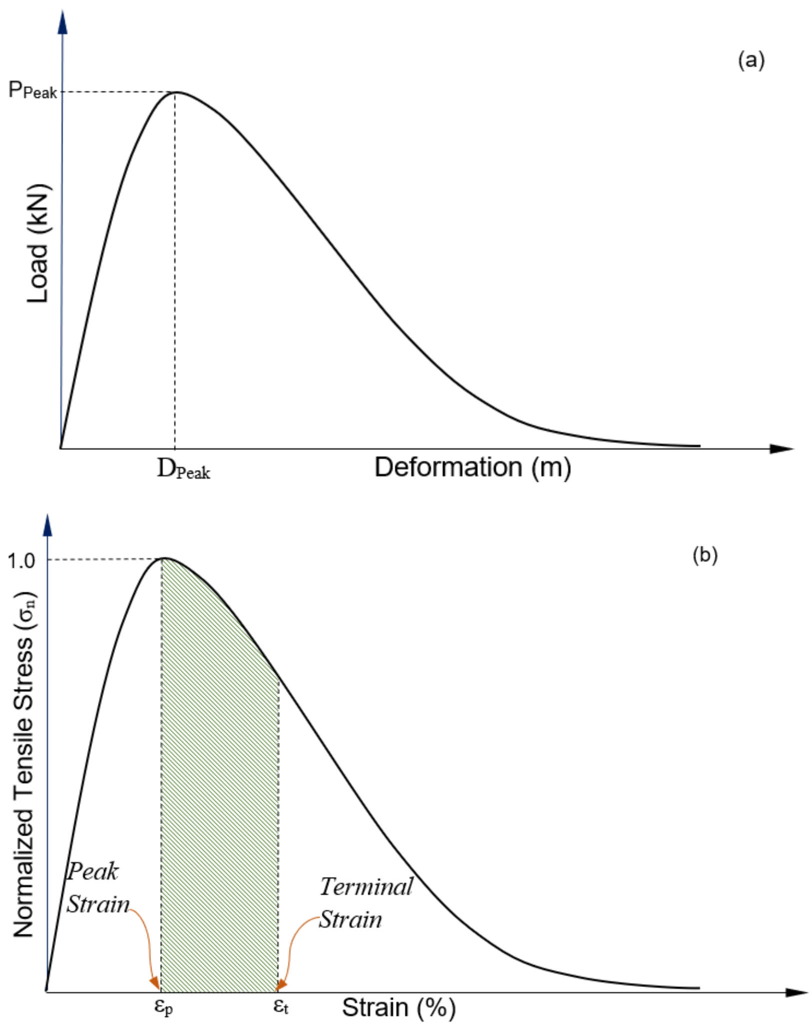


Figure 3.20 (a) Typical Load - Deformation in IDT Test (b) Typical Normalized Stress – Strain Plot

Strain energy at failure was calculated by trapezoidal method of area calculation using Equation 5 (Barman et al., 2018). Toughness index and fatigue index were calculated using Equations 6 and 7, respectively (Barman et al., 2018).

$$\text{Strain energy, U} = \sum_{j=1}^{j=n}(u_{j+1} - u_j) \times \frac{1}{2}\ (P_{j+1} + P_j) \quad (5)$$

where,

P_j = applied load (kN) at the j load step application;
P_{j+1} = applied load (kN) at the j+1 load step application;
u_j = displacement (m) at the j step; and
u_{j+1} = displacement (m) at j+1 step.

$$\text{Toughness Index, TI} = \frac{(A\varepsilon - Ap)}{(\varepsilon - \varepsilon p)} \quad (6)$$

where,

A_ε = area under normalized tensile stress-strain (%) curve up to 3% terminal strain;
ε = terminal strain (%);
A_p = area under normalized tensile stress-strain (%) curve up to strain at peak stress (εp); and
ε_p = terminal strain (%)

$$\text{Fatigue Index (FI)} = (dTI/d\varepsilon)/U \quad (7)$$

where,

U = Strain energy at failure (kN-m)

3.3.5 Semicircular Bend (SCB) Test

The SCB test was conducted at 25°C on the laboratory-compacted specimens using an asphalt standard tester (AST) in accordance with ASTM D8044-16 (ASTM, 2016) standard method. The semicircular specimens (dry and moisture-conditioned) having notch depths of 25.4 mm, 31.8 mm, and 38.1 mm were prepared and tested. The specimens were tested at a constant monotonic load application rate of 0.5 mm/min (Figure 3.21) as specified in ASTM D8044-16 (ASTM, 2016). The load was applied along the direction of the notch to allow propagation of the cracks along the notch. Figure 3.22 shows a SCB specimen after testing. Before testing, the actual dimensions of the specimen were measured and entered in the testing procedure program and later used for calculation of the average sample thickness. After conducting the test, the load and deformation data were exported as an MS-Excel file and were used to further analyze the test results and calculate the critical strain energy release rate, J-integral (ASTM, 2016). A typical load-deformation output data obtained by conducting the SCB test on samples having different notch depths is shown in Figure 3.23. The area of the load-deformation curve up to peak load was used to calculate total strain energy (U) at failure (Figure 3.24). Trapezoidal method for discrete integration was applied to obtain total strain energy through calculation of the area under the load-deformation curve up to failure, using Equation 8 (ASTM, 2016).

$$U = \sum_{j=1}^{j=n}(u_{j+1} - u_j) \times P_j + \frac{1}{2} \times (u_{j+1} - u_j) \times (P_{j+1} - P_j) \quad (8)$$

P_j = applied load (kN) at the j load step application;
P_{j+1} = applied load (kN) at the j+1 load step application;
u_j = displacement (m) at the j step; and
u_{j+1} = displacement (m) at j+1 step.

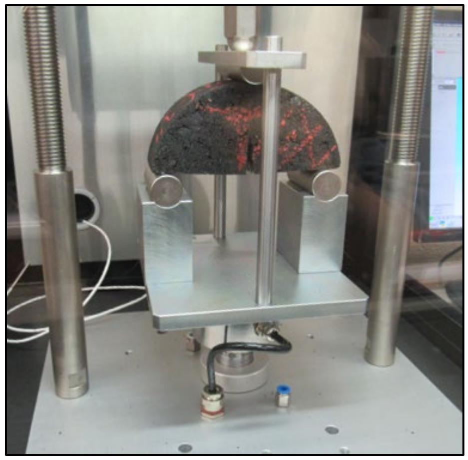


Figure 3.21 Semicircular Bend (SCB) In Progress

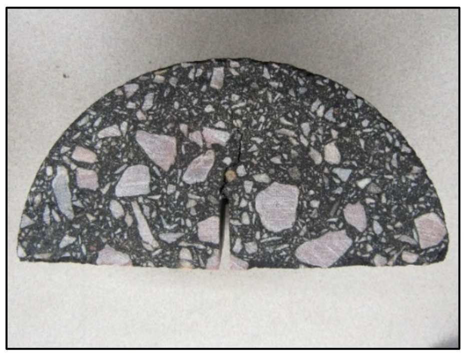


Figure 3.22 SCB Specimen after Testing

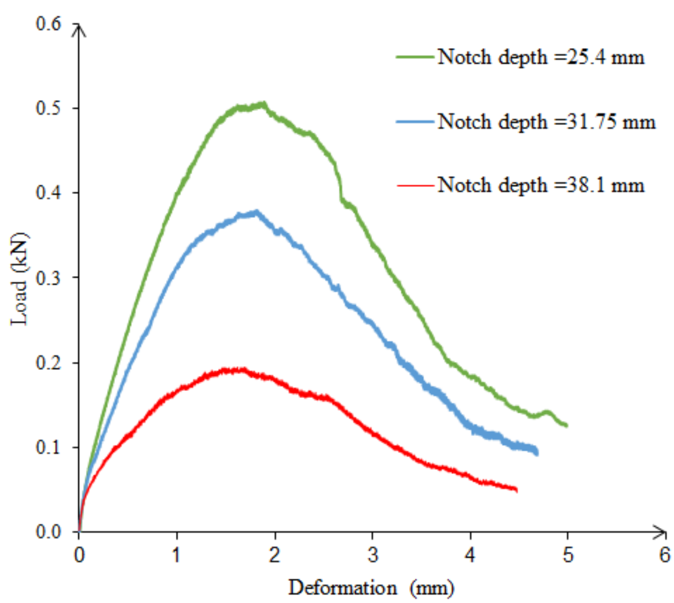


Figure 3.23 Typical SCB Load Deformation for Samples with Different Notch Depths

The slope of the linear regression (dU/da) developed between the average strain energy at failure and notch depths was divided by average thickness of the specimens to calculate the critical strain energy release rate (J_c). Critical strain energy release rate (J_c) was calculated using Equation 9 (ASTM, 2016).

$$J_c = \frac{-1}{b}(dU/da) \quad (9)$$

where,

J_c = critical strain energy release rate (kJ/m^2);
b = sample thickness (m);
a = notch depth (m);
U = strain energy to failure (kJ); and
dU/da = change of strain energy with notch depth.

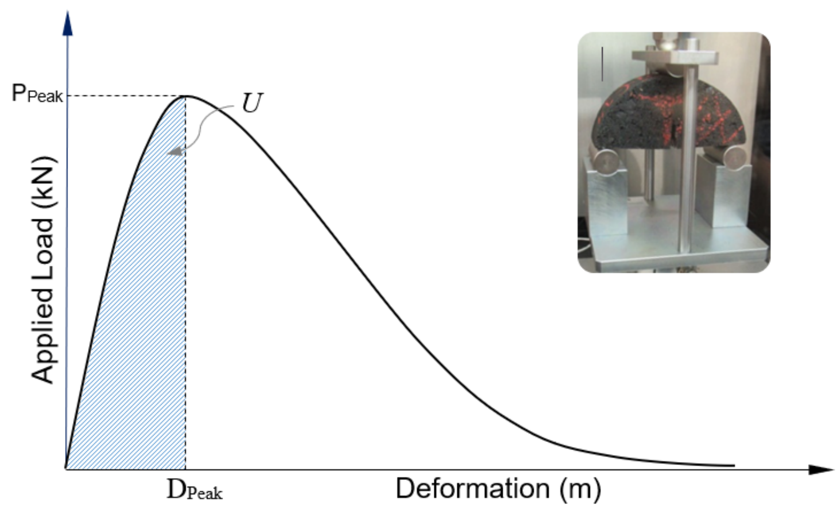


Figure 3.24 Typical Load and Deformation and Area Representing the Strain Energy up to Failure

3.3.6 Binder Bond Strength (BBS) Test

The BBS tests were carried out using a pneumatic adhesion tensile testing instrument (PATTI) on various aggregate-asphalt binder samples to measure their pull-off strengths (Figure 3.25). PATTI setup consisted of pull stub, piston, and compressed air supply (Figure 3.25). Figure 3.26 shows a pull stub attached to an aggregate sample by a thin layer of asphalt binder. Before testing, the dry samples temperature-controlled environmental chamber was utilized to maintain the temperature at 25°C (Figure 3.27). The temperature was found to be one of the major factors affecting the measured pull-off strength.

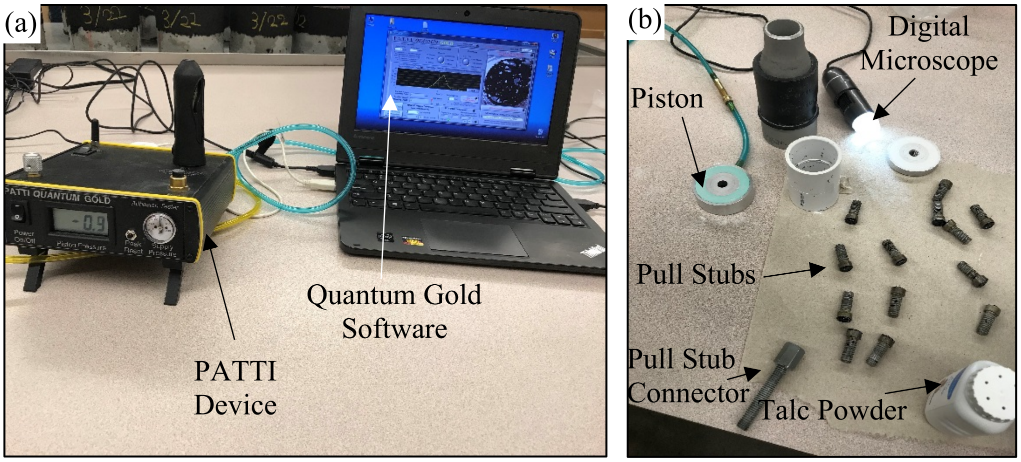


Figure 3.25 Components of PATTI used for conducting BBS Tests(a) PATTI Device and Quantum Gold Software; (b) F-2 Piston, Talc Powder, Digital Microscope, Pull Stubs, and Connector

After temperature-conditioning was complete, testing of the dry samples was conducted (Figure 3.28). Another set of samples kept in the water for moisture-conditioning (Figure 3.29), as described in section 3.2.3, were tested while kept in the water (Figure 3.30). Tensile strength obtained from the PATTI quantum gold software was used for analysis. Failure occurred when the applied stress exceeded the pull-off strength of the asphalt binder-aggregate. The tensile stress and time data were obtained by exporting the recorded data as a text file.

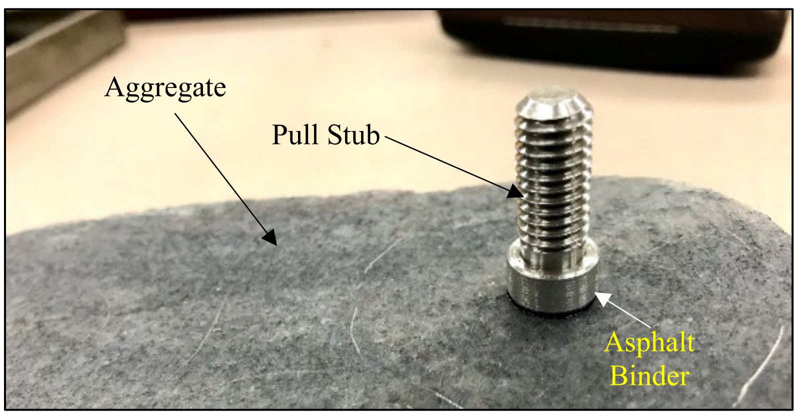


Figure 3.26 Typical BBS Sample


Figure 3.27 Dry BBS Samples Inside an Environmental Chamber at 25°C

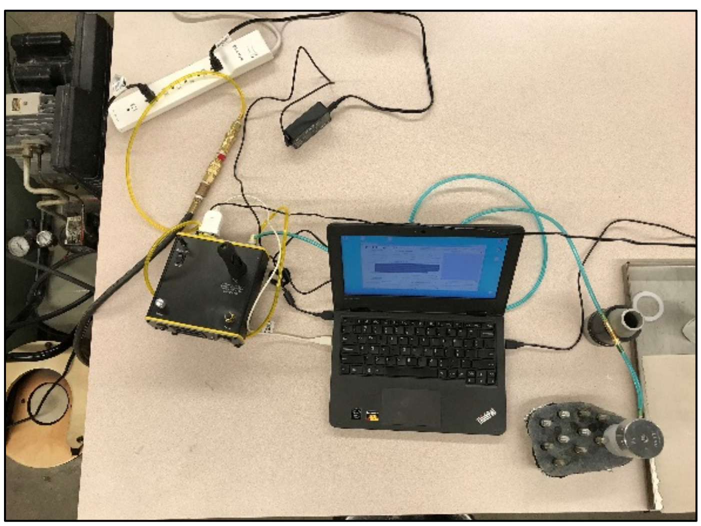


Figure 3.28 Binder Bond Strength Test Setup of Dry Asphalt Binder-Aggregate Sample

Figure 3.29 Moisture Conditioning of BBS Samples

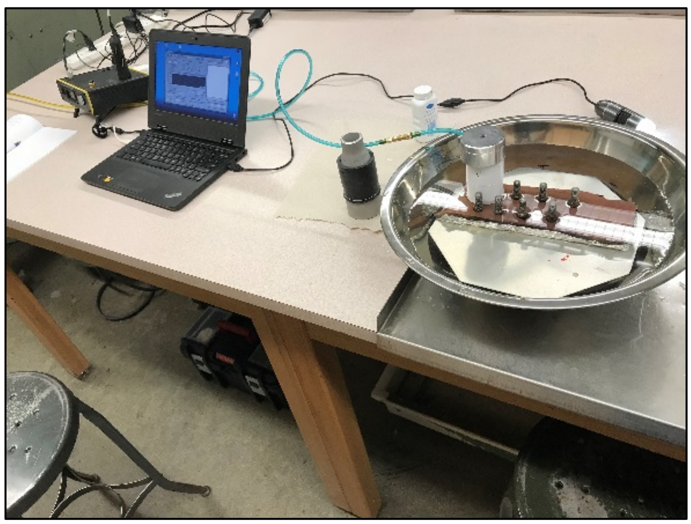


Figure 3.30 BBS Test Setup Used for Testing Moisture-Conditioned Samples

4. RESULTS AND DISCUSSIONS

4.1 Asphalt Mix Testing

The result of testing asphalt mixes by conducting volumetric tests, and TSR, IDT, and SCB tests, are presented in discussed in this section.

4.1.1 Volumetric Tests

Volumetric tests, namely the theoretical maximum specific gravity and bulk specific gravity. were conducted on loose mix and compacted asphalt samples in accordance with AASHTO T 209-10 (AASHTO, 2013b) and AASHTO T 166 (AASHTO, 2016), respectively. The results of the volumetric tests were used to determine the air voids in compacted specimens. To simulate the compaction conditions in the field, air voids of the compacted specimens for performance testing were maintained at 7.0% ± 0.5% (AASHTO, 2010). The maximum theoretical specific gravity values for asphalt mixes, along with the bulk specific gravity, and the air voids calculated for SCB and TSR test specimens are tabulated and presented in APPENDIX A.

4.1.2 Performance Tests

Result and discussions of TSR/IDT, SCB, and BBS tests are analyzed and presented in this section.

4.1.2.1 Tensile Strength Ratio Test (TSR)

Tensile strength and TSR values of the HMA-Lime, HMA-RAP, and C-WMA are presented numerically and graphically in Table 4.1 and Figure 4.1, respectively.

Table 4.1 Summary of The Tensile Strength Ratio (TSR) Test Result

Asphalt Mix	**HMA-Lime**		**HMA-RAP**		**C-WMA**	
Performance Grade	PG 64-34		PG 58-28		PG 64-34	
Aggregates	Quartzite		Quartzite, Gravel		Granite, Gravel	
NMAS	12.5 mm		12.5 mm		12.5 mm	
Moisture Condition	Unconditioned	Moisture-conditioned	Unconditioned	Moisture-conditioned	Unconditioned	Moisture-conditioned
Average Tensile Strength (kPa)	915.4	1226.4	858.7	704.9	662.9	631.3
Standard Deviation (kPa)	124.8	70.0	110.4	108.7	36.8	54.5
Coeffiecient of Variation (%)	13.6	5.7	12.9	15.4	5.6	8.6
Tensile Strength Ratio (TSR)	1.34		0.82		0.95	
Remark	> 0.8		> 0.8		> 0.8	
Visual Rating	1		1		1	

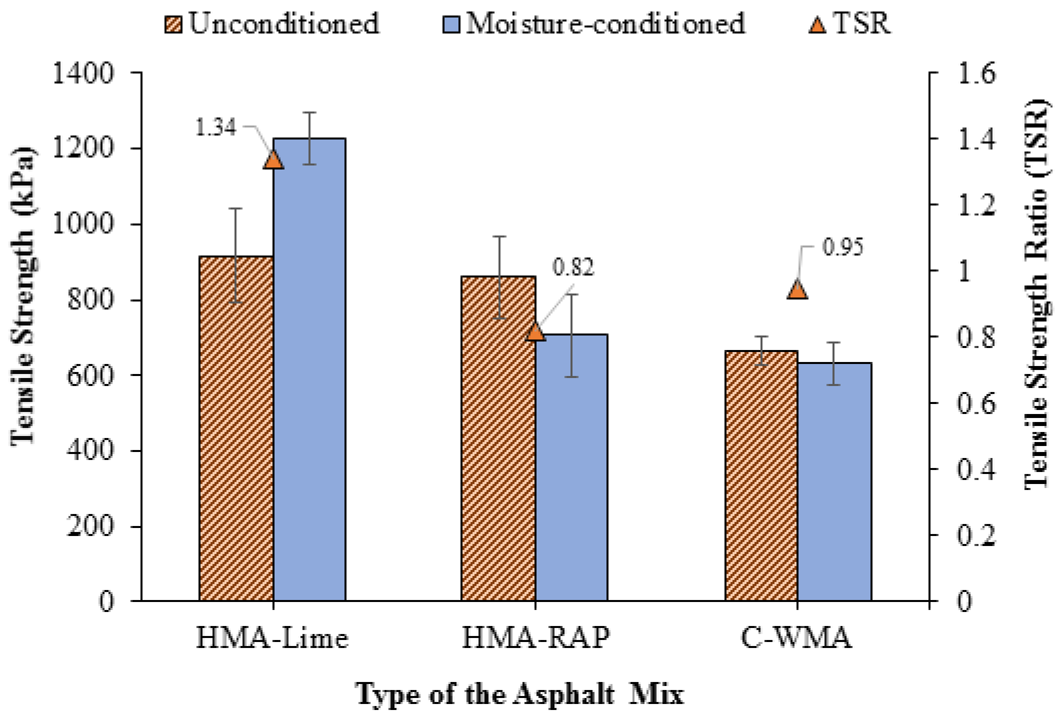


Figure 4.1 Dry and Moisture-Conditioned Samples' Tensile Strengths and TSR Values

The TSR values were determined from the average tensile strength values measured for dry and moisture-conditioned subsets. A minimum TSR value requirement of 0.8 is set by AASHTO Superpave® mix design specification (AASHTO, 2012) to minimize moisture-induced damage potential for asphalt mixes. From Table 4.1 and Figure 4.1, it is evident that the average tensile strength values of the HMA mix containing 1% hydrated lime (HMA-Lime), HMA mix containing 20% RAP (HMA-RAP), and asphalt mix containing 0.5% chemical WMA additive (C-WMA) in dry condition were found to be 915.4, 858.7, and 662.9 kPa, respectively. The tensile strength values of the HMA-Lime, HMA-RAP, and C-WMA were found to become 1226.4, 704.9, and 631.3 kPa, respectively, after moisture conditioning. To statistically verify the significance of the differences between the tensile strength values measured in dry and moisture-conditioned samples, a two tailed t-test ($\alpha = 0.05$) was conducted. The differences between the tensile strength of dry and moisture-conditioned samples were statistically significant ($\alpha = 0.05$) in HMA-Lime. However, no significant differences were observed between the tensile strength of dry and moisture-conditioned samples in the HMA-RAP and C-WMA mixes. The TSR values calculated for each mix indicated the extent of the moisture-induced damage observed as loss of tensile strengths. Also, from Table 4.1 and Figure 4.1 the TSR values of the HMA-Lime, HMA-RAP and C-WMA were 1.34, 0.82, and 0.85, respectively. The TSR values for all the tested mixes were greater than 0.8, indicating their satisfactory resistance to moisture-induced damage according to the mix design requirements. An important observation is that the HMA-Lime has gained 34% more tensile strength after moisture-conditioning. This could be due to the fact that lime has reacted with the water and other minerals and developed a cementitious compound as a result of hydration, leading to an improved tensile strength. Also, a high TSR value observed for C-WMA mix (0.95) indicates a significant resistance to moisture-induced damage. This could be attributed to the amine-based WMA additive used in this mix, which acted as an ASA and improved the adhesion between asphalt binder and aggregates. Finally, the HMA-RAP with a TSR value of 0.82 had an acceptable resistance to moisture-induced damage (TSR>0.8). Photographic views of the failure surfaces after conducting the TSR tests on HMA-Lime, HMA-RAP, and C-WMA mixes are presented in Figures 4.2, 4.3, and 4.4, respectively. Visual ratings of 1 in accordance with AASHTO T 283 (AASHTO, 2010) specification were assigned to each mix. This rating indicates minor visible stripping damage due to moisture. In visual rating, very few aggregates were found to be exposed in moisture-conditioned samples and in the dry samples, most of the aggregates were found to be broken. Mostly cohesive and minimum adhesive failures were observed in failure surfaces.

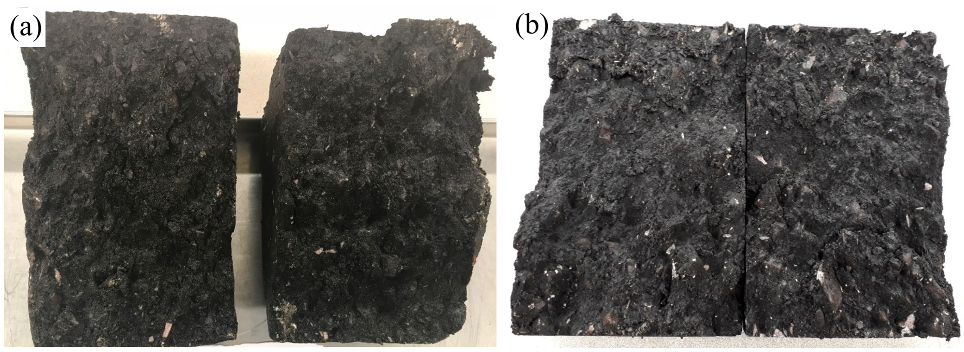


Figure 4.2 Photographic Views of the Failure Surfaces Observed in HMA-Lime Mix After Conducting TSR Tests on (a) Dry Samples; and (b) Moisture-Conditioned Samples

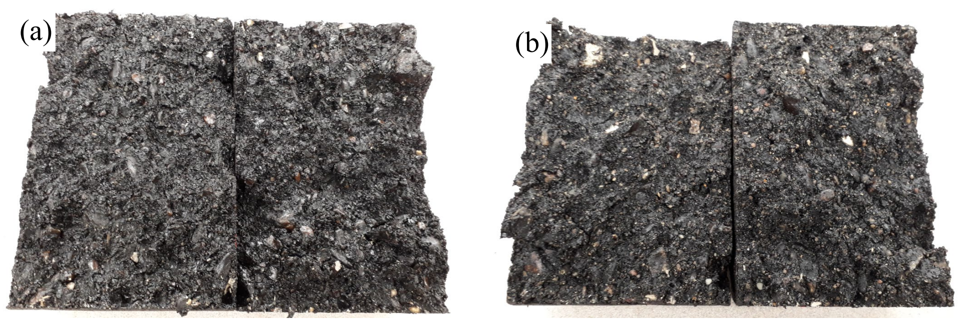


Figure 4.3 Photographic Views of the Failure Surfaces Observed in HMA-RAP Mix After Conducting TSR Tests on (a) Dry Samples; and (b) Moisture-Conditioned Samples

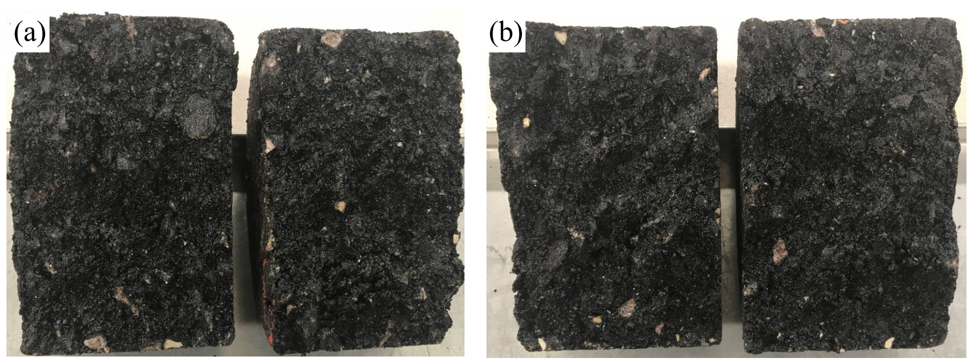


Figure 4.4 Photographic Views of the Failure Surfaces Observed in C-WMA Mix After Conducting TSR Tests on (a) Dry Samples; and (b) Moisture-Conditioned Samples

4.1.2.2 Indirect Tensile Test (IDT) Result

A typical plot of load-deformation obtained from conducting the indirect tension tests (IDT) on asphalt samples is shown in Figure 4.5. The load-deformation data obtained from conducting the indirect tension tests (IDT) were utilized to determine important fracture energy parameters, namely toughness index (TI), fatigue index (FI), toughness index ratio (TIR), and fatigue index ratio (FIR) by following the procedure presented by (Barman et al., 2018). These parameters were determined for moisture-conditioned and unconditioned samples to evaluate their moisture-induced damage potentials

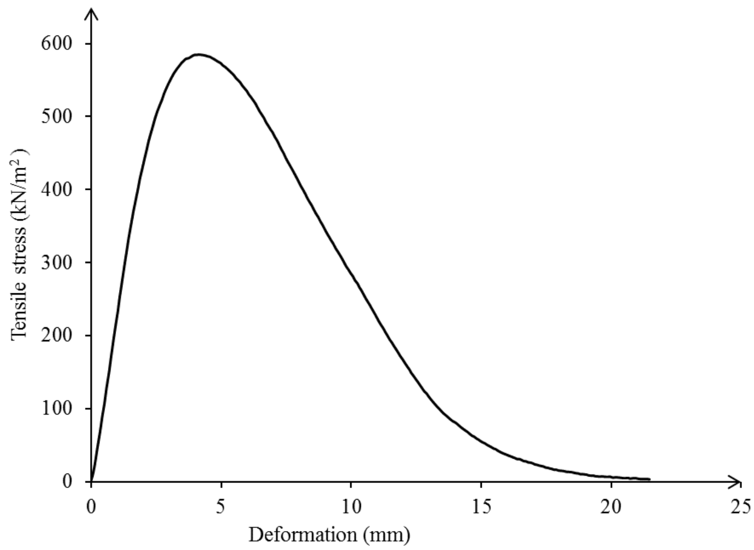


Figure 4.5 Typical Tensile Stress-Deformation Plot Obtained from Conducting IDT Test

The FI, TI, FIR, and TIR values calculated for the mixes are presented in Table 4.2 and graphically summarized in Figures 4.6 and 4.7. Higher toughness and fatigue indices represent higher resistance to fracture and higher fatigue resistance, respectively (Barman et al., 2018).

Table 4.2 Summary of Indirect Tension Test (IDT) Results

Mix type	Moisture Condition	Toughness Index: Terminal Strain (%) (ε)	Toughness Index: Average Toughness Index (TI)	Toughness Index: Standard Deviation	Slope (dTI/dε)	Average Strain Energy at Failure (kN-m)	Fatigue Index (kN-m)	Toughness Index Ratio (TIR)	Fatigue Index Ratio (FIR)
HMA-Lime	Unconditioned	3	0.89	0.02	-0.08	0.040	0.52	0.90	1.27
		6	0.42						
		9	0.24						
		12	0.16						
	Moisture-conditioned	3	0.80	0.08	-0.07	0.047	0.66		
		6	0.30						
		9	0.18						
		12	0.12						
HMA-RAP	Unconditioned	3	0.91	0.01	-0.08	0.039	0.50	1.01	1.23
		6	0.49						
		9	0.29						
		12	0.21						
	Moisture-conditioned	3	0.92	0.03	-0.07	0.045	0.62		
		6	0.69						
		9	0.41						
		12	0.29						
C-WMA	Unconditioned	3	0.91	0.08	-0.07	0.039	0.59	1.02	1.02
		6	0.75						
		9	0.48						
		12	0.33						
	Moisture-conditioned	3	0.93	0.05	-0.06	0.038	0.60		
		6	0.80						
		9	0.54						
		12	0.37						

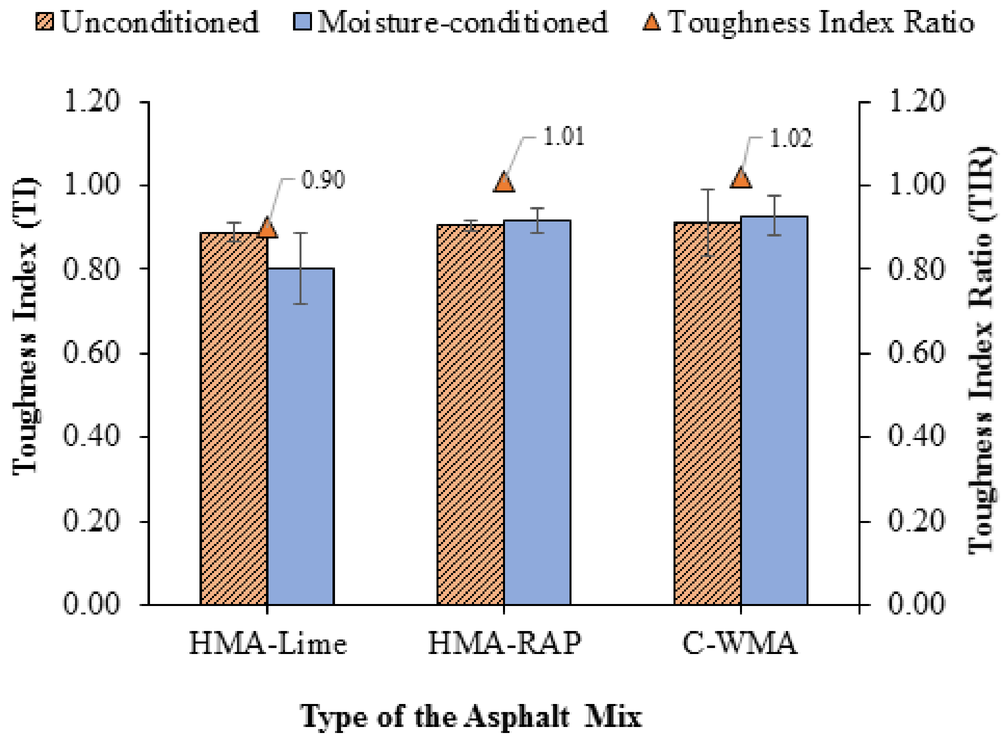


Figure 4.6 Toughness Indices and Toughness Inded Ratios Determined for Different Mixes

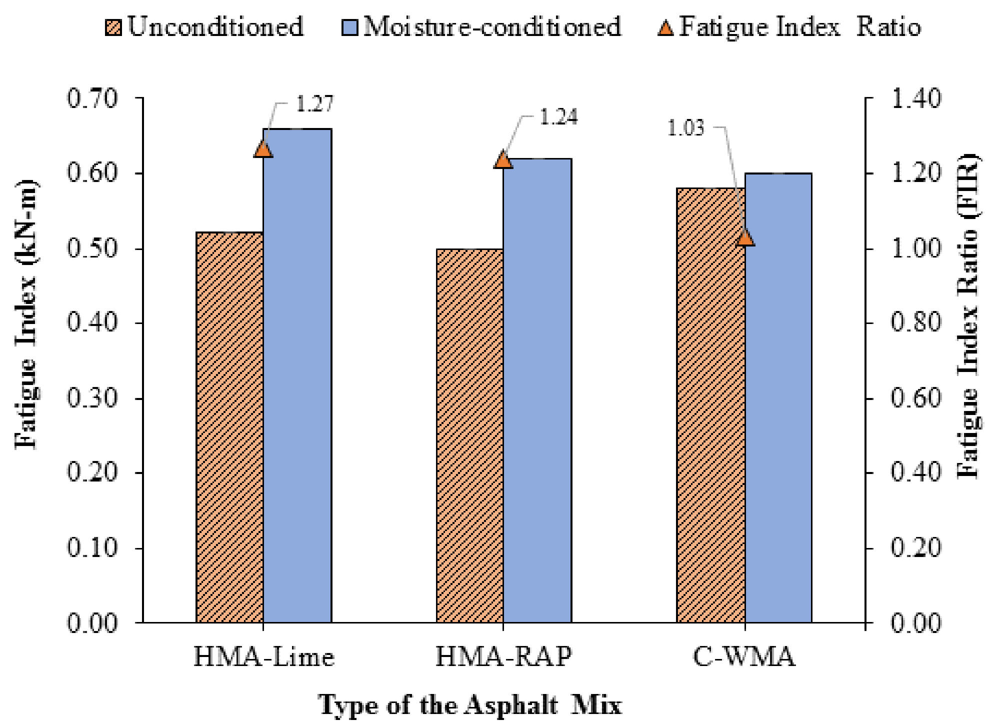


Figure 4.7 Fatigue Indices and Fatigue Index Ratios Determined for Different Mixes

As it is evident from Table 4.2, TI, TIR, FI, and FIR values were determined for unconditioned and moisture-conditioned samples to determine the effect of the moisture on different fracture parameters. It is important to note that the toughness indices were determined at a terminal strain of 3%.

From Figure 4.6 and Table 4.2, it can be observed that the toughness indices for unconditioned and moisture-conditioned specimens of all three mixes were relatively close. For example, the toughness indices (TIs) for HMA-Lime in unconditioned and moisture-conditioned states were 0.89 and 0.80, respectively, yielding a toughness index ratio (TIR) of 0.90. In other words, the strain energy absorption of the HMA mix containing hydrated lime decreased by 10% after moisture conditioning. The TI values for HMA-RAP in unconditioned and moisture-conditioned states were 0.91 and 0.92, respectively, yielding a TIR of 1.01. It is to say that, the strain energy absorption of the HMA mix containing 20% RAP remained almost unchanged after moisture conditioning. Finally, the TI values for C-WMA in unconditioned and moisture-conditioned states were 0.91 and 0.93, respectively, a TIR of 1.02. This means that, the strain energy absorption of the mix containing a chemical WMA additive remained almost unchanged after moisture conditioning. These findings are consistent with those obtained from TSR tests, suggesting high resistance of these mixes to moisture-induced damage. To statistically determine significance of the differences between the TI values in unconditioned and moisture-conditioned samples, a two tailed t-test ($\alpha = 0.05$) was conducted. The difference between the toughness index of unconditioned and moisture-conditioned samples was statistically significant ($\alpha = 0.05$) only in HMA-Lime. However, no significant difference was observed between the toughness index of unconditioned and moisture-conditioned samples of the HMA-RAP, and C-WMA mixes.

Fatigue index (FI) and the fatigue index ratio (FIR) are two other parameters obtained by analyzing the IDT test results. From Table 4.2 and Figure 4.7, it is evident that the FI values for HMA-Lime in unconditioned and moisture-conditioned states were 0.52 and 0.66, respectively, yielding an FIR value of 1.27. The FI value of the HMA mix containing 1% hydrated lime increased by 27% after moisture-conditioning. Also, the FI values for unconditioned and moisture-conditioned samples of the HMA-RAP were found to be 0.50 and 0.62, respectively, resulting in a FIR value of 1.23. The fatigue index of the HMA mix containing 20% RAP increased by 23% after moisture-conditioning. Finally, the FI values for C-WMA in unconditioned and moisture-conditioned states were found to be 0.59 and 0.60, respectively, a FIR value of 1.02. It means that, the fatigue index of the mix containing 0.5% of a chemical WMA additive remained almost unchanged after moisture-conditioning. These results, although indicate a resistance of the asphalt mixes to moisture-induced damage they are not ranking the mixes in the same order as the TSR test ranked them.

4.1.2.3 Semi-Circular Bend (SCB) Test Results

The SCB tests were conducted on asphalt mixes to obtain and compare their cracking resistance through determining the critical strain energy release rate (J_c) for each mix. According to ASTM D8044-16 standard test method (ASTM, 2016) , the J_c values of 0.5 kJ/m^2 to 0.6 kJ/m^2 are typically recommended for asphalt mixes having an acceptable resistance to cracking. Therefore, a higher strain energy release rate is desirable for an asphalt mix to exhibit a better resistance to cracking. Table 4.3 and Figure 4.8 present the critical strain energy release rate (J_c) values calculated for the HMA-Lime, HMA-RAP and C-WMA mixes in unconditioned and moisture-conditioned states and their ratios, in numerical and graphical formats, respectively. Variation of strain energy with notch depth (dU/da) utilized in calculation of the J_c values for tested mixes are presented in APPENDIX B.

Table 4.3 Critical strain energy release rate (J_c) and J_c ratio values from SCB test

Asphalt Mix	HMA-Lime		HMA-RAP		C-WMA	
Bindder Type	PG 64-22		PG 58-28		PG 64-34	
Additive	Lime (1%)		RAP (20%)		WMA add.	
NMAS	12.5 mm		12.5 mm		12.5 mm	
Moisture Conditioning	No	Yes	No	Yes	No	Yes
J_c (KJ/m2)	0.29	0.32	0.48	0.85	0.59	0.68
ERR	1.10		1.77		1.15	

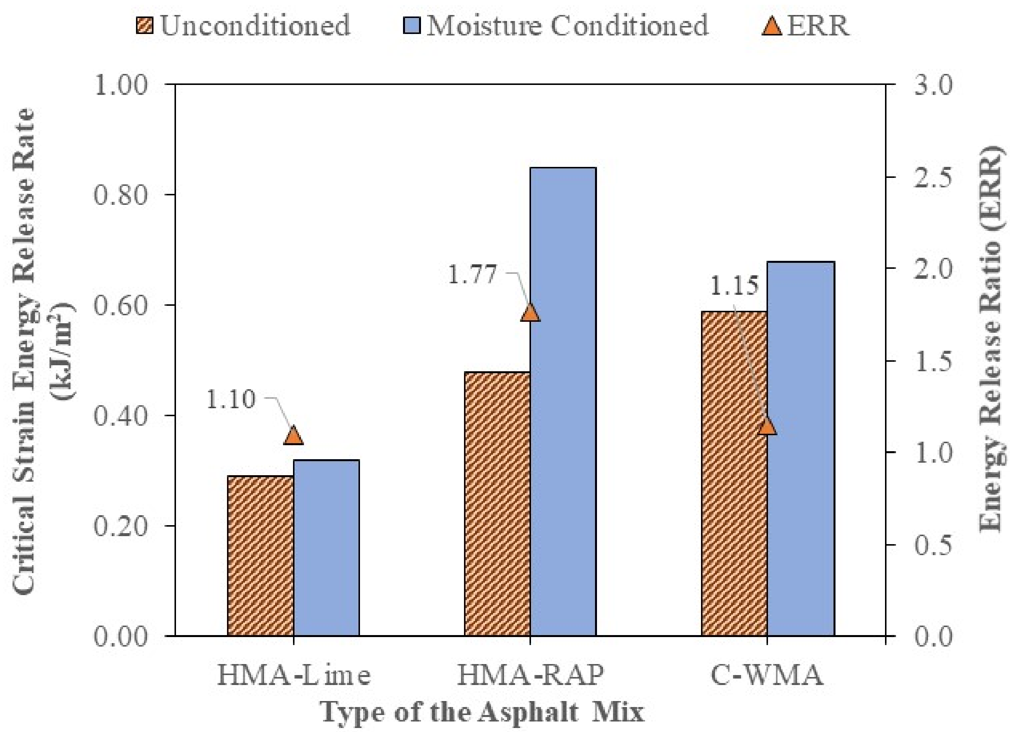


Figure 4.8 Strain Energy Release Rate and ERR values for Different Asphalt Mixes

From Table 4.3 and Figure 4.8, it is evident that critical strain energy release rate of the HMA-Lime increased by 10% after moisture conditioning, yielding an energy release ratio (ERR) of 1.10. Strain energy absorption of the HMA-Lime mix increased after moisture-conditioning, leading to a higher cracking resistance possibly due to reaction between hydrated lime, water and the minerals. In other studies, incorporation of hydrated lime in asphalt mixes improved cracking resistance (Abuawad et al., 2015). However, J_c value of HMA-Lime in the unconditioned and moisture-conditioned samples were found to be 0.29 kJ/m^2, and 0.32 kJ/m^2, respectively, less than the minimum J_c required value of 0.5 kJ/m^2 (ASTM, 2016). Also, from Table 4.3 and Figure 4.8, the ERR value of the HMA-RAP mix was 1.77 with critical strain energy release rate of 0.48 kJ/m^2, and 0.85 kJ/m^2 for unconditioned and moisture-conditioned samples, respectively. Strain energy absorption was found to increase by 77%, which in unlikely. It can be said that cracking resistance of the HMA-RAP was not decreased after moisture conditioning. The critical strain energy release rate of HMA-RAP, after moisture-conditioning met the minimum J_c value requirement of 0.5 kJ/m^2 set by the ASTM D8044 (ASTM, 2016). In a different study, addition of RAP increased the resistance of the asphalt mixes to moisture-induced damage (Ghabchi et al., 2014). However, some other studies have found that inclusion of RAP in mixes can decrease the resistance of mixes to moisture-induced damage (Fakhri et al., 2017a). Finally, the J_c value for C-WMA in unconditioned and moisture-conditioned states were 0.59, and 0.68 respectively, an ERR value of 1.15. This means that the strain energy absorption of the mix containing chemical WMA additive increased by 15% after moisture conditioning. The C-WMA mix passed the minimum J_c requirement set by ASTM D8044 (ASTM, 2016). Visual inspection of the SCB samples after testing revealed that very few aggregates were exposed, an indication of minimum moisture-induced damage. Figures 4.9, 4.10, and 4.11 show selected number of failure surfaces observed for HMA-Lime, HMA-RAP and C-WMa, respectively.

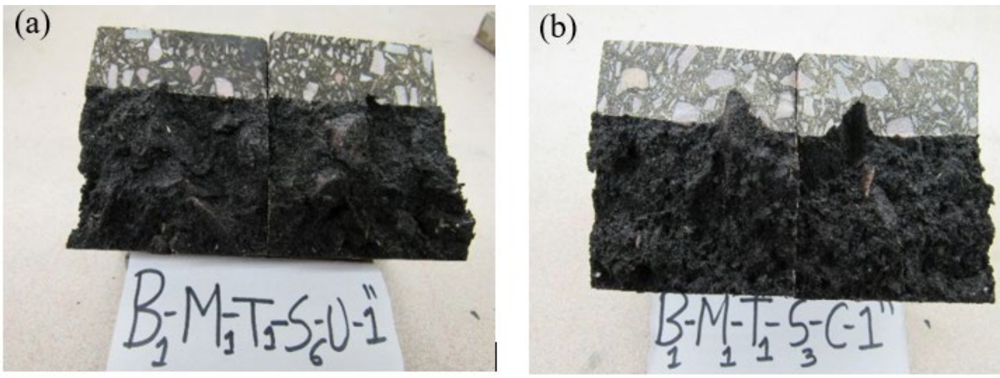


Figure 4.9 Photographic Views of the Failure Planes Observed in HMA-Lime after SCB test (a) Unconditioned Specimen; and (b) Moisture-Conditioned Specimen

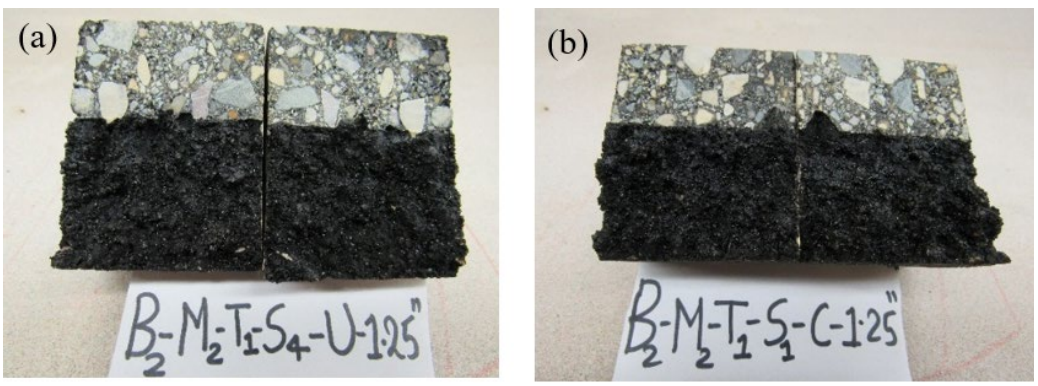


Figure 4.10 Photographic Views of the Failure Planes Observed in HMA-RAP after SCB test (a) Unconditioned Specimen; and (b) Moisture-Conditioned Specimen

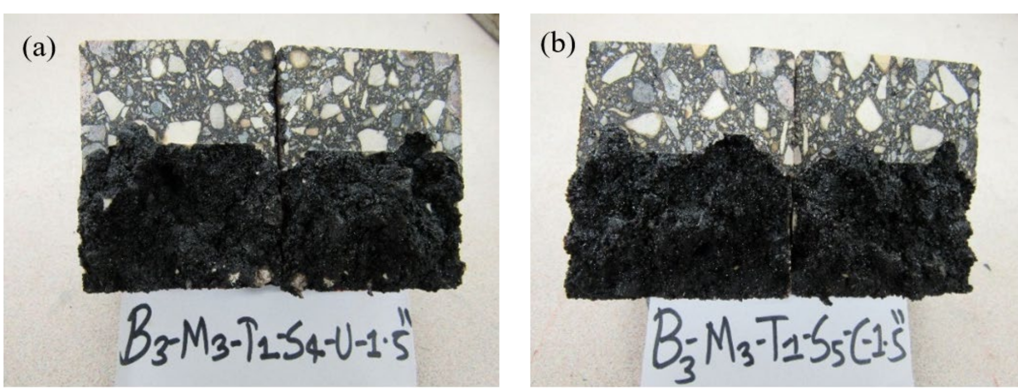


Figure 4.11 Photographic Views of the Failure Planes Observed in C-WMA after SCB test (a) Unconditioned Specimen; and (b) Moisture-Conditioned Specimen

A relative comparison between the tensile strength (ITS), fatigue index (FI), toughness index (TI), and critical strain energy release rate (J_c) was made by developing linear correlations between the TSR, ERR, FIR, and TIR values as shown in Figure 4.12. Also, the coefficient of determination (R^2) for each model is displayed. A higher R^2 value suggests a better correlation between each pair of the parameters. From Figure 4.12 it is evident that only the TSR and TIR have a strong correlation.

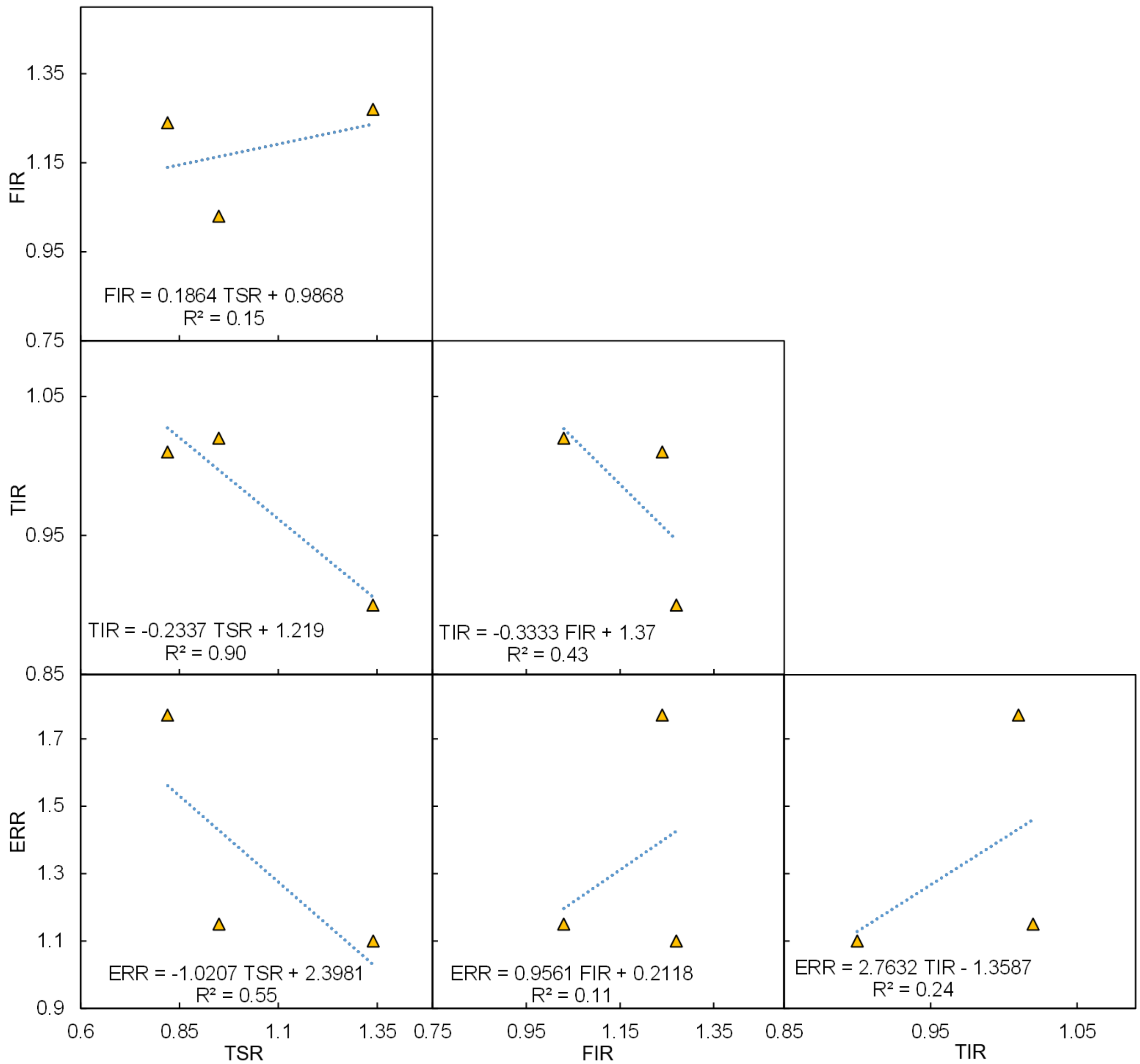


Figure 4.12 Linear Regression Models for TSR, FIR, TIR, and ERR and Their Coefficients of Determination

4.2 Asphalt Binder-Aggregate Testing

4.2.1 Binder Bond Strength (BBS) Test Results

The BBS tests were conducted on asphalt binder-aggregate samples consisting of four4 types of asphalt binders — PG 58-28, PG 64-22, PG 64-34, and PG 70-28 — and three types of aggregates — Granite-II, Quartzite, and Granite-I. The BBS tests were conducted on moisture-conditioned and unconditioned samples.

4.2.1.1 Moisture-Induced Damage Evaluation in Granite-II Aggregate with PG 58-28 Binder

Figure 4.13 and Table 4.4 present a summary of the pull-off strength (POS) values obtained by conducting BBS tests on Granite-II samples prepared with asphalt binders (PG 58-28, PG 64-22, PG 64-34, and PG 70-28) without any additives and those blended with 20% S-RAP, 0.5% WMA additive, and 0.5% ASA with and without moisture conditioning. Also, the pull-off strength ratios (PSR) calculated by dividing the POS values of moisture-conditioned samples to those of dry ones are presented in Table 4.4 and Figure 4.13. In addition, the failure modes, namely adhesive and cohesive, and the standard deviation (SD) and coefficient of variation (COV) values for BBS tests are presented in Table 4.4. Statistical analysis was conducted using two-tailed t-test to examine the statistical significance of the difference between the average POS values with 95% confidence interval. Figure 4.14 shows the examples of failure mode determination. A summary of the statistical analysis for determination of significance of difference between the average pull-off strength values at 95 % confidence interval is presented in APPENDIX C.

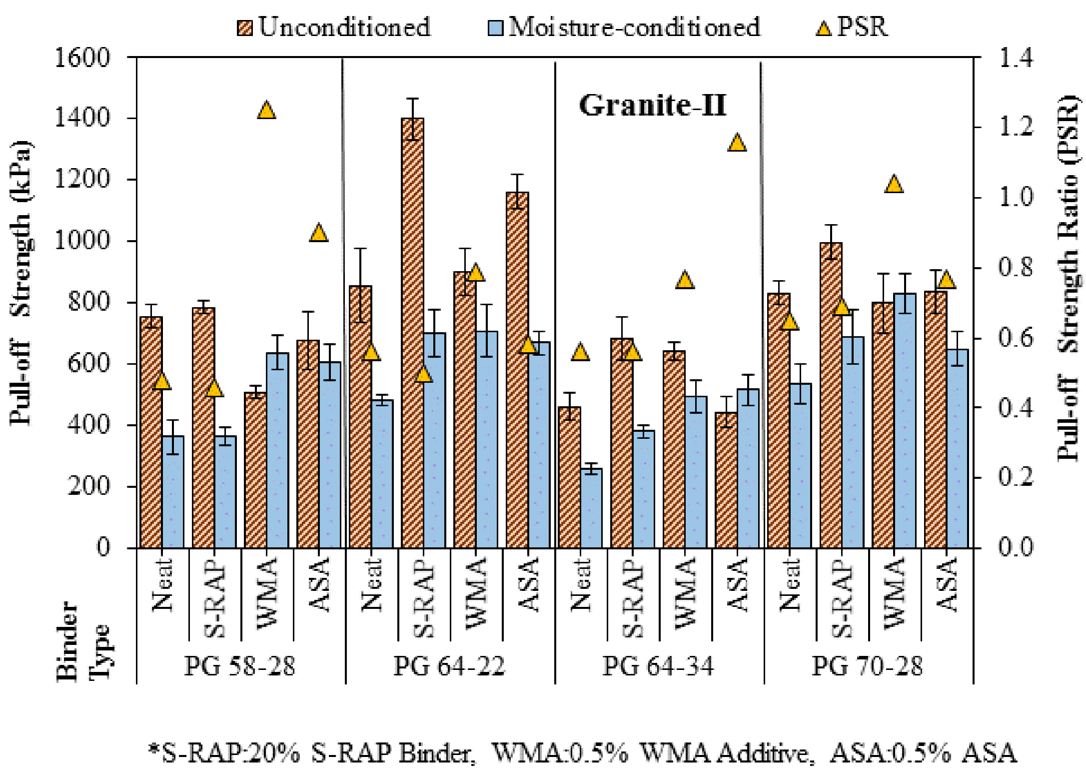


Figure 4.13 Comparison of Pull-off Strength of Different Binder Blends with Granite-II

Table 4.4 Binder Bond Strength Test Results for Different Asphalt Binder Blends with Granite-II

Aggregate: Granite-II

Binder Type	Additive	Unconditioned				Moisture-conditioned				Average *PSR
		Average *POS (kPa)	*SD (kPa)	*COV (%)	Failure Type (Visual)	Average *POS (kPa)	*SD (kPa)	*COV (%)	Failure Type (Visual)	
PG 58-28	Neat (0%)	756.36	39.99	5.30	100% cohesive	361.97	54.47	15.00	100% adhesive	0.48
	S-RAP (20%)	785.31	22.06	2.80	100% cohesive	364.04	28.27	7.80	98% adhesive	0.46
	WMA (0.5%)	508.83	20.68	4.00	100% cohesive	637.77	56.54	8.80	99% adhesive	1.25
	ASA (0.5%)	676.38	92.39	13.70	100% cohesive	606.74	57.23	9.40	91% cohesive	0.9
PG 64-22	Neat (0%)	854.95	121.35	14.20	100% cohesive	483.32	19.31	4.00	100% adhesive	0.56
	S-RAP (20%)	1399.64	66.19	4.70	100% cohesive	703.27	76.53	10.80	99% adhesive	0.5
	WMA (0.5%)	902.52	77.22	8.50	100% cohesive	708.78	86.87	12.30	94% adhesive	0.79
	ASA (0.5%)	1161.77	55.16	4.70	100% cohesive	670.17	38.61	5.70	58% adhesive	0.58
PG 64-34	Neat (0%)	461.95	42.75	9.20	100% cohesive	257.17	18.62	7.30	100% adhesive	0.56
	S-RAP (20%)	683.27	71.71	10.50	100% cohesive	381.28	21.37	5.70	100% adhesive	0.56
	WMA (0.5%)	641.90	29.65	4.70	100% cohesive	495.04	51.02	10.40	97% adhesive	0.77
	ASA (0.5%)	444.02	51.02	11.50	100% cohesive	516.42	48.95	9.50	95% cohesive	1.16
PG 70-28	Neat (0%)	831.51	39.30	4.80	100% cohesive	538.48	64.81	12.10	97% adhesive	0.65
	S-RAP (20%)	997.67	57.23	5.80	100% cohesive	690.17	89.63	13.00	85% adhesive	0.69
	WMA (0.5%)	800.48	97.22	12.10	100% cohesive	830.13	67.57	8.20	75% adhesive	1.04
	ASA (0.5%)	837.71	71.71	8.60	100% cohesive	648.80	56.54	8.70	87% adhesive	0.77

*SD:Standard Deviation*COV:Coeffiecient of Variation*POS:Pull-off Strength*PSR:Pull-off Strength Ratio

From Table 4.4, it is evident that the dry pull-off strength (POS_{dry}) of the neat PG 58-28 binder with Granite-II (756.4 kPa) slightly increased (by 3.8%) as a result of addition of 20% S-RAP binder to the blend. The POS_{dry} values of the PG 58-28 binder blends containing 0.5% WMA additive and 0.5% ASA with Granite-II, however, were found to be 32.7% and 10.6% less than that of the neat binder. This clearly shows that adhesion of the asphalt binder and aggregate in dry condition can be affected by the binder type and aggregate mineralogy. Therefore, selection of the additive type should be made based on the aggregate type and binder properties to maximize adhesion. Adhesion is known to play an important role in durability of a mix in the field (Zhang et al., 2017). Also, from Table 4.4 and Figure 4.13, it is evident that average pull-off strength of the moisture-conditioned specimens (POS_{wet}) of the neat PG 58-28 binder with Granite-II (362.0 kPa) remained almost unchanged (0.6% increase) as a result of addition of 20% S-RAP binder to the blend. Also, the POS_{wet} values of the PG 58-28 binder blends containing 0.5% WMA additive and 0.5% ASA with Granite-II were 76.2% and 67.6% higher than that of the neat binder. So while addition of S-RAP did not significantly affect the adhesion of the PG 58-28 binder to Granite-II after moisture conditioning, addition of an amine-based WMA additive and ASA to the binder significantly increased the POS_{wet} values compared to that of neat PG 58-28 binder.

To compare the effect of moisture-conditioning on the POS values, a parameter, namely pull-off strength ratio (PSR) was calculated by dividing POS_{wet} to POS_{dry} for each asphalt binder blend-aggregate system. The PSR value is analogous to TSR value and is desirable to be higher to represent a mix with a better resistance to moisture-induced damage. From Table 4.4 and Figure 4.13, it was observed that the PSR value of neat PG 58-28 asphalt binder with Granite-II (0.48) did not significantly improve by adding 20% S-RAP to the binder blend. However, PSR values calculated for binder blends containing WMA additive and ASA were found to be 1.25 and 0.9, exhibiting significant improvement. Therefore, it can be concluded that the amine-based additives (WMA and ASA) significantly improved the resistance of the tested PG 58-28 asphalt binder with Granite-II aggregate to moisture-induced damage. It is important to note that the mode of failure was recorded by visual observation and calculation of the adhesive and cohesive areas from pictures taken from the failure surfaces after BBS tests (Figure 4.14).

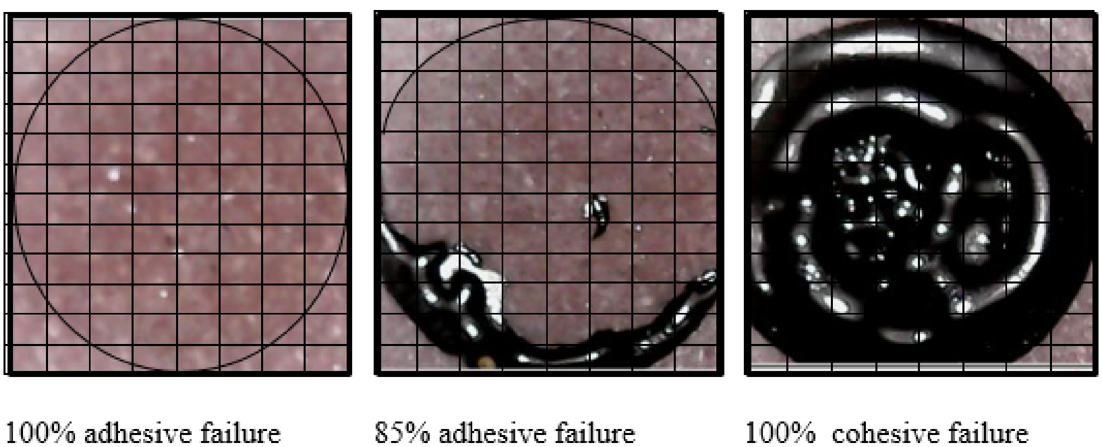


Figure 4.14 Observed Failure Modes in BBS test

From Table 4.4, the failure mode for all blends of the unconditioned PG 58-28 binder- Granite-II samples were cohesive (i.e., adhesive POS > cohesive POS). However, the pull-off failure mode of the neat PG 58-28 binder and blends containing 20% S-RAP and 0.5% WMA additive with Granite-II aggregate mainly changed to adhesive failure, after moisture-conditioning of the samples (i.e., adhesive POS < cohesive POS). Moisture-conditioning had a detrimental effect on the adhesion of binder and aggregates. However, addition of the ASA to PG 58-28 binder resulted in a cohesive failure with Granite-II after moisture conditioning, indicating an improved resistance to moisture-induced damage.

4.2.1.2 Moisture-Induced Damage Evaluation in Granite-II Aggregate with PG 64-22 Binder

From Table 4.4, it is clear that the dry pull-off strength (POS_{dry}) of the neat PG 64-22 binder with Granite-II (854.95 kPa) increased by 63.7% as a result of addition of 20% S-RAP to the blend. The POS_{dry} values of the PG 64-22 binder blend containing 0.5% WMA additive and that containing 0.5% ASA with Granite-II were 5.6% and 35% higher than that of the neat binder, respectively. Also, from Table 4.4 and Figure 4.13, it is evident that the moisture-conditioned pull-off strength (POS_{wet}) of the neat PG 64-22 binder with Granite-II (483.32 kPa) increased by 45.5% as a result of the addition of 20% S-RAP to the blend.

Additionally, the POS_{wet} values of the PG 64-22 binder blend containing 0.5% WMA additive and the blend containing 0.5% ASA with Granite-II were 46.6% and 38.7% higher than that of the neat binder. Addition of S-RAP, amine-based WMA additive, and ASA to the blend increased the adhesion of the PG 64-22 binder to Granite-II after moisture conditioning with significant increase in the POS_{wet} values compared to that of neat PG 64-22 binder. From Table 4.4 and Figure 4.13, it was found that the PSR value of neat PG 64-22 asphalt binder with Granite-II (0.56) did not significantly improve the adhesion by adding 20% S-RAP to the binder blend. Also, blending the binder with ASA did not significantly improve the adhesion. However, the PSR value calculated for the binder blend containing WMA additive was 0.79, exhibiting a significant improvement in its resistance to moisture-induced damage compared to neat binder (0.56). Therefore, it can be concluded that the amine-based WMA additive significantly improved resistance of the tested PG 64-22 asphalt binder with Granite-II aggregate to moisture-induced damage. From Table 4.4, the failure mode for all blends of the unconditioned PG 64-22 binder-Granite-II samples was cohesive (i.e., adhesive POS > cohesive POS). However, the pull-off failure mode of the neat 64-22 binder and blends containing 20% S-RAP, 0.5% ASA and 0.5% WMA additive with Granite-II aggregate mainly changed to adhesive failure, after moisture-conditioning of the samples. It is important to note that addition of the WMA additive to PG 64-22 binder resulted in an adhesive failure after moisture conditioning and the PSR values improved by the addition of WMA additive to blend. Even though the addition of 0.5% ASA did not increase the PSR value, it resulted in a change in failure mode in the moisture-conditioned samples from 100% adhesive for neat binder to 58% adhesive and 42% cohesive for the blend containing ASA. Moisture-conditioning had an adverse effect on the adhesion of binder and aggregates, which addition of the ASA partially mitigated.

4.2.1.3 Moisture-Induced Damage Evaluation in Granite-II Aggregate with PG 64-34 Binder

From Table 4.4 the dry pull-off strength (POS_{dry}) of the neat PG 64-34 binder with Granite-II (461.95 kPa) significantly increased (by 43.9%) after addition of 20% S-RAP binder to the blend. The POS_{dry} values of the PG 64-34 binder blends containing 0.5% WMA additive, and those with 0.5% ASA and Granite-II were 38.9% higher and 3% less (statistically the same) than that of the neat binder. It is apparent that the selection of the additive type should be made based on both the aggregate type and binder properties to result in a durable blend. Table 4.4 and Figure 4.13 show that the moisture-conditioned pull-off strength (POS_{wet}) of the neat PG 64-34 binder with Granite-II (257.17 kPa) increased by 48.3% after addition of 20% S-RAP to the blend. Also, the POS_{wet} values of the PG 64-34 binder blends containing 0.5% WMA additive and that containing 0.5% ASA with Granite-II were 92.5% and 100.8% higher than that of the neat binder. Addition of S-RAP, amine-based WMA additive, and ASA to PG 64-34 binder increased its adhesion to Granite-II after moisture conditioning with significant increase in the POS_{wet} values compared to that of neat binder. From Table 4.4 and Figure 4.13 it is clear that the PSR value of neat PG 64-34 asphalt binder with Granite-II (0.56) did not improve significantly either by addition of 20% S-RAP (0.69) or by addition of 0.5% WMA additive (0.77) to the binder blend.

Additionally, the PSR value of the PG 64-34 binder with Granite-II increased significantly as a result of using 0.5% ASA (1.16). Therefore, one can say that an amine-based ASA is expected to significantly improve the resistance of a mix of PG 64-34 asphalt binder with Granite-II aggregates to moisture-induced damage. Also, from Table 4.4, it is evident that the failure mode for all blends of the unconditioned PG 64-34 binder-Granite-II samples were cohesive (i.e., adhesive POS > cohesive POS). However, the pull-off failure mode of the neat PG 64-34 binder and blends containing 20% S-RAP and 0.5% WMA additive with Granite-II aggregate mainly changed to adhesive failure, after moisture-conditioning of the samples. However, addition of the ASA to PG 64-34 binder resulted in a cohesive failure after moisture conditioning, indicating an improved adhesion with Granite-II as a result of using an amine-based ASA in binder blend.

4.2.1.4 Moisture-Induced Damage Evaluation in Granite-II Aggregate with PG 70-28 Binder

From Table 4.4, it is evident that the dry pull-off strength (POS_{dry}) of the neat PG 70-28 binder with Granite-II (831.51 kPa) increased by 19.9% as a result of the addition of 20% S-RAP binder to the blend. However, the POS_{dry} values of the PG 70-28 binder blends containing 0.5% WMA additive and 0.5% ASA with Granite-II were found to be 3% less (statistically the same) and 0.74% higher (statistically the same) than that of the neat binder. Table 4.4 and Figure 4.13 clearly show that the average pull-off strength of the moisture-conditioned specimens (POS_{wet}) of the neat PG 70-28 binder with Granite-II (538.48 kPa) increased by 28.2% as a result of the addition of 20% S-RAP binder to the blend.

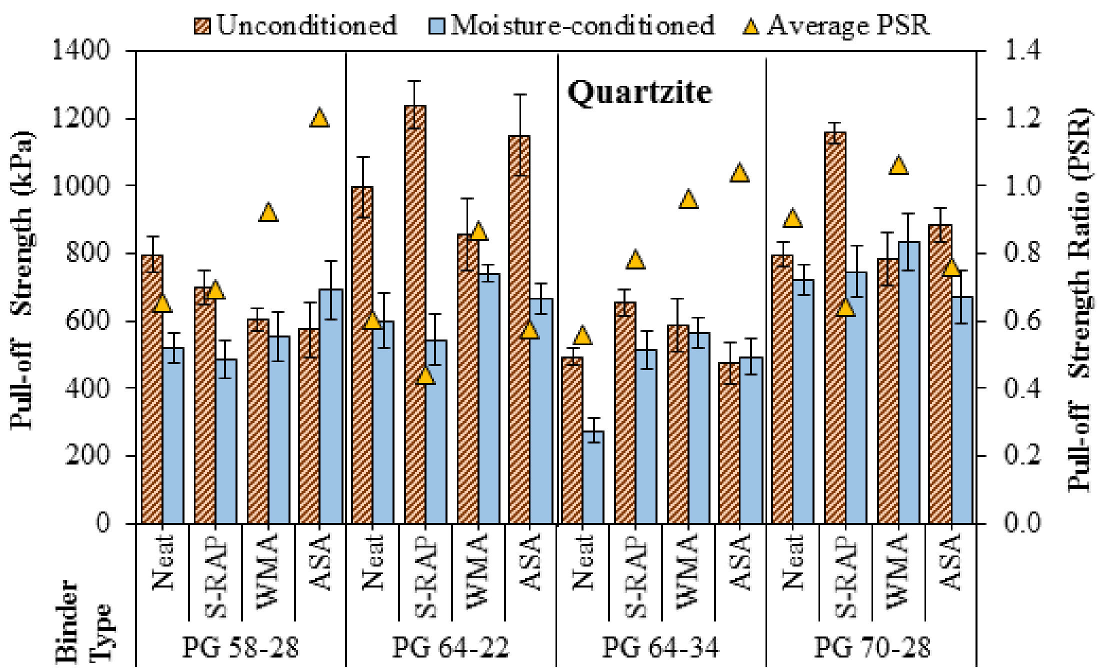
Also, the POS_{wet} values of the PG 70-28 binder blends containing 0.5% WMA additive and those with 0.5% ASA with Granite-II were 54.2% and 20.5% higher than that of the neat binder. Addition of S-RAP, amine-based WMA additive, and ASA to PG 70-28 binder increased its adhesion to Granite-II after moisture conditioning with significant increase in the POS_{wet} values compared to that of the neat binder. From Table 4.4 and Figure 4.13 it was found that the PSR value of neat PG 70-28 asphalt binder with Granite-II (0.65) did not significantly improve as a result of adding 20% S-RAP to the neat binder. Also, incorporating ASA in the binder blend did not significantly improve the adhesion. However, PSR value of the PG 70-28 with Granite-II increased significantly to 1.04, an improvement in moisture-induced damage. Therefore, it can be concluded that the amine-based WMA additive (WMA) significantly improved the resistance of the tested PG 70-28 asphalt binder with Granite-II aggregate to moisture-induced damage. The mode of failure recorded by visual inspection and calculation of the adhesive and cohesive areas from pictures taken from the failure surfaces showed that the failure mode for all blends of the unconditioned PG 70-28 binder-Granite-II samples were cohesive (i.e., adhesive POS > cohesive POS). However, the pull-off failure mode of the neat 70-28 binder and blends containing 20% S-RAP, 0.5% ASA, and 0.5% WMA additive with Granite-II aggregate mainly changed to adhesive failure, after moisture-conditioning.

4.2.1.5 Moisture-Induced Damage Evaluation in Quartzite Aggregate with PG 58-28 Binder

Figure 4.15 and Table 4.5 present a summary of the pull-off strength (POS) values obtained by conducting BBS tests on Quartzite samples prepared with asphalt binders (PG 58-28, PG 64-22, PG 64-34, and PG 70-28) without any additives and those blended with 20% S-RAP, 0.5% WMA additive, and 0.5% ASA with and without moisture conditioning. From Table 4.5, it can be observed that the dry pull-off strength (POS_{dry}) of the neat PG 58-28 binder with Quartzite (794.97 kPa) decreased by 12.2% as a result of addition of 20% S-RAP to the blend. However, the POS_{dry} values of the PG 58-28 binder blend containing 0.5% WMA additive and 0.5% ASA with Quartzite were found to be by 24.2% and 27.8% less than that of the neat binder. Also, from Table 4.5 and Figure 4.15, it is apparent that the moisture-conditioned pull-off strength (POS_{wet}) of the neat PG 58-28 binder with Quartzite (519.18 kPa) remained almost unchanged (6% increase) as a result of addition of 20% S-RAP binder to the blend. Also, the POS_{wet} value of the PG 58-28 binder blends containing 0.5% WMA additive and 0.5% ASA with

Quartzite, were found to be 7.0% and 33.2% higher than that of the neat binder. while addition of S-RAP, and 0.5% WMA additive did not significantly affect the adhesion of the PG 58-28 binder to Quartzite after moisture conditioning, addition of ASA to the binder significantly increased the POS_{wet} values compared to that of the neat PG 58-28 binder. From Table 4.5 and Figure 4.15, it is clear that the PSR value of the neat PG 58-28 asphalt binder with Quartzite (0.65) did not significantly improve by adding 20% S-RAP to the binder blend.

However, the PSR values calculated for PG 58-28 asphalt binder increased from 0.65 for neat binder to 0.92 and 1.2, after incorporating WMA additive and ASA in the blend, respectively. Therefore, it can be concluded that the amine-based additives (WMA and ASA) significantly improved resistance of the tested PG 58-28 asphalt binder with Quartzite aggregate to moisture-induced damage. Also, from Table 4.5, the failure mode for all blends of the unconditioned PG 58-28 binder-Quartzite samples were found to be cohesive (i.e., adhesive POS > cohesive POS). However, the pull-off failure mode of the neat PG 58-28 binder and blends containing 20% S-RAP with Quartzite aggregate changed to mostly adhesive failure, after moisture conditioning. Moisture conditioning had a detrimental effect on the adhesion of binder to aggregates. However, addition of the 0.5% WMA additive and 0.5% ASA to PG 58-28 binder both resulted in a cohesive failure after moisture conditioning, indicating an improved adhesion with Quartzite.



*S-RAP:20% S-RAP Binder, WMA:0.5% WMA Additive, ASA :0.5% ASA

Figure 4.15 Comparison of Pull-off Strength Between Quartzite and Different Binder Blends

Table 4.5 Binder Bond Strength Test Results for Different Asphalt Binder Blends with Quartzite

Aggregate: Quartzite

Binder Type	Additive	Unconditioned				Moisture-conditioned				Average *PSR
		Average *POS (kPa)	*SD (kPa)	*COV (%)	Failure Type (Visual)	Average *POS (kPa)	*SD (kPa)	*COV (%)	Failure Type (Visual)	
PG 58-28	Neat (0%)	794.97	53.09	6.30	100% cohesive	519.18	44.13	8.50	94% adhesive	0.65
	S-RAP (20%)	698.44	50.33	7.20	100% cohesive	486.08	55.16	11.40	92% adhesive	0.70
	WMA (0.5%)	602.60	33.78	5.60	100% cohesive	555.72	73.08	13.20	100% cohesive	0.92
	ASA (0.5%)	574.33	79.98	14.00	100% cohesive	691.54	88.94	12.90	100% cohesive	1.20
PG 64-22	Neat (0%)	996.98	88.94	9.00	100% cohesive	599.84	80.67	13.40	72% adhesive	0.60
	S-RAP (20%)	1238.30	70.33	5.70	100% cohesive	544.00	74.46	13.60	80% adhesive	0.44
	WMA (0.5%)	855.64	105.49	12.30	100% cohesive	741.19	26.20	3.60	69% adhesive	0.87
	ASA (0.5%)	1150.05	117.90	10.20	100% cohesive	666.03	44.82	6.70	87% cohesive	0.58
PG 64-34	Neat (0%)	493.66	25.51	5.10	100% cohesive	276.48	34.47	12.50	98% adhesive	0.56
	S-RAP (20%)	655.00	37.92	5.80	100% cohesive	514.35	55.85	10.90	82% adhesive	0.79
	WMA (0.5%)	588.12	79.29	13.50	100% cohesive	566.75	45.51	8.00	80% adhesive	0.96
	ASA (0.5%)	476.43	62.05	13.00	100% cohesive	495.04	53.78	10.80	88% cohesive	1.04
PG 70-28	Neat (0%)	796.34	37.92	4.80	100% cohesive	721.19	45.51	6.30	75% adhesive	0.91
	S-RAP (20%)	1157.63	31.03	2.70	100% cohesive	746.70	77.91	10.40	50% adhesive	0.65
	WMA (0.5%)	783.93	79.29	10.20	100% cohesive	834.27	84.12	10.10	69% adhesive	1.06
	ASA (0.5%)	883.91	50.33	5.70	100% cohesive	671.55	76.53	11.40	80% cohesive	0.76

*SD:Standard Deviation*COV:Coeffiecient of Variation*POS:Pull-off Strength*PSR:Pull-off Strength Ratio

4.2.1.6 Moisture-Induced Damage Evaluation in Quartzite Aggregate with PG 64-22 Binder

From Table 4.5, it was observed that the dry pull-off strength (POS_{dry}) of the neat PG 64-22 binder with Quartzite (996.98 kPa) increased by 24.2% as a result of addition of 20% S-RAP binder to the blend. The POS_{dry} values of the PG 64-22 binder blend containing 0.5% WMA additive and that containing 0.5% ASA with Quartzite, were found to be by 14.8% and 15.4% higher than that of the neat binder. Also, from Table 4.5 and Figure 4.15, it is evident that the moisture-conditioned pull-off strength (POS_{wet}) of the neat PG 64-22 binder with Quartzite (599.84 kPa) decreased by 9.3% as a result of addition of 20% S-RAP binder to the blend. Also, the POS_{wet} values of the PG 64-22 binder containing 0.5% WMA additive with Quartzite was 23.6% higher than that of the neat binder. However, addition of 0.5% ASA to the neat binder was not found to have a significant effect on improving the adhesion. Adhesion of the PG 64-22 binder to Quartzite increased as a result of adding an amine-based WMA additive to the blend and resulted in an increase in the POS_{wet} value compared to that of neat PG 64-22 binder. From Table 4.5 and Figure 4.15 it was also found that the PSR value of the neat PG 64-22 asphalt binder with Quartzite (0.6) decreased after addition of 20% S-RAP to the binder blend (0.44). Also, the PSR value of the binder blend containing ASA (0.58) was not significantly different from that measured for the neat binder with Quartzite (0.60). It should be noted that, the PSR value calculated for the binder blend containing WMA additive was 0.87, exhibiting significant improvement in resistance to moisture-induced damage when compared to that of the neat binder with Quartzite. Therefore, it can be concluded that an amine-based additive (WMA) significantly improved the resistance of the tested PG 64-22 asphalt binder with Quartzite aggregate to moisture-induced damage. From Table 4.5, the failure mode for all blends of the unconditioned PG 64-22 binder-Quartzite samples was cohesive (i.e., adhesive POS > cohesive POS). However, the pull-off failure mode of the neat PG 64-22 binder and blends containing 20% S-RAP, and 0.5% WMA additive with Quartzite aggregate mainly changed to adhesive failure after moisture-conditioning. The failure mode of the binder blend containing 0.5% ASA, remained cohesive after moisture-conditioning, an indication of an acceptable adhesion and a high resistance to moisture-induced damage of binder with aggregate as a result of using ASA in the blend.

4.2.1.7 Moisture-Induced Damage Evaluation in Quartzite Aggregate with PG 64-34 Binder

From Table 4.5, it can be observed that the dry pull-off strength (POS_{dry}) of the neat PG 64-34 binder with Quartzite (493.66 kPa) increased by 32.7% after addition of 20% S-RAP binder to the blend. The POS_{dry} values of the Quartzite samples with the PG 64-34 binder blends containing 0.5% WMA additive and that with 0.5% ASA were 19% higher and 3% lower than that of the neat binder. Also, from Table 4.5 and Figure 4.15, it was found that the moisture-conditioned pull-off strength (POS_{wet}) of the neat PG 64-34 binder with Quartzite (276.48 kPa) increased by 86.0%, 105.0%, and 79.1% as a result of addition of 20% S-RAP binder, 0.5% WMA additive, and 0.5% ASA, respectively. Addition of S-RAP, amine-based WMA additive, or ASA to the binder increased the adhesion of the PG 64-34 binder to Quartzite after moisture conditioning with significant increase in the POS_{wet} values compared to that of neat PG 64-34 binder. The pull-off strength ratio (PSR) of neat PG 64-34 asphalt binder with Quartzite (0.56) was also observed to significantly increase as a result of adding 20% S-RAP to the binder blend, which is completely different from observations made for Granite-II, and Granite-I aggregates.

Also, PSR values calculated for binder blends containing WMA additive, and binder blend containing ASA with Quartzite were 0.96, and 1.04 significantly higher than that measured for the neat binder. Therefore, it is reasonable to say that, an amine-based WMA additive, or ASA significantly improved the adhesion of the tested PG 64-34 asphalt binder with Quartzite aggregate. Also, addition of 20% S-RAP to neat PG 64-34 binder improved its adhesion with Quartzite. From Table 4.5, it is evident that the failure mode for all the unconditioned samples prepared with blends of PG 64-34 binder and Quartzite aggregate were cohesive (i.e., adhesive POS > cohesive POS). However, the pull-off failure mode of the neat PG 64-34 binder and blends containing 20% S-RAP and 0.5% WMA additive with Quartzite aggregate mainly changed to adhesive failure, after moisture-conditioning. Hence, it is clear that moisture-conditioning had an adverse effect on the adhesion between binder and aggregates. However, addition of the ASA to PG 64-34 binder resulted in a cohesive failure after moisture conditioning, indicating an improved adhesion with Quartzite as a result of using ASA in binder blend.

4.2.1.8 Moisture-Induced Damage Evaluation in Quartzite Aggregate with PG 70-28 Binder

From Table 4.5, it is evident that the dry pull-off strength (POS_{dry}) of the neat PG 70-28 binder with Quartzite (796.34 kPa) increased by 45.4% as a result of addition of 20% S-RAP binder to the blend. The POS_{dry} values of the PG 70-28 binder blends containing 0.5% WMA additive and 0.5% ASA with Quartzite were 1% lower (significantly the same) and 11% higher than that of the neat binder. Table 4.5 and Figure 4.15 show that the pull-off strength of the moisture-conditioned samples (POS_{wet}) of the neat PG 70-28 binder with Quartzite (721.19 kPa) increased by 3.5% as a result of addition of 20% S-RAP binder to the blend. Also, the average POS_{wet} value of the PG 70-28 binder blends each containing 0.5% WMA additive and 0.5% ASA with Quartzite were 15.7% higher and 6.8% lower (significantly the same) than that of the neat binder with the same aggregate. Addition of amine-based WMA additive increased the adhesion of the PG 70-28 binder to Quartzite after moisture conditioning with significant increase in the POS_{wet} values compared to that of neat PG 70-28 binder. From Table 4.5 and Figure 4.15, it was found that the PSR value of neat PG 70-28 asphalt binder (0.91) with Quartzite did not significantly improved by adding 20% S-RAP to the binder blend. Also, the addition of 0.5% ASA did not significantly improve adhesion of the neat binder with Quartzite. However, the PSR value calculated for PG 70-28 binder containing WMA additive with Quartzite was 1.04, exhibiting an improvement as a result of using an amine-based WMA additive in blend. Therefore, it can be concluded that the 0.5% WMA additive significantly improved the resistance of the tested PG 70-28 asphalt binder with Quartzite aggregate to moisture-induced damage. From Table 4.5, and Figure 4.14, it is also clear that the failure mode for all blends of the unconditioned PG 70-28 binder-Quartzite samples was cohesive (i.e., adhesive POS > cohesive POS). However, the pull-off failure modes of the neat PG 70-28 binder blends of PG 70-28 each containing 20% S-RAP, and 0.5% WMA additive with Quartzite aggregate mainly changed to adhesive failure, after moisture-conditioning of the samples. It is important to note that the addition of 0.5% ASA in the PG 70-28 binder with a PSR value less than that of neat binder with Quartzite aggregate showed cohesive failure after moisture conditioning.

4.2.1.9 Moisture-Induced Damage Evaluation in Granite-I Aggregate and PG 58-28 Binder

Figure 4.16 and Table 4.6 present a summary of the pull-off strength (POS) values obtained by conducting BBS tests on Granite-I samples prepared with asphalt binders (PG 58-28, PG 64-22, PG 64-34, and PG 70-28) without any additives and those blended with 20% S-RAP, 0.5% WMA additive, and 0.5% ASA with and without moisture conditioning. From Table 4.6, it is evident that the dry pull-off strength (POS_{dry}) of the neat PG 58-28 binder with Granite-I (752.22 kPa) increased by 2.8% as a result of addition of 20% S-RAP binder. The POS_{dry} values of the PG 58-28 binder blends containing 0.5% WMA additive and 0.5% ASA with Granite-I were 13.4% and 14.8% less than that of the neat PG 58-28 binder, respectively. Also, from Figure 4.16 and Table 4.6, it is evident that the pull-off strength of the moisture-conditioned samples (POS_{wet}) of the neat PG 58-28 binder with Granite-I (667.41 kPa) significantly decreased (by 74.5%) as a result of addition of 20% S-RAP binder to neat PG 58-28. Additionally, the POS_{wet} value of the PG 58-28 binder blend containing 0.5% ASA with Granite-I was 6.2% higher than that of the neat binder with the same aggregate. However, the POS_{wet} value of the PG 58-28 binder with Granite-I increased by 28% as a result of blending it with 0.5% WMA additive. While addition of S-RAP and 0.5% ASA resulted in a reduction in the pull-off strength of the of the PG 58-28 binder with Granite-I after moisture conditioning, incorporating WMA additive in PG 58-28 binder prevented the reduction of the in adhesion as a result of moisture-conditioning. Also, it was observed that the PSR value of neat PG 58-28 binder with Granite-I (0.89) exhibited a significant decline (became 0.22) as a result of incorporating 20% S-RAP in the binder blend. Addition of ASA to the neat PG 58-28 binder with Granite-I was not found to increase the PSR value (0.75). However, the PSR value calculated for the binder blend containing WMA additive was 1.2, exhibiting a significant improvement in adhesion as a result of incorporating WMA additive in binder. Therefore, it can be concluded that the addition of an amine-based WMA additive significantly improved the resistance of the tested PG 58-28 asphalt binder with Granite-I aggregate to moisture-induced damage. From Figure 4.16 and Table 4.6, it is evident that the failure mode for all blends of the unconditioned PG 58-28 binder-Granite-I samples was cohesive (i.e., adhesive POS > cohesive POS). However, the pull-off failure mode of the neat PG 58-28 binder blends containing 20% S-RAP and those containing 0.5% ASA with Granite-I aggregate mainly changed to adhesive failure after moisture-conditioning, indicating a weakened adhesive bond due to moisture. However, addition of the 0.5% WMA additive to PG 58-28 binder resulted in a cohesive failure after moisture conditioning, indicating an improved adhesion with Granite-I as a result of using WMA additive in the binder.

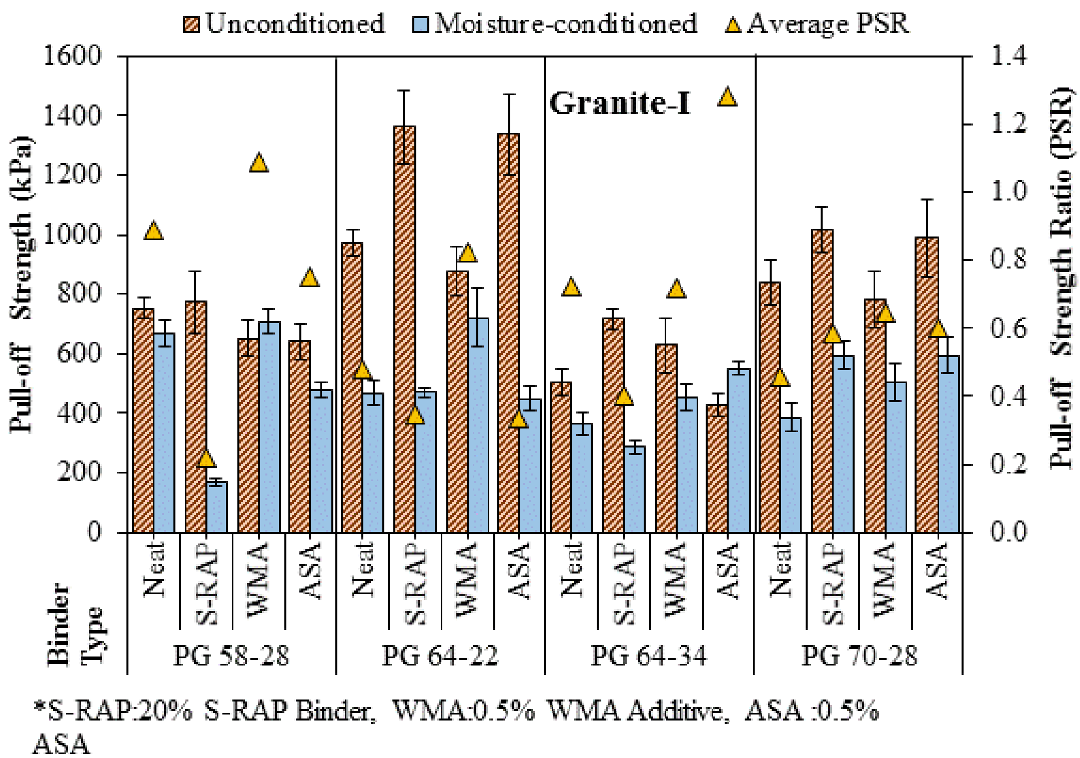


Figure 4.16 Comparison of Pull-off Strength Between Granite-I and Different Binder Blends

Table 4.6 Binder Bond Strength Test Results for Different Asphalt Binder Blends with Granite-I

Aggregate: Granite-I										
		Unconditioned				Moisture Conditioned				
Binder Type	Additive	Average *POS (kPa)	*SD (kPa)	*COV (%)	Failure Type (Visual)	Average *PS (kPa)	*SD (kPa)	*COV (%)	Failure Type (Visual)	Average *PSR
PG 58-28	Neat (0%)	752.22	33.78	4.50	100% cohesive	667.41	44.13	6.60	100% adhesive	0.89
	S-RAP (20%)	773.59	104.80	13.60	100% cohesive	170.30	13.10	7.60	100% adhesive	0.22
	WMA (0.5%)	651.55	61.36	9.40	100% cohesive	708.78	39.99	5.70	60% cohesive	1.09
	ASA (0.5%)	640.52	61.36	9.60	100% cohesive	480.56	25.51	5.30	97% adhesive	0.75
PG 64-22	Neat (0%)	974.92	44.82	4.60	100% cohesive	468.15	40.68	8.70	100% adhesive	0.48
	S-RAP (20%)	1362.40	125.48	9.20	100% cohesive	469.53	18.62	4.00	99% adhesive	0.34
	WMA (0.5%)	877.01	80.67	9.20	100% cohesive	721.19	99.28	13.70	87% adhesive	0.82
	ASA (0.5%)	1336.89	138.58	10.40	100% cohesive	449.54	40.68	9.10	99% adhesive	0.34
PG 64-34	Neat (0%)	506.08	43.44	8.60	100% cohesive	366.11	36.54	9.90	100% adhesive	0.72
	S-RAP (20%)	717.06	36.54	5.10	100% cohesive	286.82	21.37	7.50	100% adhesive	0.40
	WMA (0.5%)	629.49	91.70	14.60	100% cohesive	452.30	43.44	9.70	100% adhesive	0.72
	ASA (0.5%)	429.54	37.92	8.80	100% cohesive	550.20	22.75	4.10	92% cohesive	1.28
PG 70-28	Neat (0%)	841.85	76.53	9.10	100% cohesive	384.73	48.26	12.50	100% adhesive	0.46
	S-RAP (20%)	1016.98	75.15	7.40	100% cohesive	595.02	46.19	7.80	100% adhesive	0.59
	WMA (0.5%)	783.24	96.53	12.30	100% cohesive	504.70	63.43	12.60	99% adhesive	0.64
	ASA (0.5%)	990.09	129.62	13.10	100% cohesive	595.71	57.23	9.60	97% adhesive	0.60

*SD:Standard Deviation*COV:Coeffiecient of Variation*POS:Pull-off Strength*PSR:Pull-off Strength Ratio

4.2.1.10 Moisture-Induced Damage Evaluation in Granite-I Aggregate and PG 64-22 Binder

From Table 4.6, it was observed that the dry pull-off strength (POS_{dry}) of the neat PG 64-22 binder with Granite-I (974.92 kPa) increased by 39.7% as a result of addition of 20% S-RAP binder to neat binder. The POS_{dry} values measured for samples of Granite-II and PG 64-22 binder blended with 0.5% WMA additive and those containing 0.5% ASA were 10% less (significantly the same) and 37% higher than that of the neat binder. Also, from Table 4.6 and Figure 4.16, it was evident that the pull-off strength of the moisture-conditioned samples (POS_{wet}) of Granite-I with neat PG 64-22 binder (468.15 kPa) remained statistically unchanged after addition of 20% S-RAP or 0.5% ASA. The POS_{wet} values of the PG 64-22 binder blends containing 0.5% WMA additive with Granite-I was 54% higher than that of the neat binder. Addition of amine-based WMA additive improved the adhesion of PG 64-22 binder to Granite-I after moisture conditioning with significant increase in the POS_{wet} values compared to that of neat PG 64-22 binder. Additionally, from Table 4.6 and Figure 4.16, it was found that the PSR value of neat PG 64-22 asphalt binder with Granite-I (0.48) decreased to 0.34 as a result of blending the neat binder with 20% S-RAP or 0.5% ASA, indicative of adverse effect of moisture on adhesive bond to aggregate. However, a high PSR value (0.82) observed for the samples of Granite-I with PG 64-22 binder containing WMA additive indicates a significant improvement in resistance of the aggregate-binder system to moisture-induced damage when an amine-based WMA additive was used. The mode of failure recorded by visual observation and calculation of the adhesive and cohesive areas from pictures taken from the failure surfaces after BBS tests are presented in Table 4.6. From Table 4.6, the failure mode for all blends of the dry PG 64-22 binder-Granite-I samples was found to be cohesive (i.e., adhesive POS > cohesive POS). However, the pull-off failure mode of the samples of Granite-I with neat PG 64-22 binder, blends containing 20% S-RAP, those containing 0.5% WMA additive, or 0.5% ASA mainly changed to adhesive failure, after moisture-conditioning. Moisture-conditioning had an adverse effect on the adhesion of binder and aggregates.

4.2.1.11 Moisture-Induced Damage Evaluation in Granite-I Aggregate and PG 64-34 Binder

Table 4.6 shows that the dry pull-off strength (POS_{dry}) of the neat PG 64-34 binder with Granite-I (506.08 kPa) increased by 41.7% after addition of 20% S-RAP binder to the blend. The POS_{dry} value of the Granite-I aggregate with PG 64-34 binder increased by 24.4% and decreased by 15% as a result of incorporating 0.5% WMA additive and 0.5% ASA in the neat binder, respectively. From Table 4.6 and Figure 4,16, it is also interesting to note that the pull-off strength of the moisture-conditioned samples (POS_{wet}) of Granite-I with neat PG 64-34 binder (366.1 kPa) decreased by 21.6% and increased by 23.5 and 50.3% as a result of addition of 20% S-RAP binder, 0.5% WMA additive, and 0.5% ASA, respectively, to the neat binder. Addition of amine-based WMA additive and ASA to PG 64-34 binder increased its adhesion to Granite-I after moisture conditioning, indicative of an improved resistance to moisture-induced damage.

From Table 4.6 and Figure 4.16, it is evident that, the PSR value of neat PG 64-34 asphalt binder (0.72) with Granite-I improved by 78% (PSR=1.28) as a result of incorporating 0.5% ASA in the binder. Also, the PSR value of neat PG 64-34 asphalt binder with Granite-I (0.72) remained unchanged (PSR=0.721) as a result of blending the neat binder with 0.5% ASA. However, addition of S-RAP to neat PG 64-34 binder resulted in 44% reduction in its PSR value (PSR=0.40). Therefore, it is credible to say that the amine-based ASA significantly improved resistance of the tested PG 64-34 asphalt binder with Granite-I aggregate. Additionally, from Table 4.6 it is evident that the failure mode for all unconditioned samples of the Granite-I prepared with PG 64-34 binder were found to be cohesive (i.e., adhesive POS > cohesive POS). However, the pull-off failure mode of the Granite-I samples with neat PG 64-34 binder and its blends containing 20% S-RAP and 0.5% WMA additive changed to mainly adhesive failure, after moisture-conditioning. Therefore, from these observations and PSR values it can be said that moisture-conditioning had a detrimental effect on the adhesive bond between binder and aggregate. However, addition of the ASA to PG 64-34 binder resulted in a cohesive failure after moisture conditioning, indicating an improved resistance to moisture-induced damage as a result of using ASA in PG 64-34 binder with Granite-I aggregate.

4.2.1.12 Moisture-Induced Damage Evaluation in Granite-I Aggregate and PG 70-28 Binder

From Table 4.6, it is clear that, the POS_{dry} value measured for the neat PG 70-28 binder with Granite-I (841.85 kPa) increased by 20.8% as a result of blending the neat binder with 20% S-RAP. However, the POS_{dry} values of the PG 70-28 binder with Granite-I changed by 21, -7, and 18% a result of blending it with 20% S-RAP, 0.5% WMA additive, and 0.5% ASA, respectively. By comparing these results with those observed for other binders and aggregate types, it is safe to say that to achieve a strong adhesion selection of the additive type should be based on the aggregate type and binder properties. Also, Table 4.6 and Figure 4.16 show that the POS_{wet} value measured for the neat PG 70-28 binder with Granite-I (384.73 kPa) increased by 54.7% as a result of addition of 20% S-RAP binder to the blend. Also, the POS_{wet} values of the PG 70-28 binder blends containing 0.5% WMA additive and 0.5% ASA with Granite-I, were 31.2 and 54.8% higher than that of the neat binder, respectively. Addition of an amine-based additives (ASA and WMA), and S-RAP binder increased the adhesion of the PG 70-28 binder to Granite-I after moisture conditioning with significant increase in the POS_{wet} values compared to that of neat PG 70-28 binder. Additionally, from Table 4.6 and Figure 4.16, it was found that the PSR value of neat PG 70-28 asphalt binder with Granite-I (0.46) significantly improved as a result of adding 20% S-RAP, 0.5% ASA, and 0.5%WMA additive to the binder. The failure mode for all blends of the unconditioned PG 70-28 binder and Granite-I samples was found to be cohesive (i.e., adhesive POS > cohesive POS). However, the pull-off failure mode of the neat PG 70-28 binder that blended with 20% S-RAP, 0.5% WMA additive, and 0.5% ASA each with Granite-I aggregate mainly changed to adhesive failure, after moisture-conditioning of the samples.

4.2.1.13 Ranking Asphalt Binder Aggregates Based on their PSR Values

To summarize the effect of binder, aggregate type, and the additive on moisture-induced damage potential all combinations of the aggregates, binders and additives were ranked based on their PSR values and presented in Table 4.7. From Table 4.7 it can be observed that out of 15 aggregate-binder combinations having a PSR value greater than 0.8, 13 blends contained an amine-based additive (ASA or WMA). This shows effectiveness of the amine-based additives in improving the resistance of asphalt mixes to moisture-induced damage. Also, it was found that out of 10 binder blends having the lowest PSR values, seven contained S-RAP in the blend. Inclusion of RAP in an asphalt mix may increase its propensity to moisture-induced damage.

Table 4.7 Resistance to moisture-induced damage based on average PSR

Aggregate type	Binder Type	Additive	Average PSR	Rank	Aggregate type	Binder Type	Additive	Average PSR	Rank
Granite-I	PG 64-34	ASA	1.28	1	Granite-II	PG 70-28	S-RAP	0.69	21
Granite-II	PG 58-28	WMA	1.25	2	Quartzite	PG 58-28	Neat	0.65	22
Quartzite	PG 58-28	ASA	1.20	3	Granite-II	PG 70-28	Neat	0.65	22
Granite-II	PG 64-34	ASA	1.16	4	Quartzite	PG 70-28	S-RAP	0.65	23
Granite-I	PG 58-28	WMA	1.09	5	Granite-I	PG 70-28	WMA	0.64	24
Quartzite	PG 70-28	WMA	1.06	6	Granite-I	PG 70-28	ASA	0.60	25
Granite-II	PG 70-28	WMA	1.04	7	Quartzite	PG 64-22	Neat	0.60	25
Quartzite	PG 64-34	ASA	1.04	7	Granite-I	PG 70-28	S-RAP	0.59	26
Quartzite	PG 64-34	WMA	0.96	8	Granite-II	PG 64-22	ASA	0.58	27
Quartzite	PG 58-28	WMA	0.92	9	Quartzite	PG 64-22	ASA	0.58	27
Quartzite	PG 70-28	Neat	0.91	10	Quartzite	PG 64-34	Neat	0.56	28
Granite-II	PG 58-28	ASA	0.90	11	Granite-II	PG 64-22	Neat	0.56	28
Granite-I	PG 58-28	Neat	0.89	12	Granite-II	PG 64-34	Neat	0.56	28
Quartzite	PG 64-22	WMA	0.87	13	Granite-II	PG 64-34	S-RAP	0.56	28
Granite-I	PG 64-22	WMA	0.82	14	Granite-II	PG 64-22	S-RAP	0.50	29
Granite-II	PG 64-22	WMA	0.79	15	Granite-I	PG 64-22	Neat	0.48	30
Quartzite	PG 64-34	S-RAP	0.79	15	Granite-II	PG 58-28	Neat	0.48	30
Granite-II	PG 64-34	WMA	0.77	16	Granite-II	PG 58-28	S-RAP	0.46	31
Granite-II	PG 70-28	ASA	0.77	16	Granite-I	PG 70-28	Neat	0.46	31
Quartzite	PG 70-28	ASA	0.76	17	Quartzite	PG 64-22	S-RAP	0.44	32
Granite-I	PG 58-28	ASA	0.75	18	Granite-I	PG 64-34	S-RAP	0.40	33
Granite-I	PG 64-34	Neat	0.72	19	Granite-I	PG 64-22	S-RAP	0.34	34
Granite-I	PG 64-34	WMA	0.72	19	Granite-I	PG 64-22	ASA	0.34	34
Quartzite	PG 58-28	S-RAP	0.70	20	Granite-I	PG 58-28	S-RAP	0.22	35

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Based on the tests conducted on the three mixes — HMA-Lime, HMA-RAP, and C-WMA — the following conclusions were drawn:

1. The asphalt mixes — HMA-Lime, HMA-RAP, and C-WMA — met the minimum tensile strength ratio (TSR) requirement of 0.80 set by the Superpave® mix design for screening the mixes for their susceptibility to moisture-induced damage.
2. The critical strain energy release rate of moisture-conditioned samples of HMA-Lime mix was lower than minimum value, 0.5 kJ/m^2 set by ASTM D8044-16 standard. HMA-Lime may be susceptible to cracking as a result of exposure to moisture. However, the C-WMA and HMA-RAP samples passed the minimum critical strain energy release rate requirement of 0.5 kJ/m^2, indicating the possibility of a better resistance to cracking after moisture conditioning when compared with HMA-RAP. However, energy release ratio (ERR) of the each mix was greater than one, an indicator of no reduction in fracture energy as a result of moisture conditioning.
3. The fatigue index ratio (FIR) values obtained by conducting IDT test on each mix were greater than one, indicating no reduction in fracture energy as a result of moisture conditioning. However, the fracture toughness decreased in HMA-Lime due to moisture conditioning.
4. The toughness index ratio (TIR) obtained from IDT test was less than one in HMA-Lime with a decrease in the fracture toughness in moisture-conditioned samples. However, TIR of HMA-RAP, and C-WMA mixes were greater than one, indicative of no effect on fracture toughness as a result of moisture conditioning.
5. The ITS and FI values were significantly correlated ($R^2 = 0.9525$) for both dry and moisture-conditioned samples. The coefficient of determination was 0.8043 and 0.9525 for the dry and moisture-conditioned samples, respectively.

Based on the binder bond strength (BBS) tests conducted on asphalt binder-aggregate systems, the following conclusions were drawn:

1. The pull-off strength ratio (PSR) obtained from BBS tests showed that the PG 64-34 binder containing 0.5% ASA with Granite-I, and PG 58-28 binder containing 0.5% WMA additive with Granite-II had the highest resistance to moisture-induced damage among the tested asphalt binder-aggregate combinations. The PG 58-28 binder containing 20% RAP with Granite-I was found to have the lowest PSR value compared to other asphalt binder-aggregate systems.
2. Adhesive failure was observed in all moisture-conditioned asphalt binder-aggregate samples containing 20% S-RAP. Addition of 20% S-RAP to the neat asphalt binder increased the PSR (increased adhesion) value of the asphalt binder-aggregate samples prepared with both PG 64-34 and PG 70-28 binders and Quartzite aggregate.
3. Addition of 0.5% amine-based WMA additive to the neat binder increased the PSR (improved adhesion) of the asphalt binder-aggregate samples prepared with PG 58-28, PG 64-22, and PG 70-28 binders with Granite-II, Quartzite and Granite-I aggregates, respectively. Also, addition of 0.5% amine-based WMA additive to neat PG 64-34 binder with Quartzite aggregate resulted in an improved adhesion compared to that of the neat binder.
4. Addition of 0.5% ASA to the neat binder increased the PSR (improved adhesion) of the asphalt binder-aggregate samples prepared by PG 58-28 and PG 64-34 binders with Granite-II, and Quartzite aggregates, respectively. Also, addition of 0.5% ASA to PG 64-34, and PG

70-28 binders with Granite-I aggregate improved their adhesion. Cohesive failure was observed in the PG 64-34 binder with Granite-I, and PG 58-28, PG 64-22 and PG 64-34 with Quartzite.

5.2 Recommendations

A new pass/fail criterion for screening the mixes using BBS test is suggested as PSR values obtained from BBS testing were found to be less than 0.8 (rounded) in all aggregates with neat binders except for PG 58-28 binder with Granite-I, and PG 70-28 binder with Granite-I. Field/laboratory testing of asphalt mixes is suggested with the same asphalt binder-aggregate combinations used in this study to develop a correlation between TSR of asphalt mixes and PSR of asphalt binder-aggregate combinations. Also recommended is additional testing of asphalt mixes by using more mechanistic methods such as Hamburg wheel tracking test, dynamic modulus tests before and after moisture conditioning and surface free energy measurements for developing correlations between BBS test results and results of testing asphalt mixes.

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APPENDIX A

Summary of G_{mm} test result

S.N.	Type of asphalt mix	Average G_{mm}	COV
1	HMA-Lime	2.461	0.12
2	HMA-RAP	2.488	0.13
3	C-WMA	2.453	0.11

Summary of G_{mb} test result and AV calculation in TSR specimens

Asphalt mix type	Name of the TSR specimen	G_{mb}	AV (%)
HMA-Lime	B1-M1-T2-S1	2.29	6.9
	B1-M1-T2-S2	2.284	7.2
	B1-M1-T2-S3	2.295	6.7
	B1-M1-T2-S4	2.281	7.3
	B1-M1-T2-S5	2.295	6.7
	B1-M1-T2-S6	2.283	7.2
	B1-M1-T2-S7	2.296	6.7
	B1-M1-T2-S8	2.285	7.2
HMA-RAP	B2-M2-T2-S1	2.312	7.1
	B2-M2-T2-S2	2.310	7.2
	B2-M2-T2-S3	2.305	7.4
	B2-M2-T2-S4	2.310	7.2
	B2-M2-T2-S5	2.310	7.2
	B2-M2-T2-S6	2.306	7.3
	B2-M2-T2-S7	2.306	7.3
	B2-M2-T2-S8	2.311	7.1
C-WMA	B3-M3-T2-S1	2.294	6.5
	B3-M3-T2-S2	2.285	6.8
	B3-M3-T2-S3	2.273	7.3
	B3-M3-T2-S4	2.283	6.9
	B3-M3-T2-S5	2.287	6.8
	B3-M3-T2-S6	2.280	7.1
	B3-M3-T2-S7	2.280	7.1
	B3-M3-T2-S8	2.286	6.8

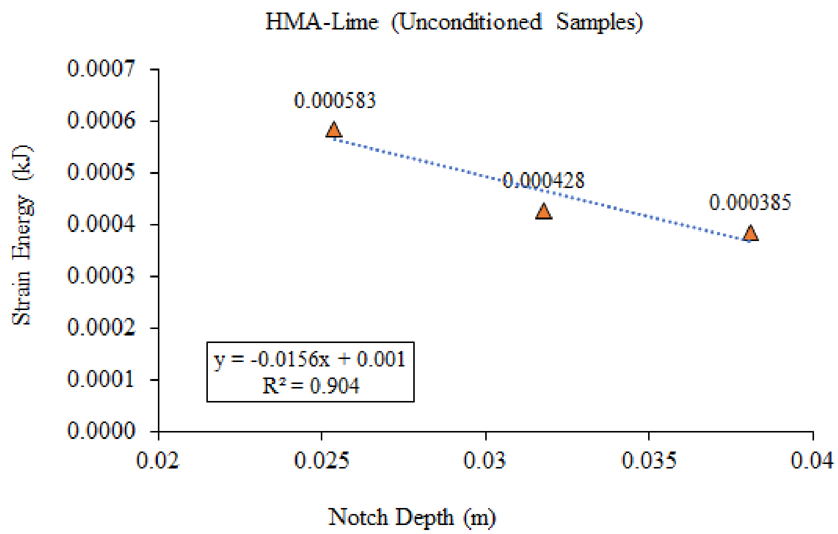
Summary of G_{mb} test result and AV calculation of SCB specimens prepared by HMA

Asphalt mix type	Name of the SCB specimen	G_{mb}	AV (%)
HMA-Lime	B1-M1-T1-S1-25.4 mm	2.284	7.2
	B1-M1-T1-S1-31.75 mm	2.276	7.5
	B1-M1-T1-S1-38.1 mm	2.285	7.2
	B1-M1-T1-S2-25.4 mm	2.280	7.4
	B1-M1-T1-S2-31.75 mm	2.295	6.7
	B1-M1-T1-S2-38.1 mm	2.283	7.2
	B1-M1-T1-S3-25.4 mm	2.282	7.3
	B1-M1-T1-S3-31.75 mm	2.277	7.5
	B1-M1-T1-S3-38.1 mm	2.296	6.7
	B1-M1-T1-S4-25.4 mm	2.277	7.5
	B1-M1-T1-S4-31.75 mm	2.289	7
	B1-M1-T1-S4-38.1 mm	2.292	6.9
	B1-M1-T1-S5-25.4 mm	2.286	7.1
	B1-M1-T1-S5-31.75 mm	2.283	7.2
	B1-M1-T1-S5-38.1 mm	2.280	7.4
	B1-M1-T1-S6-25.4 mm	2.287	7.1
	B1-M1-T1-S6-31.75 mm	2.284	7.2
	B1-M1-T1-S6-38.1 mm	2.280	7.4
HMA-RAP	B2-M2-T1-S1-25.4 mm	2.314	7
	B2-M2-T1-S1-31.75 mm	2.314	7
	B2-M2-T1-S1-38.1 mm	2.32	6.8
	B2-M2-T1-S2-25.4 mm	2.313	7
	B2-M2-T1-S2-31.75 mm	2.303	7.4
	B2-M2-T1-S2-38.1 mm	2.311	7.1
	B2-M2-T1-S3-25.4 mm	2.307	7.3
	B2-M2-T1-S3-31.75 mm	2.301	7.5
	B2-M2-T1-S3-38.1 mm	2.316	6.9
	B2-M2-T1-S4-25.4 mm	2.324	6.6
	B2-M2-T1-S4-31.75 mm	2.316	6.9
	B2-M2-T1-S4-38.1 mm	2.302	7.5
	B2-M2-T1-S5-25.4 mm	2.301	7.5

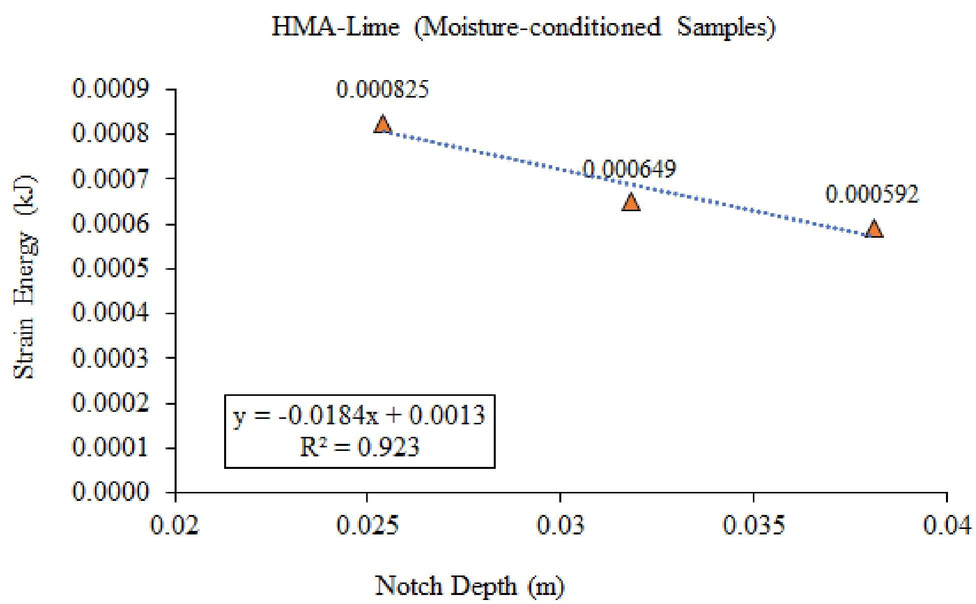
	B2-M2-T1-S5-31.75 mm	2.301	7.5
	B2-M2-T1-S5-38.1 mm	2.304	7.4
	B2-M2-T1-S6-25.4 mm	2.301	7.5
	B2-M2-T1-S6-31.75 mm	2.303	7.4
	B2-M2-T1-S6-38.1 mm	2.314	7
Asphalt mix type	**Name of the SCB specimen**	**G_{mb}**	**AV (%)**
C-WMA	B3-M3-T1-S1-25.4 mm	2.269	7.5
	B3-M3-T1-S1-31.75 mm	2.291	6.6
	B3-M3-T1-S1-38.1 mm	2.285	6.8
	B3-M3-T1-S2-25.4 mm	2.291	6.6
	B3-M3-T1-S2-31.75 mm	2.274	7.3
	B3-M3-T1-S2-38.1 mm	2.283	6.9
	B3-M3-T1-S3-25.4 mm	2.268	7.5
	B3-M3-T1-S3-31.75 mm	2.273	7.3
	B3-M3-T1-S3-38.1 mm	2.289	6.7
	B3-M3-T1-S4-25.4 mm	2.294	6.5
	B3-M3-T1-S4-31.75 mm	2.28	7.1
	B3-M3-T1-S4-38.1 mm	2.282	7
	B3-M3-T1-S5-25.4 mm	2.274	7.3
	B3-M3-T1-S5-31.75 mm	2.274	7.3
	B3-M3-T1-S5-38.1 mm	2.279	7.1
	B3-M3-T1-S6-25.4 mm	2.273	7.3
	B3-M3-T1-S6-31.75 mm	2.286	6.8
	B3-M3-T1-S6-38.1 mm	2.288	6.7

APPENDIX B

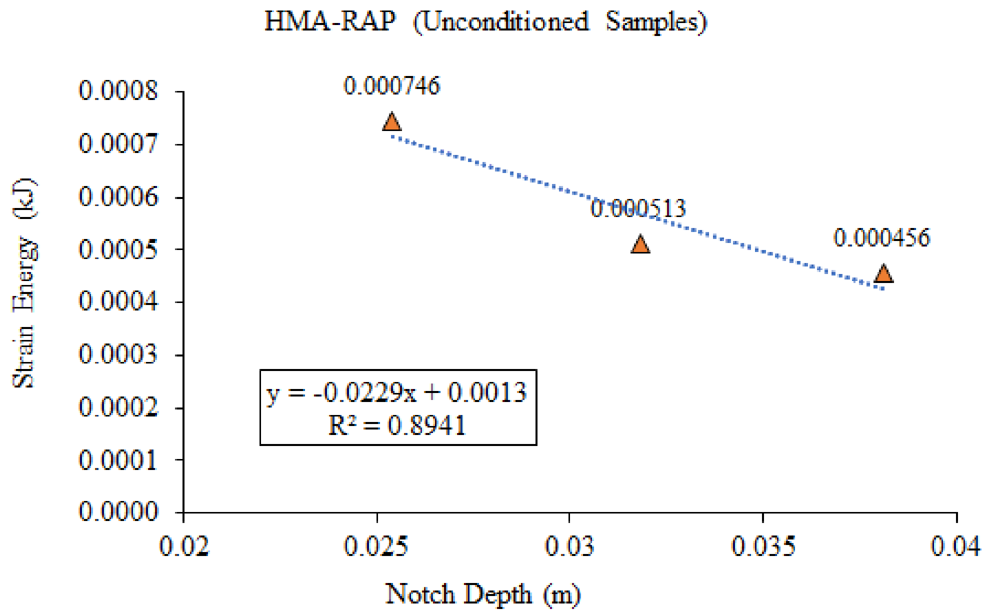
Variation of strain energy with notch depth in unconditioned HMA-Lime



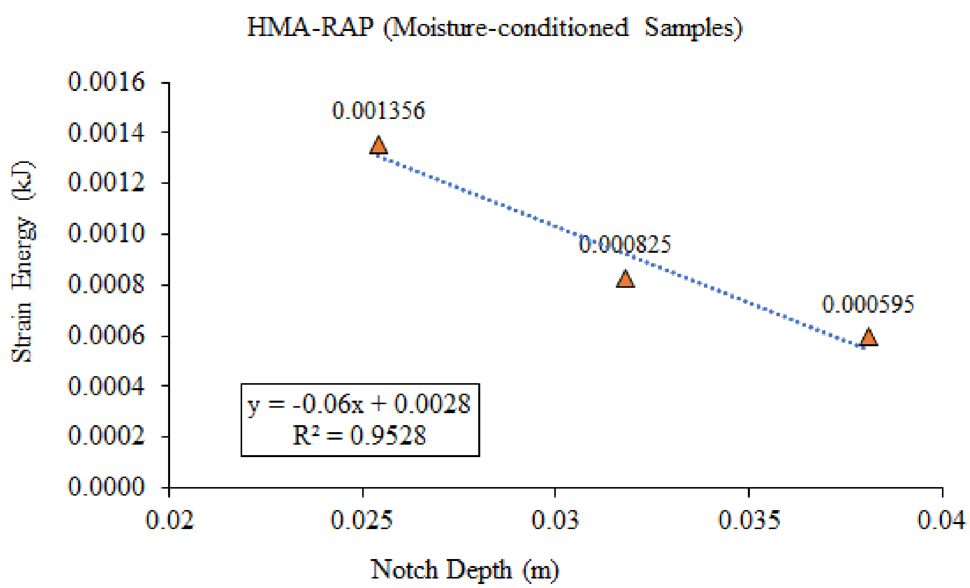
Variation of strain energy with notch depth in moisture-conditioned HMA-Lime samples



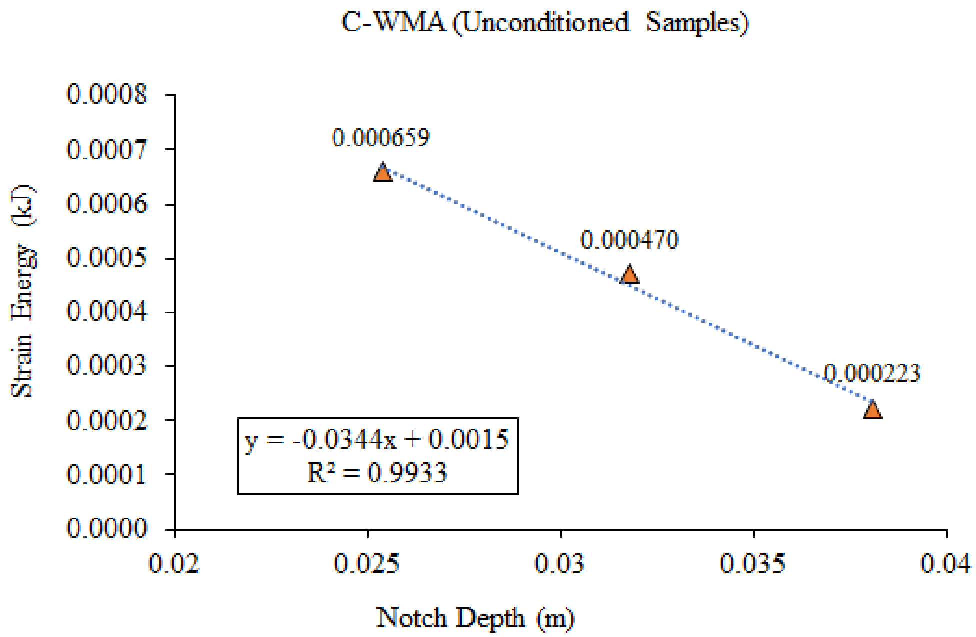
Variation of strain energy with notch depth in unconditioned HMA-RAP samples



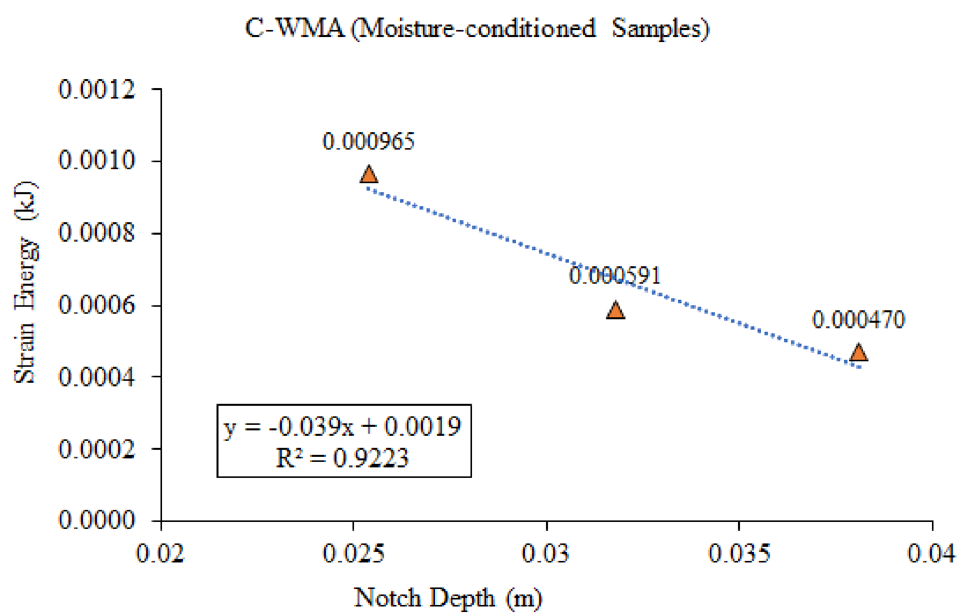
Variation of strain energy with notch depth in moisture-conditioned HMA-RAP samples



Variation of strain energy with notch depth in unconditioned C-WMA samples



Relation between strain energy and notch depth in moisture-conditioned C-WMA samples



APPENDIX C

- Two sample two-tailed t-test (difference in mean), F test (difference in variance)
- Unpaired (two groups tested once), F (ratio of larger variance to small variance)
- $F > F_{critical}$ for the degree of freedom (4)/unequal variance, p value<0.05
- Unequal variance: degree of freedom= $\dfrac{\left(\frac{s1^2}{n1}+\frac{s2^2}{n2}\right)^2}{\dfrac{\left(\frac{s1^2}{n1}\right)^2}{n1-1}+\dfrac{\left(\frac{s2^2}{n2}\right)^2}{n2-1}}$
- Equal variance: $sp^2 = \dfrac{(n1-1)s1^2+(n2-1)s2^2}{n1+n2-2}$
- $t_{equal} = \dfrac{\left((\overline{X1}) - (\overline{X2})\ \right)-(\mu1-\mu2)}{\sqrt{\left(\frac{sp^2}{n1}\right)+\left(\frac{sp^2}{n2}\right)}}$, $t_{unequal} = \dfrac{\left((\overline{X1}) - (\overline{X2})\ \right)-(\mu1-\mu2)}{\sqrt{\left(\frac{s1^2}{n1}\right)+\left(\frac{s2^2}{n2}\right)}}$

D=Significantly different average pull-off strength **S=Significantly same average pull-off strength**				Gravel															
Statistical significance				Unconditioned															
				PG 58-28				PG 64-22				PG 64-34				PG 70-28			
				Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA
Gravel	Unconditioned	PG 58-28	Neat	S	S	D	S	S	D	D	D	D	S	D	D	D	D	S	S
			RAP	S	S	D	S	S	D	D	D	D	D	D	D	S	D	S	S
			WMA	D	D	S	D	D	D	D	D	S	D	D	D	D	D	D	D
			ASA	S	S	D	S	D	D	D	D	D	S	S	D	D	D	S	D
		PG 64-22	Neat	S	S	D	D	S	D	S	D	D	D	D	D	S	D	S	S
			RAP	D	D	D	D	D	S	D	D	D	D	D	D	D	D	D	D
			WMA	D	D	D	D	S	D	S	D	D	D	D	D	S	S	S	S
			ASA	D	D	D	D	D	D	D	S	D	D	D	D	D	D	D	D
		PG 64-34	Neat	D	D	S	D	D	D	D	D	S	D	D	S	D	D	D	D
			RAP	S	D	D	S	D	D	D	D	D	S	S	D	D	D	S	D
			WMA	D	D	D	S	D	D	D	D	D	S	S	D	D	D	D	D
			ASA	D	D	D	D	D	D	D	D	S	D	D	S	D	D	D	D
		PG 70-28	Neat	D	S	D	D	S	D	S	D	D	D	D	D	S	D	S	S
			RAP	D	D	D	D	D	D	S	D	D	D	D	D	D	S	D	D
			WMA	S	S	D	S	S	D	S	D	D	S	D	D	S	D	S	S
			ASA	S	S	D	D	S	D	S	D	D	D	D	D	S	D	S	S

D=Significantly different average pull-off strength S=Significantly same average pull-off strength				Gravel															
Statistical significance				Moisture Conditioned															
				PG 58-28				PG 64-22				PG 64-34				PG 70-28			
				Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA
Gravel	Unconditioned	PG 58-28	Neat	D	D	D	D	D	S	S	D	D	D	D	D	D	S	S	D
			RAP	D	D	D	D	D	S	S	D	D	D	D	D	D	S	S	D
			WMA	D	D	D	D	S	D	D	D	D	D	S	S	S	D	D	D
			ASA	D	D	S	S	D	S	S	S	D	D	D	D	D	S	D	S
		PG 64-22	Neat	D	D	D	D	D	D	S	D	D	D	D	D	D	D	S	D
			RAP	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
			WMA	D	D	D	D	D	D	D	D	D	D	D	D	D	D	S	D
			ASA	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
		PG 64-34	Neat	D	D	D	D	S	D	D	D	D	D	S	S	S	D	D	D
			RAP	D	D	S	S	D	S	S	S	D	D	D	D	D	S	D	S
			WMA	D	D	S	S	D	S	S	S	D	D	D	D	D	S	D	S
			ASA	D	D	D	D	S	D	D	D	D	D	S	S	D	D	D	D
		PG 70-28	Neat	D	D	D	D	D	D	D	D	D	D	D	D	D	D	S	D
			RAP	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
			WMA	D	D	D	D	D	S	S	D	D	D	D	D	D	S	S	D
			ASA	D	D	D	D	D	D	D	D	D	D	D	D	D	D	S	D

D=Significantly different average pull-off strength S=Significantly same average pull-off strength				Quartzite															
Statistical significance				Unconditioned															
				PG 58-28				PG 64-22				PG 64-34				PG 70-28			
				Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA
Gravel	Unconditioned	PG 58-28	Neat	S	S	D	D	D	D	S	D	D	D	D	D	S	D	S	D
			RAP	S	D	D	D	D	D	S	D	D	D	D	D	S	D	S	D
			WMA	D	D	D	S	D	D	D	D	S	D	S	S	D	D	D	D
			ASA	D	S	S	S	D	D	D	D	D	S	S	D	D	D	S	D
		PG 64-22	Neat	S	D	D	D	S	D	S	D	D	D	D	D	S	D	S	S
			RAP	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
			WMA	D	D	D	D	S	D	S	D	D	D	D	D	D	D	D	S
			ASA	D	D	D	D	D	S	D	S	D	D	D	D	D	S	D	D
		PG 64-34	Neat	D	D	D	D	D	D	D	D	S	D	D	S	D	D	D	D
			RAP	D	S	S	S	D	D	D	D	D	S	S	D	D	D	S	D
			WMA	D	S	S	S	D	D	D	D	D	S	S	D	D	D	D	D
			ASA	D	D	D	D	D	D	D	D	S	D	D	S	D	D	D	D
		PG 70-28	Neat	S	D	D	D	D	D	S	D	D	D	D	D	S	D	S	S
			RAP	D	D	D	D	S	D	D	D	D	D	D	D	D	D	D	D
			WMA	S	S	D	D	D	D	S	D	D	D	D	D	S	D	S	S
			ASA	S	D	D	D	D	D	S	D	D	D	D	D	S	D	S	S

D=Significantly different average pull-off strength S=Significantly same average pull-off strength				Quartzite															
Statistical significance				Moisture Conditioned															
				PG 58-28				PG 64-22				PG 64-34				PG 70-28			
				Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA
Gravel	Unconditioned	PG 58-28	Neat	D	D	D	S	D	D	S	D	D	D	D	D	S	S	S	S
			RAP	D	D	D	S	D	D	D	D	D	D	D	D	D	S	S	D
			WMA	S	S	S	D	S	S	D	D	D	S	D	S	D	D	D	D
			ASA	D	D	S	S	S	D	S	S	D	D	D	D	S	S	D	S
		PG 64-22	Neat	D	D	D	D	D	D	S	D	D	D	D	D	S	S	S	D
			RAP	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
			WMA	D	D	D	D	D	D	D	D	D	D	D	D	D	D	S	D
			ASA	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
		PG 64-34	Neat	S	S	D	D	D	S	D	D	D	S	D	S	D	D	D	D
			RAP	D	D	D	S	S	D	S	S	D	D	D	D	S	S	D	S
			WMA	D	D	D	S	S	D	D	S	D	D	D	D	D	D	D	S
			ASA	D	S	D	D	D	D	D	D	D	S	D	S	D	D	D	D
		PG 70-28	Neat	D	D	D	D	D	D	D	D	D	D	D	D	D	S	S	D
			RAP	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
			WMA	D	D	D	S	D	D	S	D	D	D	D	D	S	S	S	D
			ASA	D	D	D	D	D	D	D	D	D	D	D	D	D	S	S	D

D=Significantly different average pull-off strength S=Significantly same average pull-off strength				Granite															
Statistical significance				Unconditioned															
				PG 58-28				PG 64-22				PG 64-34				PG 70-28			
				Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA
Gravel	Unconditioned	PG 58-28	Neat	S	S	D	D	D	D	D	D	D	S	D	D	S	D	S	D
			RAP	S	S	D	D	D	D	S	D	D	D	D	D	S	D	S	D
			WMA	D	D	D	D	D	D	D	D	S	D	D	D	D	D	D	D
			ASA	S	S	S	S	D	D	D	D	D	S	S	D	D	D	S	D
		PG 64-22	Neat	S	S	D	D	S	D	S	D	D	S	D	D	S	D	S	S
			RAP	D	D	D	D	D	S	D	S	D	D	D	D	D	D	D	D
			WMA	D	S	D	D	S	D	S	D	D	D	D	D	S	D	S	S
			ASA	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
		PG 64-34	Neat	D	D	D	D	D	D	D	D	S	D	D	S	D	D	D	D
			RAP	S	S	S	S	D	D	D	D	D	S	S	D	D	D	S	D
			WMA	D	S	S	S	D	D	D	D	D	D	S	D	D	D	D	D
			ASA	D	D	D	D	D	D	D	D	S	D	D	S	D	D	D	D
		PG 70-28	Neat	D	S	D	D	D	D	S	D	D	D	D	D	S	D	S	S
			RAP	D	D	D	D	S	D	D	D	D	D	D	D	D	S	D	S
			WMA	S	S	D	D	D	D	S	D	D	S	D	D	S	D	S	D
			ASA	D	S	D	D	D	D	S	D	D	D	D	D	S	D	S	S

D=Significantly different average pull-off strength S=Significantly same average pull-off strength				Granite															
				Moisture Conditioned															
Statistical significance				PG 58-28				PG 64-22				PG 64-34				PG 70-28			
				Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA
Gravel	Unconditioned	PG 58-28	Neat	D	D	S	D	D	D	S	D	D	D	D	D	D	D	D	D
			RAP	D	D	D	D	D	D	S	D	D	D	D	D	D	D	D	D
			WMA	D	D	D	S	S	D	D	D	D	D	D	D	D	D	S	D
			ASA	S	D	S	D	D	D	S	D	D	D	D	D	D	S	D	S
		PG 64-22	Neat	D	D	S	D	D	D	S	D	D	D	D	D	D	D	D	D
			RAP	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
			WMA	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
			ASA	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
		PG 64-34	Neat	D	D	D	S	S	S	D	S	D	D	S	D	D	D	S	D
			RAP	S	D	S	D	D	D	S	D	D	D	D	D	D	D	D	S
			WMA	S	D	D	D	D	D	S	D	D	D	D	D	D	S	D	S
			ASA	D	D	D	S	S	S	D	S	D	D	S	D	S	D	S	D
		PG 70-28	Neat	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
			RAP	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
			WMA	D	D	S	D	D	D	S	D	D	D	D	D	D	D	D	D
			ASA	D	D	D	D	D	D	S	D	D	D	D	D	D	D	D	D

D=Significantly different average pull-off strength S=Significantly same average pull-off strength				Gravel															
				Unconditioned															
Statistical significance				PG 58-28				PG 64-22				PG 64-34				PG 70-28			
				Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA
Gravel	Moisture Conditioned	PG 58-28	Neat	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
			RAP	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
			WMA	D	D	D	S	D	D	D	D	D	S	S	D	D	D	D	D
			ASA	D	D	D	S	D	D	D	D	D	S	S	D	D	D	D	D
		PG 64-22	Neat	D	D	S	D	D	D	D	D	S	D	D	S	D	D	D	D
			RAP	S	S	D	S	D	D	D	D	D	S	S	D	D	D	S	D
			WMA	S	S	D	S	S	D	D	D	D	S	S	D	D	D	S	D
			ASA	D	D	D	S	D	D	D	D	D	S	S	D	D	D	D	D
		PG 64-34	Neat	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
			RAP	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
			WMA	D	D	S	D	D	D	D	D	S	D	D	S	D	D	D	D
			ASA	D	D	S	D	D	D	D	D	S	D	D	S	D	D	D	D
		PG 70-28	Neat	D	D	S	D	D	D	D	D	S	D	D	D	D	D	D	D
			RAP	S	S	D	S	D	D	D	D	D	S	S	D	D	D	S	D
			WMA	S	S	D	D	S	D	S	D	D	D	D	D	S	D	S	S
			ASA	D	D	D	S	D	D	D	D	D	S	S	D	D	D	D	D

D=Significantly different average pull-off strength S=Significantly same average pull-off strength				Gravel															
				Moisture Conditioned															
Statistical significance				PG 58-28				PG 64-22				PG 64-34				PG 70-28			
				Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA
Gravel	Moisture Conditioned	PG 58-28	Neat	S	S	D	D	D	D	D	D	D	S	D	D	D	D	D	D
			RAP	S	S	D	D	D	D	D	D	D	S	D	D	D	D	D	D
			WMA	D	D	S	S	D	S	S	S	D	D	D	D	D	S	D	S
			ASA	D	D	S	S	D	S	S	S	D	D	D	D	S	S	D	S
		PG 64-22	Neat	D	D	D	D	S	D	D	D	D	D	S	S	S	D	D	D
			RAP	D	D	S	S	D	S	S	S	D	D	D	D	D	S	D	S
			WMA	D	D	S	S	D	S	S	S	D	D	D	D	D	S	D	S
			ASA	D	D	S	S	D	S	S	S	D	D	D	D	D	S	D	S
		PG 64-34	Neat	D	D	D	D	D	D	D	D	S	D	D	D	D	D	D	D
			RAP	S	S	D	D	D	D	D	D	D	S	D	D	D	D	D	D
			WMA	D	D	D	D	S	D	D	D	D	D	S	S	S	D	D	D
			ASA	D	D	D	D	S	D	D	D	D	D	S	S	S	D	D	D
		PG 70-28	Neat	D	D	D	S	S	D	D	D	D	D	S	S	S	D	D	D
			RAP	D	D	S	S	D	S	S	S	D	D	D	D	D	S	D	S
			WMA	D	D	D	D	D	D	D	D	D	D	D	D	D	D	S	D
			ASA	D	D	S	S	D	S	S	S	D	D	D	D	D	S	D	S

D=Significantly different average pull-off strength S=Significantly same average pull-off strength				Quartzite															
				Unconditioned															
Statistical significance				PG 58-28				PG 64-22				PG 64-34				PG 70-28			
				Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA
Gravel	Moisture Conditioned	PG 58-28	Neat	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
			RAP	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
			WMA	D	S	S	S	D	D	D	D	D	S	S	D	D	D	D	D
			ASA	D	D	S	S	D	D	D	D	D	S	S	D	D	D	D	D
		PG 64-22	Neat	D	D	D	S	D	D	D	D	S	D	D	S	D	D	D	D
			RAP	S	S	D	D	D	D	D	D	D	S	D	D	D	D	S	D
			WMA	S	S	S	D	D	D	D	D	D	S	S	D	S	D	S	D
			ASA	D	S	D	D	D	D	D	D	D	S	S	D	D	D	D	D
		PG 64-34	Neat	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
			RAP	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
			WMA	D	D	D	S	D	D	D	D	S	D	S	S	D	D	D	D
			ASA	D	D	D	S	D	D	D	D	S	D	S	S	D	D	D	D
		PG 70-28	Neat	D	D	S	S	D	D	D	D	S	D	S	S	D	D	D	D
			RAP	S	S	S	S	D	D	D	D	D	S	S	D	D	D	S	D
			WMA	S	D	D	D	D	D	S	D	D	D	D	D	S	D	S	S
			ASA	D	S	S	S	D	D	D	D	D	S	S	D	D	D	D	D

D=Significantly different average pull-off strength S=Significantly same average pull-off strength				Quartzite															
Statistical significance				Moisture Conditioned															
				PG 58-28				PG 64-22				PG 64-34				PG 70-28			
				Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA
Gravel	Moisture Conditioned	PG 58-28	Neat	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
			RAP	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
			WMA	D	D	S	S	S	S	D	S	D	D	S	D	D	D	D	S
			ASA	D	D	S	S	S	S	D	S	D	D	S	D	D	D	D	S
		PG 64-22	Neat	S	S	S	D	D	S	D	D	D	S	D	S	D	D	D	D
			RAP	D	D	D	S	S	D	S	S	D	D	D	D	S	S	D	S
			WMA	D	D	D	S	S	D	S	S	D	D	D	D	S	S	D	S
			ASA	D	D	D	S	S	D	D	S	D	D	D	D	S	S	D	S
		PG 64-34	Neat	D	D	D	D	D	D	D	D	S	D	D	D	D	D	D	D
			RAP	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
			WMA	S	S	S	D	D	S	D	D	D	S	D	S	D	D	D	D
			ASA	S	S	S	D	S	S	D	D	D	S	S	S	D	D	D	D
		PG 70-28	Neat	S	S	S	D	S	S	D	D	D	S	S	S	D	D	D	D
			RAP	D	D	D	S	S	D	S	S	D	D	D	D	S	S	D	S
			WMA	D	D	D	D	D	D	D	D	D	D	D	D	D	S	S	D
			ASA	D	D	S	S	S	D	D	S	D	D	D	D	S	S	D	S

D=Significantly different average pull-off strength S=Significantly same average pull-off strength				Granite															
Statistical significance				Unconditioned															
				PG 58-28				PG 64-22				PG 64-34				PG 70-28			
				Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA
Gravel	Moisture Conditioned	PG 58-28	Neat	D	D	D	D	D	D	D	D	D	D	D	S	D	D	D	D
			RAP	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
			WMA	D	D	S	S	D	D	D	D	D	D	S	D	D	D	D	D
			ASA	D	D	S	S	D	D	D	D	D	D	S	D	D	D	D	D
		PG 64-22	Neat	D	D	D	D	D	D	D	D	S	D	D	D	D	D	D	D
			RAP	S	S	S	S	D	D	D	D	D	S	S	D	D	D	S	D
			WMA	S	S	S	S	D	D	D	D	D	S	S	D	D	D	S	D
			ASA	D	S	S	S	D	D	D	D	D	S	S	D	D	D	D	D
		PG 64-34	Neat	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
			RAP	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
			WMA	D	D	D	D	D	D	D	D	S	D	D	S	D	D	D	D
			ASA	D	D	D	D	D	D	D	D	S	D	D	D	D	D	D	D
		PG 70-28	Neat	D	D	D	D	D	D	D	D	S	D	S	D	D	D	D	D
			RAP	S	S	S	S	D	D	D	D	D	S	S	D	D	D	S	D
			WMA	D	S	D	D	D	D	S	D	D	D	D	D	S	D	S	D
			ASA	D	D	S	S	D	D	D	D	D	S	S	D	D	D	D	D

D=Significantly different average pull-off strength S=Significantly same average pull-off strength				Granite															
Statistical significance				Moisture Conditioned															
				PG 58-28				PG 64-22				PG 64-34				PG 70-28			
				Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA
Gravel	Moisture Conditioned	PG 58-28	Neat	D	D	D	D	D	D	D	D	S	D	D	D	S	D	D	D
			RAP	D	D	D	D	D	D	D	D	S	D	D	D	S	D	D	D
			WMA	S	D	S	D	D	D	S	D	D	D	D	D	D	S	D	S
			ASA	S	D	D	D	D	D	S	D	D	D	D	S	D	S	D	S
		PG 64-22	Neat	D	D	D	S	S	S	D	S	D	D	S	D	D	D	S	D
			RAP	S	D	S	D	D	D	S	D	D	D	D	D	D	D	D	D
			WMA	S	D	S	D	D	D	S	D	D	D	D	D	D	D	D	D
			ASA	S	D	S	D	D	D	S	D	D	D	D	D	D	D	D	D
		PG 64-34	Neat	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
			RAP	D	D	D	D	D	D	D	D	S	D	D	D	S	D	D	D
			WMA	D	D	D	S	S	S	D	S	D	D	S	S	D	D	S	D
			ASA	D	D	D	S	S	S	D	D	D	D	S	S	D	D	S	D
		PG 70-28	Neat	D	D	D	S	S	S	D	D	D	D	D	S	D	S	S	S
			RAP	S	D	S	D	D	D	S	D	D	D	D	D	D	S	D	S
			WMA	D	D	D	D	D	D	S	D	D	D	D	D	D	D	D	D
			ASA	S	D	S	D	D	D	S	D	D	D	D	D	D	S	D	S

D=Significantly different average pull-off strength S=Significantly same average pull-off strength				Gravel															
Statistical significance				Unconditioned															
				PG 58-28				PG 64-22				PG 64-34				PG 70-28			
				Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA
Quartzite	Unconditioned	PG 58-28	Neat	S	S	D	D	S	D	D	D	D	D	D	D	S	D	S	S
			RAP	S	D	D	S	D	D	D	D	D	S	S	D	D	D	S	D
			WMA	D	D	D	S	D	D	D	D	D	S	S	D	D	D	D	D
			ASA	D	D	S	S	D	D	D	D	D	S	S	D	D	D	D	D
		PG 64-22	Neat	D	D	D	D	S	D	S	D	D	D	D	D	D	S	D	D
			RAP	D	D	D	D	D	D	D	S	D	D	D	D	D	D	D	D
			WMA	S	S	D	D	S	D	S	D	D	D	D	D	S	D	S	S
			ASA	D	D	D	D	D	D	D	S	D	D	D	D	D	D	D	D
		PG 64-34	Neat	D	D	S	D	D	D	D	D	S	D	D	S	D	D	D	D
			RAP	D	D	D	S	D	D	D	D	D	S	S	D	D	D	D	D
			WMA	D	D	S	S	D	D	D	D	D	S	S	D	D	D	D	D
			ASA	D	D	S	D	D	D	D	D	S	D	D	S	D	D	D	D
		PG 70-28	Neat	S	S	D	D	S	D	D	D	D	D	D	D	S	D	S	S
			RAP	D	D	D	D	D	D	D	S	D	D	D	D	D	D	D	D
			WMA	S	S	D	S	S	D	D	D	D	S	D	D	S	D	S	S
			ASA	D	D	D	D	S	D	S	D	D	D	D	D	S	D	S	S

D=Significantly different average pull-off strength S=Significantly same average pull-off strength				Gravel															
Statistical significance				Moisture Conditioned															
				PG 58-28				PG 64-22				PG 64-34				PG 70-28			
				Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA
Quartzite	Unconditioned	PG 58-28	Neat	D	D	D	D	D	S	S	D	D	D	D	D	D	S	S	D
			RAP	D	D	S	D	D	S	S	S	D	D	D	D	D	S	D	S
			WMA	D	D	S	S	D	D	S	D	D	D	D	D	S	S	D	S
			ASA	D	D	S	S	S	D	D	D	D	D	S	S	S	S	D	S
		PG 64-22	Neat	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
			RAP	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
			WMA	D	D	D	D	D	D	D	D	D	D	D	D	D	D	S	D
			ASA	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
		PG 64-34	Neat	D	D	D	D	S	D	D	D	D	D	S	S	S	D	D	D
			RAP	D	D	S	S	D	S	S	S	D	D	D	D	D	S	D	S
			WMA	D	D	S	S	D	D	S	S	D	D	S	S	S	S	D	S
			ASA	D	D	D	D	S	D	D	D	D	D	S	S	S	D	D	D
		PG 70-28	Neat	D	D	D	D	D	D	S	D	D	D	D	D	D	D	S	D
			RAP	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
			WMA	D	D	D	D	D	S	S	D	D	D	D	D	D	S	S	D
			ASA	D	D	D	D	D	D	D	D	D	D	D	D	D	D	S	D

D=Significantly different average pull-off strength S=Significantly same average pull-off strength				Quartzite															
Statistical significance				Unconditioned															
				PG 58-28				PG 64-22				PG 64-34				PG 70-28			
				Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA
Quartzite	Unconditioned	PG 58-28	Neat	S	D	D	D	D	D	S	D	D	D	D	D	S	D	S	D
			RAP	D	S	D	D	D	D	D	D	D	S	D	D	D	D	S	D
			WMA	D	D	S	S	D	D	D	D	D	D	S	D	D	D	D	D
			ASA	D	D	S	S	D	D	D	D	S	S	S	S	D	D	D	D
		PG 64-22	Neat	D	D	D	D	S	D	S	D	D	D	D	D	D	D	D	D
			RAP	D	D	D	D	D	S	D	S	D	D	D	D	D	D	D	D
			WMA	S	D	D	D	S	D	S	D	D	D	D	D	S	D	S	S
			ASA	D	D	D	D	D	S	D	S	D	D	D	D	D	S	D	D
		PG 64-34	Neat	D	D	D	S	D	D	D	D	S	D	S	S	D	D	D	D
			RAP	D	S	D	S	D	D	D	D	D	S	S	D	D	D	D	D
			WMA	D	D	S	S	D	D	D	D	S	S	S	D	D	D	D	D
			ASA	D	D	D	S	D	D	D	D	S	D	D	S	D	D	D	D
		PG 70-28	Neat	S	D	D	D	D	D	S	D	D	D	D	D	S	D	S	D
			RAP	D	D	D	D	D	D	D	S	D	D	D	D	D	S	D	D
			WMA	S	S	D	D	D	D	S	D	D	D	D	D	S	D	S	D
			ASA	D	D	D	D	D	D	S	D	D	D	D	D	D	D	D	S

D=Significantly different average pull-off strength S=Significantly same average pull-off strength				Quartzite															
Statistical significance				Moisture Conditioned															
				PG 58-28				PG 64-22				PG 64-34				PG 70-28			
				Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA
Quartzite	Unconditioned	PG 58-28	Neat	D	D	D	S	D	D	S	D	D	D	D	D	D	S	S	D
			RAP	D	D	D	S	D	D	S	S	D	D	D	D	S	S	D	S
			WMA	D	D	S	S	S	S	D	D	D	D	S	D	D	D	D	S
			ASA	S	S	S	S	S	S	D	S	D	S	S	S	D	D	D	S
		PG 64-22	Neat	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
			RAP	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
			WMA	D	D	D	D	D	D	S	D	D	D	D	D	D	S	S	D
			ASA	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
		PG 64-34	Neat	S	S	S	D	D	S	D	D	D	S	D	S	D	D	D	D
			RAP	D	D	D	S	S	D	D	S	D	D	D	D	D	D	D	S
			WMA	S	D	S	S	S	S	D	S	D	S	S	S	D	D	D	S
			ASA	S	S	S	D	D	S	D	D	D	S	D	S	D	D	D	D
		PG 70-28	Neat	D	D	D	D	D	D	D	D	D	D	D	D	D	S	S	D
			RAP	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
			WMA	D	D	D	S	D	D	S	D	D	D	D	D	S	S	S	S
			ASA	D	D	D	D	D	D	D	D	D	D	D	D	D	D	S	D

D=Significantly different average pull-off strength S=Significantly same average pull-off strength				Granite															
Statistical significance				Unconditioned															
				PG 58-28				PG 64-22				PG 64-34				PG 70-28			
				Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA
Quartzite	Unconditioned	PG 58-28	Neat	S	S	D	D	D	D	S	D	D	D	D	D	S	D	S	D
			RAP	S	S	S	S	D	D	D	D	D	S	S	D	D	D	S	D
			WMA	D	D	S	S	D	D	D	D	D	D	S	D	D	D	D	D
			ASA	D	D	S	S	D	D	D	D	S	D	S	D	D	D	D	D
		PG 64-22	Neat	D	D	D	D	S	D	S	D	D	D	D	D	D	S	D	S
			RAP	D	D	D	D	D	S	D	S	D	D	D	D	D	D	D	D
			WMA	S	S	D	D	D	D	S	D	D	S	D	D	S	D	S	S
			ASA	D	D	D	D	D	D	D	S	D	D	D	D	D	S	D	S
		PG 64-34	Neat	D	D	D	D	D	D	D	D	S	D	D	D	D	D	D	D
			RAP	D	S	S	S	D	D	D	D	D	D	S	D	D	D	D	D
			WMA	D	D	S	S	D	D	D	D	S	D	S	D	D	D	D	D
			ASA	D	D	D	D	D	D	D	D	S	D	D	S	D	D	D	D
		PG 70-28	Neat	S	S	D	D	D	D	S	D	D	D	D	D	S	D	S	D
			RAP	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
			WMA	S	S	D	D	D	D	S	D	D	S	D	D	S	D	S	D
			ASA	D	S	D	D	D	D	S	D	D	D	D	D	S	D	S	S

D=Significantly different average pull-off strength S=Significantly same average pull-off strength				Granite															
Statistical significance				Moisture Conditioned															
				PG 58-28				PG 64-22				PG 64-34				PG 70-28			
				Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA
Quartzite	Unconditioned	PG 58-28	Neat	D	D	D	D	D	D	S	D	D	D	D	D	D	D	D	D
			RAP	S	D	S	D	D	D	S	D	D	D	D	D	D	D	D	D
			WMA	D	D	D	D	D	D	S	D	D	D	D	D	D	S	D	S
			ASA	S	D	D	S	D	D	D	D	D	D	D	S	D	S	S	S
		PG 64-22	Neat	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
			RAP	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
			WMA	D	D	D	D	D	D	S	D	D	D	D	D	D	D	D	D
			ASA	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
		PG 64-34	Neat	D	D	D	S	S	S	D	S	D	D	S	D	D	D	S	D
			RAP	S	D	S	D	D	D	S	D	D	D	D	D	D	S	D	S
			WMA	S	D	D	D	D	D	D	D	D	D	D	S	D	S	S	S
			ASA	D	D	D	S	S	S	D	S	D	D	S	S	D	D	S	D
		PG 70-28	Neat	D	D	D	D	D	D	S	D	D	D	D	D	D	D	D	D
			RAP	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
			WMA	D	D	S	D	D	D	S	D	D	D	D	D	D	D	D	D
			ASA	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D

D=Significantly different average pull-off strength S=Significantly same average pull-off strength				Gravel															
Statistical significance				Unconditioned															
				PG 58-28				PG 64-22				PG 64-34				PG 70-28			
				Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA
Quartzite	Moisture Conditioned	PG 58-28	Neat	D	D	S	D	D	D	D	D	S	D	D	D	D	D	D	D
			RAP	D	D	S	D	D	D	D	D	S	D	D	S	D	D	D	D
			WMA	D	D	S	S	D	D	D	D	D	D	D	D	D	D	D	D
			ASA	S	S	D	S	D	D	D	D	D	S	S	D	D	D	S	D
		PG 64-22	Neat	D	D	S	S	D	D	D	D	D	S	S	D	D	D	D	D
			RAP	D	D	S	D	D	D	D	D	S	D	D	D	D	D	D	D
			WMA	S	D	D	S	S	D	D	D	D	S	D	D	D	D	S	D
			ASA	D	D	D	S	D	D	D	D	D	S	S	D	D	D	D	D
		PG 64-34	Neat	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
			RAP	D	D	S	D	D	D	D	D	S	D	D	S	D	D	D	D
			WMA	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
			ASA	D	D	S	D	D	D	D	D	S	D	D	S	D	D	D	D
		PG 70-28	Neat	S	D	D	S	S	D	D	D	D	S	D	D	D	D	S	D
			RAP	S	S	D	S	S	D	D	D	D	S	D	D	S	D	S	S
			WMA	S	S	D	D	S	D	S	D	D	D	D	D	S	D	S	S
			ASA	S	D	D	S	D	D	D	D	D	S	S	D	D	D	D	D

D=Significantly different average pull-off strength
S=Significantly same average pull-off strength

Statistical significance				Gravel															
				Moisture Conditioned															
				PG 58-28				PG 64-22				PG 64-34				PG 70-28			
				Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA
Quartzite	Moisture Conditioned	PG 58-28	Neat	D	D	D	D	S	D	D	D	D	D	S	S	S	D	D	D
			RAP	D	D	D	D	S	D	D	D	D	D	S	S	S	D	D	D
			WMA	D	D	S	S	S	D	D	D	D	D	S	S	S	D	D	S
			ASA	D	D	S	S	D	S	S	S	D	D	D	D	D	S	D	S
		PG 64-22	Neat	D	D	S	S	D	S	S	S	D	D	D	S	S	S	D	S
			RAP	D	D	S	S	S	D	D	D	D	D	S	S	S	D	D	D
			WMA	D	D	D	D	D	S	S	D	D	D	D	D	D	S	D	D
			ASA	D	D	S	S	D	S	S	S	D	D	D	D	D	S	D	S
		PG 64-34	Neat	D	D	D	D	D	D	D	D	S	D	D	D	D	D	D	D
			RAP	D	D	D	D	S	D	D	D	D	D	S	S	S	D	D	D
			WMA	D	D	S	S	D	D	D	D	D	D	D	S	S	D	D	D
			ASA	D	D	D	D	S	D	D	D	D	D	S	S	S	D	D	D
		PG 70-28	Neat	D	D	D	D	D	S	S	S	D	D	D	D	D	S	D	S
			RAP	D	D	D	D	D	S	S	S	D	D	D	D	D	S	S	S
			WMA	D	D	D	D	D	D	D	D	D	D	D	D	D	D	S	D
			ASA	D	D	S	S	D	S	S	S	D	D	D	D	D	S	D	S

D=Significantly different average pull-off strength
S=Significantly same average pull-off strength

Statistical significance				Quartzite															
				Unconditioned															
				PG 58-28				PG 64-22				PG 64-34				PG 70-28			
				Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA
Quartzite	Moisture Conditioned	PG 58-28	Neat	D	D	D	S	D	D	D	D	S	D	S	S	D	D	D	D
			RAP	D	D	D	S	D	D	D	D	S	D	D	S	D	D	D	D
			WMA	D	D	S	S	D	D	D	D	S	D	S	S	D	D	D	D
			ASA	S	S	S	S	D	D	D	D	D	S	S	D	D	D	S	D
		PG 64-22	Neat	D	D	S	S	D	D	D	D	D	S	S	D	D	D	D	D
			RAP	D	D	S	S	D	D	D	D	S	D	S	S	D	D	D	D
			WMA	S	S	D	D	D	D	S	D	D	D	D	D	D	D	S	D
			ASA	D	S	D	S	D	D	D	D	D	S	S	D	D	D	D	D
		PG 64-34	Neat	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
			RAP	D	D	D	S	D	D	D	D	S	D	S	S	D	D	D	D
			WMA	D	D	S	S	D	D	D	D	D	D	S	D	D	D	D	D
			ASA	D	D	D	S	D	D	D	D	S	D	S	S	D	D	D	D
		PG 70-28	Neat	D	S	D	D	D	D	D	D	D	D	D	D	D	D	S	D
			RAP	S	S	D	D	D	D	S	D	D	D	D	D	S	D	S	D
			WMA	S	D	D	D	D	D	S	D	D	D	D	D	S	D	S	S
			ASA	D	S	S	S	D	D	D	D	D	S	S	D	D	D	S	D

D=Significantly different average pull-off strength S=Significantly same average pull-off strength				Quartzite															
Statistical significance				Moisture Conditioned															
				PG 58-28				PG 64-22				PG 64-34				PG 70-28			
				Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA
Quartzite	Moisture Conditioned	PG 58-28	Neat	S	S	S	D	S	S	D	D	D	S	S	S	D	D	D	D
			RAP	S	S	S	D	D	S	D	D	D	S	D	S	D	D	D	D
			WMA	S	S	S	D	S	S	D	D	D	S	S	S	D	D	D	D
			ASA	D	D	D	S	S	D	S	S	D	D	D	D	S	S	D	S
		PG 64-22	Neat	S	D	S	S	S	S	D	S	D	S	S	D	D	D	D	S
			RAP	S	S	S	D	S	S	D	D	D	S	S	S	D	D	D	D
			WMA	D	D	D	S	D	D	S	D	D	D	D	D	S	S	S	S
			ASA	D	D	D	S	S	D	D	S	D	D	D	D	S	S	D	S
		PG 64-34	Neat	D	D	D	D	D	D	D	D	S	D	D	D	D	D	D	D
			RAP	S	S	S	D	S	S	D	D	D	S	S	S	D	D	D	D
			WMA	S	D	S	D	S	S	D	D	D	S	S	S	D	D	D	D
			ASA	S	S	S	D	D	S	D	D	D	S	S	S	D	D	D	D
		PG 70-28	Neat	D	D	D	S	D	D	S	S	D	D	D	D	S	S	D	S
			RAP	D	D	D	S	D	D	S	S	D	D	D	D	S	S	S	S
			WMA	D	D	D	D	D	D	S	D	D	D	D	D	D	S	S	D
			ASA	D	D	D	S	S	D	S	S	D	D	D	D	S	S	D	S

D=Significantly different average pull-off strength S=Significantly same average pull-off strength				Granite															
Statistical significance				Unconditioned															
				PG 58-28				PG 64-22				PG 64-34				PG 70-28			
				Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA
Quartzite	Moisture Conditioned	PG 58-28	Neat	D	D	D	D	D	D	D	D	S	D	D	D	D	D	D	D
			RAP	D	D	D	D	D	D	D	D	S	D	D	S	D	D	D	D
			WMA	D	D	S	S	D	D	D	D	S	D	S	D	D	D	D	D
			ASA	S	S	S	S	D	D	D	D	D	S	S	D	D	D	S	D
		PG 64-22	Neat	D	D	S	S	D	D	D	D	S	D	S	D	D	D	D	D
			RAP	D	D	D	S	D	D	D	D	S	D	S	D	D	D	D	D
			WMA	S	S	D	D	D	D	D	D	D	S	S	D	D	D	S	D
			ASA	D	S	S	S	D	D	D	D	D	S	S	D	D	D	D	D
		PG 64-34	Neat	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
			RAP	D	D	D	D	D	D	D	D	S	D	D	D	D	D	D	D
			WMA	D	D	D	S	D	D	D	D	S	D	S	D	D	D	D	D
			ASA	D	D	D	D	D	D	D	D	S	D	D	S	D	D	D	D
		PG 70-28	Neat	S	S	S	D	D	D	D	D	D	S	S	D	D	D	S	D
			RAP	S	S	S	D	D	D	D	D	D	S	S	D	S	D	S	D
			WMA	S	S	D	D	D	D	S	D	D	D	D	D	S	D	S	S
			ASA	S	S	S	S	D	D	D	D	D	S	S	D	D	D	S	D

D=Significantly different average pull-off strength S=Significantly same average pull-off strength				Granite															
Statistical significance				Moisture Conditioned															
				PG 58-28				PG 64-22				PG 64-34				PG 70-28			
				Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA
Quartzite	Moisture Conditioned	PG 58-28	Neat	D	D	D	S	S	D	D	D	D	D	D	S	D	D	S	D
			RAP	D	D	D	S	S	S	D	S	D	D	S	D	D	D	S	D
			WMA	D	D	D	S	D	S	D	D	D	D	D	S	D	S	S	S
			ASA	S	D	S	D	D	D	S	D	D	D	D	D	D	S	D	S
		PG 64-22	Neat	S	D	D	D	D	D	S	D	D	D	D	S	D	S	S	S
			RAP	D	D	D	S	S	S	D	D	D	D	D	S	D	S	S	S
			WMA	D	D	S	D	D	D	S	D	D	D	D	D	D	D	D	D
			ASA	S	D	S	D	D	D	S	D	D	D	D	D	D	D	D	S
		PG 64-34	Neat	D	D	D	D	D	D	D	D	D	S	D	D	D	D	D	D
			RAP	D	D	D	S	S	S	D	S	D	D	S	S	D	D	S	S
			WMA	D	D	D	D	D	D	D	D	D	D	D	S	D	S	S	S
			ASA	D	D	D	S	S	S	D	S	D	D	S	S	D	D	S	D
		PG 70-28	Neat	S	D	S	D	D	D	S	D	D	D	D	D	D	D	D	D
			RAP	S	D	S	D	D	D	S	D	D	D	D	D	D	D	D	D
			WMA	D	D	D	D	D	D	S	D	D	D	D	D	D	D	D	D
			ASA	S	D	S	D	D	D	S	D	D	D	D	D	D	S	D	S

D=Significantly different average pull-off strength S=Significantly same average pull-off strength				Gravel															
Statistical significance				Unconditioned															
				PG 58-28				PG 64-22				PG 64-34				PG 70-28			
				Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA
Granite	Unconditioned	PG 58-28	Neat	S	S	D	S	S	D	D	D	D	S	D	D	D	D	S	D
			RAP	S	S	D	S	S	D	S	D	D	S	S	D	S	D	S	S
			WMA	D	D	D	S	D	D	D	D	D	S	S	D	D	D	D	D
			ASA	D	D	D	S	D	D	D	D	D	S	S	D	D	D	D	D
		PG 64-22	Neat	D	D	D	D	S	D	S	D	D	D	D	D	D	S	D	D
			RAP	D	D	D	D	D	S	D	D	D	D	D	D	D	D	D	D
			WMA	D	S	D	D	S	D	S	D	D	D	D	D	S	D	S	S
			ASA	D	D	D	D	D	S	D	D	D	D	D	D	D	D	D	D
		PG 64-34	Neat	D	D	S	D	D	D	D	D	S	D	D	S	D	D	D	D
			RAP	S	D	D	S	S	D	D	D	D	S	D	D	D	D	S	D
			WMA	D	D	D	S	D	D	D	D	D	S	S	D	D	D	D	D
			ASA	D	D	D	D	D	D	D	D	S	D	D	S	D	D	D	D
		PG 70-28	Neat	S	S	D	D	S	D	S	D	D	D	D	D	S	D	S	S
			RAP	D	D	D	D	D	D	D	D	D	D	D	D	D	S	D	D
			WMA	S	S	D	S	S	D	S	D	D	S	D	D	S	D	S	S
			ASA	D	D	D	D	S	D	S	D	D	D	D	D	S	S	D	S

D=Significantly different average pull-off strength S=Significantly same average pull-off strength				Gravel															
				Moisture Conditioned															
Statistical significance				PG 58-28				PG 64-22				PG 64-34				PG 70-28			
				Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA
Granite	Unconditioned	PG 58-28	Neat	D	D	D	D	D	S	S	D	D	D	D	D	D	S	D	D
			RAP	D	D	D	D	D	S	S	S	D	D	D	D	D	S	S	D
			WMA	D	D	S	S	D	S	S	S	D	D	D	D	D	S	D	S
			ASA	D	D	S	S	D	S	S	S	D	D	D	D	D	S	D	S
		PG 64-22	Neat	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
			RAP	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
			WMA	D	D	D	D	D	D	D	D	D	D	D	D	D	D	S	D
			ASA	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
		PG 64-34	Neat	D	D	D	D	S	D	D	D	D	D	S	S	S	D	D	D
			RAP	D	D	D	D	D	S	S	S	D	D	D	D	D	S	D	S
			WMA	D	D	S	S	D	S	S	S	D	D	D	D	S	S	D	S
			ASA	S	D	D	D	D	D	D	D	D	D	S	D	D	D	D	D
		PG 70-28	Neat	D	D	D	D	D	D	D	D	D	D	D	D	D	D	S	D
			RAP	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
			WMA	D	D	D	D	D	S	S	D	D	D	D	D	D	S	S	D
			ASA	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D

D=Significantly different average pull-off strength S=Significantly same average pull-off strength				Quartzite															
				Unconditioned															
Statistical significance				PG 58-28				PG 64-22				PG 64-34				PG 70-28			
				Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA
Granite	Unconditioned	PG 58-28	Neat	S	S	D	D	D	D	S	D	D	D	D	D	S	D	S	D
			RAP	S	S	D	D	D	D	S	D	D	S	D	D	S	D	S	S
			WMA	D	S	S	S	D	D	D	D	D	S	S	D	D	D	D	D
			ASA	D	S	S	S	D	D	D	D	D	S	S	D	D	D	D	D
		PG 64-22	Neat	D	D	D	D	S	D	D	D	D	D	D	D	D	D	D	D
			RAP	D	D	D	D	D	S	D	D	D	D	D	D	D	D	D	D
			WMA	S	D	D	D	S	D	S	D	D	D	D	D	S	D	S	S
			ASA	D	D	D	D	D	S	D	S	D	D	D	D	D	D	D	D
		PG 64-34	Neat	D	D	D	S	D	D	D	D	S	D	S	S	D	D	D	D
			RAP	D	S	D	D	D	D	S	D	D	D	D	D	D	D	S	D
			WMA	D	S	S	S	D	D	D	D	D	S	S	D	D	D	D	D
			ASA	D	D	D	D	D	D	D	D	D	D	D	S	D	D	D	D
		PG 70-28	Neat	S	D	D	D	D	D	S	D	D	D	D	D	S	D	S	S
			RAP	D	D	D	D	S	D	D	S	D	D	D	D	D	D	D	D
			WMA	S	S	D	D	D	D	S	D	D	D	D	D	S	D	S	S
			ASA	D	D	D	D	S	D	S	S	D	D	D	D	D	D	D	S

D=Significantly different average pull-off strength **S=Significantly same average pull-off strength**				Quartzite															
Statistical significance				Moisture Conditioned															
				PG 58-28				PG 64-22				PG 64-34				PG 70-28			
				Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA
Granite	Unconditioned	PG 58-28	Neat	D	D	D	S	D	D	S	D	D	D	D	D	S	S	S	S
			RAP	D	D	D	S	D	D	S	S	D	D	D	D	S	S	S	S
			WMA	D	D	S	S	S	D	D	S	D	D	D	D	S	S	D	S
			ASA	D	D	S	S	S	S	D	S	D	D	S	D	D	D	D	S
		PG 64-22	Neat	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
			RAP	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
			WMA	D	D	D	D	D	D	D	D	D	D	D	D	D	D	S	D
			ASA	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
		PG 64-34	Neat	S	S	S	D	S	S	D	D	D	S	S	S	D	D	D	D
			RAP	D	D	D	S	D	D	S	S	D	D	D	D	S	S	D	S
			WMA	D	D	S	S	S	S	S	S	D	D	S	D	S	S	D	S
			ASA	D	S	D	D	D	D	D	D	D	D	D	S	D	D	D	D
		PG 70-28	Neat	D	D	D	D	D	D	D	D	D	D	D	D	D	S	S	D
			RAP	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
			WMA	D	D	D	S	D	D	S	D	D	D	D	D	S	S	S	S
			ASA	D	D	D	D	D	D	D	D	D	D	D	D	D	D	S	D

D=Significantly different average pull-off strength **S=Significantly same average pull-off strength**				Granite															
Statistical significance				Unconditioned															
				PG 58-28				PG 64-22				PG 64-34				PG 70-28			
				Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA
Granite	Unconditioned	PG 58-28	Neat	S	S	D	D	D	D	D	D	D	S	D	D	D	D	S	D
			RAP	S	S	S	D	D	D	S	D	D	S	D	D	S	D	S	D
			WMA	D	S	S	S	D	D	D	D	D	S	S	D	D	D	D	D
			ASA	D	D	S	S	D	D	D	D	D	D	S	D	D	D	D	D
		PG 64-22	Neat	D	D	D	D	S	D	D	D	D	D	D	D	D	S	D	S
			RAP	D	D	D	D	D	S	D	S	D	D	D	D	D	D	D	D
			WMA	D	S	D	D	D	D	S	D	D	D	D	D	S	D	S	S
			ASA	D	D	D	D	D	S	D	S	D	D	D	D	D	D	D	D
		PG 64-34	Neat	D	D	D	D	D	D	D	D	S	D	D	D	D	D	D	D
			RAP	S	S	S	D	D	D	D	D	D	S	S	D	D	D	S	D
			WMA	D	D	S	S	D	D	D	D	D	S	S	D	D	D	D	D
			ASA	D	D	D	D	D	D	D	D	D	D	D	S	D	D	D	D
		PG 70-28	Neat	D	S	D	D	D	D	S	D	D	D	D	D	S	D	S	S
			RAP	D	D	D	D	S	D	D	D	D	D	D	D	D	S	D	S
			WMA	S	S	D	D	D	D	S	D	D	S	D	D	S	D	S	D
			ASA	D	D	D	D	S	D	S	D	D	D	D	D	S	S	D	S

D=Significantly different average pull-off strength S=Significantly same average pull-off strength				Granite															
Statistical significance				Moisture Conditioned															
				PG 58-28				PG 64-22				PG 64-34				PG 70-28			
				Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA
Granite	Unconditioned	PG 58-28	Neat	D	D	S	D	D	D	S	D	D	D	D	D	D	D	D	D
			RAP	S	D	S	D	D	D	S	D	D	D	D	D	D	D	D	D
			WMA	S	D	S	D	D	D	S	D	D	D	D	D	D	S	D	S
			ASA	S	D	S	D	D	D	S	D	D	D	D	D	D	S	D	S
		PG 64-22	Neat	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
			RAP	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
			WMA	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
			ASA	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
		PG 64-34	Neat	D	D	D	S	S	S	D	S	D	D	S	S	D	D	S	D
			RAP	S	D	S	D	D	D	S	D	D	D	D	D	D	D	D	D
			WMA	S	D	S	D	D	D	S	D	D	D	D	S	D	S	D	S
			ASA	D	D	D	D	S	S	D	S	D	D	S	D	S	D	S	D
		PG 70-28	Neat	D	D	D	D	D	D	S	D	D	D	D	D	D	D	D	D
			RAP	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
			WMA	D	D	S	D	D	D	S	D	D	D	D	D	D	D	D	D
			ASA	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D

D=Significantly different average pull-off strength S=Significantly same average pull-off strength				Gravel															
Statistical significance				Unconditioned															
				PG 58-28				PG 64-22				PG 64-34				PG 70-28			
				Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA
Granite	Moisture Conditioned	PG 58-28	Neat	D	D	D	S	D	D	D	D	D	S	S	D	D	D	D	D
			RAP	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
			WMA	S	D	D	S	S	D	D	D	D	S	D	D	D	D	S	D
			ASA	D	D	S	D	D	D	D	D	S	D	D	S	D	D	D	D
		PG 64-22	Neat	D	D	S	D	D	D	D	D	S	D	D	S	D	D	D	D
			RAP	D	D	D	D	D	D	D	D	S	D	D	S	D	D	D	D
			WMA	S	S	D	S	S	D	D	D	D	S	S	D	D	D	S	S
			ASA	D	D	D	D	D	D	D	D	S	D	D	S	D	D	D	D
		PG 64-34	Neat	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
			RAP	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
			WMA	D	D	D	D	D	D	D	D	S	D	D	S	D	D	D	D
			ASA	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
		PG 70-28	Neat	D	D	D	D	D	D	D	D	D	D	D	S	D	D	D	D
			RAP	D	D	D	S	D	D	D	D	D	D	S	D	D	D	D	D
			WMA	D	D	S	D	D	D	D	D	S	D	D	S	D	D	D	D
			ASA	D	D	D	S	D	D	D	D	D	S	S	D	D	D	D	D

D=Significantly different average pull-off strength S=Significantly same average pull-off strength				Gravel															
Statistical significance				Moisture Conditioned															
				PG 58-28				PG 64-22				PG 64-34				PG 70-28			
				Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA
Granite	Moisture Conditioned	PG 58-28	Neat	D	D	S	S	D	S	S	S	D	D	D	D	D	S	D	S
			RAP	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
			WMA	D	D	S	D	D	S	S	S	D	D	D	D	D	S	D	S
			ASA	D	D	D	D	S	D	D	D	D	D	S	S	S	D	D	D
		PG 64-22	Neat	D	D	D	D	S	D	D	D	D	D	S	S	S	D	D	D
			RAP	D	D	D	D	S	D	D	D	D	D	S	S	S	D	D	D
			WMA	D	D	S	S	D	S	S	S	D	D	D	D	D	S	S	S
			ASA	D	D	D	D	S	D	D	D	D	D	S	D	D	D	D	D
		PG 64-34	Neat	S	S	D	D	D	D	D	D	D	S	D	D	D	D	D	D
			RAP	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
			WMA	D	D	D	D	S	D	D	D	D	D	S	S	D	D	D	D
			ASA	D	D	D	S	D	D	D	D	D	D	S	S	S	D	D	D
		PG 70-28	Neat	S	S	D	D	D	D	D	D	D	S	D	D	D	D	D	D
			RAP	D	D	S	S	D	D	D	D	D	D	D	D	S	S	D	S
			WMA	D	D	D	D	S	D	D	D	D	D	S	S	S	D	D	D
			ASA	D	D	S	S	D	D	D	D	D	D	D	D	S	S	D	S

D=Significantly different average pull-off strength S=Significantly same average pull-off strength				Quartzite															
Statistical significance				Unconditioned															
				PG 58-28				PG 64-22				PG 64-34				PG 70-28			
				Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA
Granite	Moisture Conditioned	PG 58-28	Neat	D	S	D	S	D	D	D	D	D	S	S	D	D	D	D	D
			RAP	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
			WMA	D	S	D	D	D	D	D	D	D	S	D	D	D	D	S	D
			ASA	D	D	D	S	D	D	D	D	S	D	D	S	D	D	D	D
		PG 64-22	Neat	D	D	D	D	D	D	D	D	S	D	D	S	D	D	D	D
			RAP	D	D	D	D	D	D	D	D	S	D	D	S	D	D	D	D
			WMA	S	S	S	D	D	D	S	D	D	S	D	D	S	D	S	D
			ASA	D	D	D	D	D	D	D	D	S	D	D	S	D	D	D	D
		PG 64-34	Neat	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
			RAP	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
			WMA	D	D	D	D	D	D	D	D	S	D	D	S	D	D	D	D
			ASA	D	D	D	S	D	D	D	D	D	D	S	S	D	D	D	D
		PG 70-28	Neat	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
			RAP	D	D	S	S	D	D	D	D	D	S	S	D	D	D	D	D
			WMA	D	D	D	S	D	D	D	D	S	D	S	S	D	D	D	D
			ASA	D	D	S	S	D	D	D	D	D	S	S	D	D	D	D	D

D=Significantly different average pull-off strength **S=Significantly same average pull-off strength**				Quartzite															
				Moisture Conditioned															
				PG 58-28				PG 64-22				PG 64-34				PG 70-28			
Statistical significance				Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA
Granite	Moisture Conditioned	PG 58-28	Neat	D	D	D	S	S	D	D	S	D	D	D	D	S	S	D	S
			RAP	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
			WMA	D	D	D	S	D	D	S	S	D	D	D	D	S	S	D	S
			ASA	S	S	S	D	D	S	D	D	D	S	D	S	D	D	D	D
		PG 64-22	Neat	S	S	D	D	D	S	D	D	D	S	D	S	D	D	D	D
			RAP	D	S	S	D	D	S	D	D	D	S	D	S	D	D	D	D
			WMA	D	D	D	S	S	D	S	S	D	D	D	D	S	S	S	S
			ASA	D	S	D	D	D	D	D	D	D	S	D	S	D	D	D	D
		PG 64-34	Neat	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
			RAP	D	D	D	D	D	D	D	D	S	D	D	D	D	D	D	D
			WMA	D	S	D	D	D	D	D	D	D	S	D	S	D	D	D	D
			ASA	S	D	S	D	S	S	D	D	D	S	S	S	D	D	D	D
		PG 70-28	Neat	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
			RAP	D	D	S	S	S	S	D	D	D	D	S	D	D	D	D	S
			WMA	S	S	S	D	S	S	D	D	D	S	S	S	D	D	D	D
			ASA	D	D	S	S	S	S	D	S	D	S	S	D	D	D	D	S

D=Significantly different average pull-off strength **S=Significantly same average pull-off strength**				Granite															
				Unconditioned															
				PG 58-28				PG 64-22				PG 64-34				PG 70-28			
Statistical significance				Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA
Granite	Moisture Conditioned	PG 58-28	Neat	D	S	S	S	D	D	D	D	D	S	S	D	D	D	D	D
			RAP	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
			WMA	S	S	S	S	D	D	D	D	D	S	S	D	D	D	S	D
			ASA	D	D	D	D	D	D	D	D	S	D	D	D	D	D	D	D
		PG 64-22	Neat	D	D	D	D	D	D	D	D	S	D	D	S	D	D	D	D
			RAP	D	D	D	D	D	D	D	D	S	D	D	S	D	D	D	D
			WMA	S	S	S	S	D	D	D	D	D	S	S	D	S	D	S	D
			ASA	D	D	D	D	D	D	D	D	S	D	D	S	D	D	D	D
		PG 64-34	Neat	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
			RAP	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
			WMA	D	D	D	D	D	D	D	D	S	D	D	S	D	D	D	D
			ASA	D	D	D	D	D	D	D	D	S	D	S	D	D	D	D	D
		PG 70-28	Neat	D	D	D	D	D	D	D	D	D	D	D	S	D	D	D	D
			RAP	D	D	S	S	D	D	D	D	D	D	S	D	D	D	D	D
			WMA	D	D	D	D	D	D	D	D	S	D	D	S	D	D	D	D
			ASA	D	D	S	S	D	D	D	D	D	D	S	D	D	D	D	D

D=Significantly different average pull-off strength S=Significantly same average pull-off strength				Granite															
Statistical significance				Moisture Conditioned															
				PG 58-28				PG 64-22				PG 64-34				PG 70-28			
				Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA	Neat	RAP	WMA	ASA
Granite	Moisture Conditioned	PG 58-28	Neat	S	D	S	D	D	D	S	D	D	D	D	D	D	D	D	S
			RAP	D	S	D	D	D	D	D	D	D	D	D	D	D	D	D	D
			WMA	S	D	S	D	D	D	S	D	D	D	D	D	D	D	D	D
			ASA	D	D	D	S	S	S	D	S	D	D	S	D	D	D	S	D
		PG 64-22	Neat	D	D	D	S	S	S	D	S	D	D	S	D	D	D	S	D
			RAP	D	D	D	S	S	S	D	S	D	D	S	D	D	D	S	D
			WMA	S	D	S	D	D	D	S	D	D	D	D	D	D	D	D	D
			ASA	D	D	D	S	S	S	D	S	D	D	S	D	S	D	S	D
		PG 64-34	Neat	D	D	D	D	D	D	D	D	S	D	D	D	S	D	D	D
			RAP	D	D	D	D	D	D	D	D	D	S	D	D	D	D	D	D
			WMA	D	D	D	S	S	S	D	S	D	D	S	D	D	D	S	D
			ASA	D	D	D	D	D	D	D	D	D	D	D	S	D	S	S	S
		PG 70-28	Neat	D	D	D	D	D	D	D	S	S	D	D	D	S	D	D	D
			RAP	D	D	D	D	D	D	D	D	D	D	D	S	D	S	D	S
			WMA	D	D	D	S	S	S	D	S	D	D	S	S	D	D	S	D
			ASA	S	D	D	D	D	D	D	D	D	D	D	S	D	S	D	S