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Examining the Effect of Dry Resin on Moisture Sensitivity of Asphaltic Mixtures

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Abstract

Moisture damage in asphaltic mixtures is defined by the loss of durability and resistance caused by the effect of moisture. The most common way to improve moisture damage in asphaltic mixtures is to use anti-strip additives. This study tended to use dry resin polymer additive to make a moisture-resistant asphaltic mixture. Two types of aggregate indicating different sensitivities against moisture were studied. In order to compare the effect of this material with other anti-strip additives, this study evaluated the effect of hydrated lime on reducing moisture damage and comparing its effect with dry resin polymer additive. The effect of these materials was evaluated by mechanical and thermodynamic concepts using indirect tensile ratio and surface free energy. The results indicated that dry resin polymer used in this study increased alkaline content and reduced acidic content of bituminous surface free energy, resulting in more adhesion between acidic aggregates which are more sensitive to resistance. It also improved bitumen-aggregate adhesion and reduced strip rate. Moreover, hydrated lime as an aggregate anti-strip agent and dry resin polymer as a bituminous modifier significantly increased the resistance of warm asphalt mixtures against moisture. The results of this study show that dry resin polymer can be used as an anti-strip agent instead of hydrated lime with operational problems.

Keywords: Asphalt Mixture; Moisture Damage; Anti-Strip Additive; Dry Resin Polymer; Indirect Tensile Strength; Surface Free Energy.

1. Introduction

The best way to improve roads is not to spend more on them, but to improve the design, construction and maintenance of roads. Most of the cost of asphalt stone aggregates is not followed by a good result due to moisture problems. Degradation of asphalt compounds by moisture can be defined by early loss of strength and durability due to moisture penetration in asphalt mixture and rock materials. As a result of construction and maintenance costs and low useful life of asphalt pavements, particularly in wet and humid areas, efforts have been made to produce moisture resistant asphalt mixtures. Many road organizations have made extensive efforts to reduce costs of pavement maintenance. One of the damages which cause excessive costs in asphalt pavements is moisture damage [1].

Moisture damage is defined as the loss of mechanical properties of material as a result of the presence of water in asphalt mixtures. This damage, in addition to being a significant failure, can cause or aggravate other failures such as fatigue cracking, grooving, separating bitumen from aggregates and pits in asphalt pavements. Severity of moisture damage, which is also called stripping, is related to internal and external factors. Internal factors are related to properties of materials used in asphalt mixtures, while external factors include environmental conditions, production and implementation methods, pavement design and traffic intensity. Although moisture damage has been respected by

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researchers for more than 70 years, many aspects of this kind of damage are still unknown [2]. There are two key questions in this regard: 1) the ways which can reduce moisture damage; and 2) the ways which can precisely predict potential moisture damage [3]. Currently, there is a need to use new materials in structure of asphalt mixtures to reduce moisture damage due to expansion of pavement network, increased traffic, presence of larger and heavier trucks, and in some places, the more violent environmental conditions [4-7]. There are two main methods for improving bituminous-aggregate adhesion and consequently reducing moisture damage in asphalt mixtures. The first method is to use liquid anti-strip additives to bitumen to improve bituminous bonding properties and bituminous-aggregate adhesion. Liquid anti-strip agents are in fact chemical activators which, by changing the bitumen structure, increase bitumen-aggregate adhesion and lead to better coating of bitumen on the aggregate surface. Most of liquid anti-strip agents are from the family of amines or amidoamines [7]. The second method is to use surface coatings of aggregates using suitable materials which change surface properties of aggregates, particularly acidic aggregates, and reduce hydrophilic tendency of this type of aggregates, so that stripping is reduced when the water enters the bitumen-aggregate system. The most widely used materials are hydrated lime or polymers [6, 8, 9]. Although using these materials reduces moisture damage in asphalt mixtures, their use is associated with a series of problems [10-15]. Regarding technical and executive problems in using anti-strip materials, this study tends to investigate the use of anti-strip polymeric materials.

2. Literature Review

Moisture damage or sensitivity of asphalt mixtures, which can be referred to as potential stripping, is one of the major failures occurring in asphalt concrete pavements. It should be noted that the effect of presence of moisture in asphalt mixtures is not considered as the main cause of pavement failure, because two main causes of pavement failure are traffic load and temperature changes; however, migration of moisture into the asphalt mixture can significantly increase vulnerability of asphaltic concrete to each of the above factors. In previous texts, broad definitions of this concept can be found, generally in which the phenomenon of bitumen-aggregate separation or rupture of bitumen in a compressed asphalt mixture, under repeated load of traffic and mainly under water or steam vapour, is called stripping [16].

Fromm and Lotman [17] were the first to investigate the effects of micro-scale moisture damage. Fromm (1974) generally considered two mechanisms for moisture damage; the first mechanism was to create water emulsion in bitumen and movement of water particles inside bitumen layer until reaching the aggregate surface, and the second mechanism was to fail bitumen layer caused by an interfacial tension between interfaces of three air, bitumen and water phases. The first mechanism is, in fact, theoretical foundations of a phenomenon which has been discussed later as propagation phenomenon in various studies, and the second mechanism is generally observed in recent studies on mutual relationship between moisture damage and application of mechanical load [12, 18, 19].

In various writings [20, 21], there are five stripping mechanisms, including separation, displacement, spontaneous emulsion, pore water pressure and hydraulic boiling. Other studies have presented other mechanisms which may contribute to moisture damage. These include instability in pH and environmental effects on bitumen-aggregate system.

A study evaluated moisture sensitivity of aggregates and bitumen by understanding the micro-mechanism which affects bitumen-aggregate adhesion and strength of bonding and bitumen durability. The results of this study indicated that the strength of mixtures is related to moisture damage by calculating adhesion energies and cumulative failure in dynamic mechanical analysis. The method developed in this study was used to evaluate six asphalt mixtures which showed good and poor field performance. It has been shown that field strength of mixtures is related to moisture damage by calculating adhesion energies and cumulative failure in dynamic mechanical analysis [24]. In 2006, Bhasin [25] examined and developed laboratory and analytical tools to determine the significance of important properties affecting the moisture failure of asphalt mixtures. The results of these parameters were obtained for nine different aggregate-bitumen compounds (three types of aggregates and three types of bitumen). Using these 9 aggregate-bitumen compounds, compressed asphaltic mixtures were constructed and dynamic modulus tests in compression, tension and creep were performed. The results presented in this study were not validated by laboratory tests or field tests.

In his study, Copeland used a computational-experimental method to quantify moisture damage at aggregate-mastic contact surface based on the loss of adhesion strength which was determined by pull-off test and moisture content at the contact surface [26]. A study was conducted in 2007 at the University of Oklahoma in the form of PhD dissertation. In this study, a basic method was used based on properties of surface free energy of bitumen and aggregates to describe bitumen-aggregate interfacial relationships in the moisture damage process [27]. In another study, a qualitative-quantitative method based on surface energy was used to assess moisture damage. Surveys of this study showed that surface energy, as dynamic modulus, is able to predict moisture damage. Moreover, hydrated lime significantly improved mixture strength against moisture [28]. This study focused on assessment of surface energy and moisture sensitivity of wide compounds of bitumen and aggregates. Moisture damage analysis used in this study was based on dynamic mechanical analysis which was used in some previous studies [29].

Many studies have been done on application of hydrated lime in asphalt mixtures. Hydrated lime will be able to improve fatigue strength of asphalt pavements as a result of improved bitumen due to its high stiffness and improved resistance to stripping of asphalt mixtures by slightly changing properties of the bitumen used. Other properties of hydrated lime include the increased stiffness modulus, increased moisture resistance and prevention of crack types and increased creep resistance [30]. Hamedi (2017) presented the theoretical and experimental concepts of predicting moisture damage in asphalt concrete mixes using the surface free energy (SFE) concept and laboratory dynamic test, respectively. The results of this study show that the polyvinyl chloride (PVC) coating decreases significantly the total SFE and polar SFE, and leads to an increase in the non-polar SFE of the aggregates, which make aggregates be hydrophobic. This occurrence increases the coating ability of aggregates by the asphalt binder [31]. Rafiq Kakar et al. (2015) considered the use surface free energy evaluation as a fundamental material property to assess mixture performance. Ceca base chemical surfactant additive was used to prepare warm mix asphalt binders. The results show that the use of the surfactant-based additive reduces surface free energy. It increases after short-term (Rolling Thin Film Oven) and reduces after long-term (Pressure Aging Vessel) aging [32].

Peyman Mirzababaei (2016) aimed to determine effects of zycotherm- a liquid and nano-organosilane warm mix and anti-stripping additive- on water susceptibility of Warm Mix Asphalt mixtures prepared with different aggregate types and gradations. The results indicated that although zycotherm significantly improves water susceptibility performance of asphalt mixtures pre- pared with all aggregate types and gradations, it does not function properly as a WMA additive because an effective additive should improve both the unconditioned and moisture conditioned characteristics of bituminous mixtures to make sure appropriate performance of asphalt pavements in the long run [33]. Shafabakhsh et al. (2015) aimed to improve it by reinforcing the adhesion between asphalt binder and aggregate. An anti-stripping additive named nanotechnology Zycotherm (NZ) was used to achieve this goal. The findings showed that adding NZ was a successful technique to compensate the deteriorated adhesion due to using sulfur. Also it was demonstrated that SFE test results were so compatible with the common mechanical tests in predicting moisture damages [34]. Zhang et al. (2016) evaluated the moisture sensitivity of different aggregate–bitumen combinations through three different approaches: surface energy, peel adhesion and the Saturation Ageing Tensile Stiffness (SATS) tests. The surface energy tests showed that the work of adhesion in dry conditions was bitumen type dependent, which is in agreement with the peel test. After moisture damage, all of these three tests found that the moisture sensitivity of aggregate–bitumen combinations were mainly aggregate type dependent. Based on the peel test, the moisture absorption and mineralogical compositions of aggregate were considered as two important factors to moisture sensitivity [35]. Ziari et al. (2017) considered amorphous carbon powder, a by-product of paraffin production factory, is used as a replcement of filler (25, 50, 75, and 100%) and as a modifier of bitumen (5, 10, and 15%) to improve the hydrophobicity of mixtures. The results showed that not only did the hydrophobic powder improve the moisture sensitivity, but it also increased the rutting resistance of mix- tures. Dynamic creep and wheel tracking test results showed bitumen modified mixtures are more resistant to mechanical deformation [36].

3. Materials and Methods

3.1. Rock Materials

Two types of aggregates with different properties against moisture damage were investigated in this study: limestone, which is known as a moisture-resistant aggregate, and granite, which is known as a hydrophilic aggregate and sensitive to moisture damage. Chemical and physical compounds of these aggregates are presented in Table 1 and Table 2, respectively. Aggregation used in this study is shown in Figure 1.

Table 1. Properties of mineral aggregates used in this study

Aggregate	Silicon dioxide (SiO2)	R2O3 (Al2O3+Fe2O3)	Aluminium oxide (Al2O3)	Ferric oxide (Fe3O4)	Magnesium oxide (MgO)	Calcium oxide (CaO)
Limestone	3.8	18	1	0.4	1.2	51.3
Granite	68.1	16.2	14.8	1.4	0.8	2.4

Table 2. Physical properties of rock materials [31]

Test	Standard	Granite	Limestone	Allowed limit
Special weight (coarse-grained)	ASTM C 127			
Bulk		2.651	2.622	-----
SSD		2.657	2.628	-----
Apparent		2.659	2.631	-----
Special weight (fine-grained)	ASTM C 128			
Bulk		2.646	2.614	-----

SSD		2.648	2.617	-----
Apparent		2.653	2.622	-----
Special weight (filler)	ASTM D854	2.626		-----
Allowable wear	ASTM C131	17	22	Max 30
Fracture percentage in two sides	ASTM D5821	94	91	Min 80
Long and broad particles (%)	ASTM D 4791	11	8	Max 15

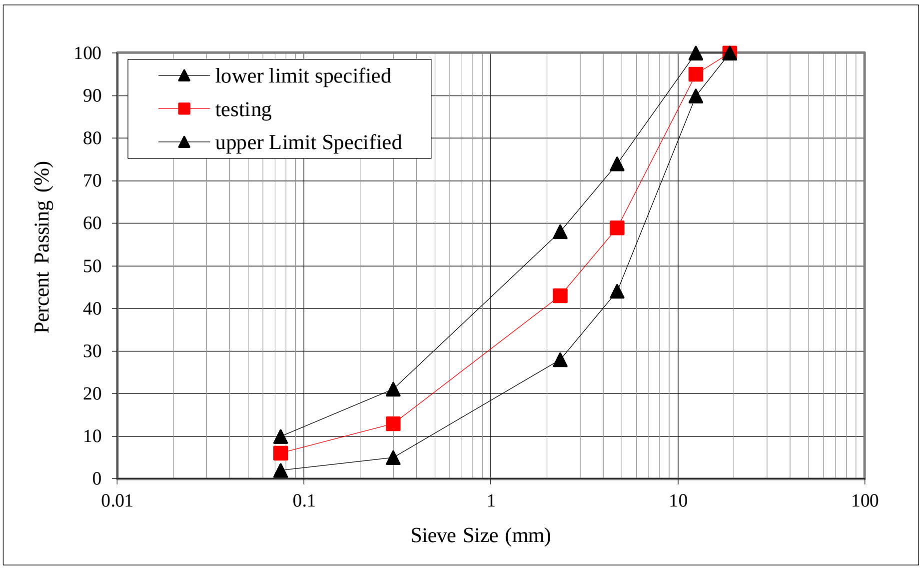

Figure 1. Aggregation used for grains [37]

3.2. Dry Resin Polymer

Dry resin is a powder polymer from the family of macromolecular polymers produced by polymerization of vinyl and acrylate copolymers. This product quickly forms an emulsion in water, which provides high adhesion to different surfaces, flexibility and high resistance to environmental conditions when drying up.

3.3. Hydrated Lime

In this study, high-calcium hydrated lime was used as an additive to asphalt mixture to improve resistance to striping of asphalt specimens. Properties of the hydrated lime are listed in Table 3.

Table 3. Properties of the used lime

Minimum wt.% calcium hydroxide	Maximum wt.% free lime	Maximum wt.% free water	Maximum wt.% retained on the sieve 6 mm (# 30)	Maximum wt.% retained on the sieve 0.075 mm (# 200)
90	7	3	2	12

3.4. Bitumen

In this study, bitumen used was a pure bitumen with a penetration grade of 60.70 which was produced in Isfahan Refinery; properties of basic and modified bitumen are presented in Table 4.

Table 4. Properties of the bitumen used for specimens

Type of bitumen	Degree of penetration (mm/10)	Flashpoint (°C)	Ductility (cm)	Viscosity (mPas)			Softness point (°C)
				115°C	135°C	150°C	
Basic bitumen	69	313	112	0.156	0.289	0.776	47
Basic bitumen with 2% dry resin polymer	64	327	114	0.174	0.318	0.942	53
Basic bitumen with 4% dry resin polymer	62	335	119	0.208	0.359	0.997	56

Figure 2. Bitumen refinement using two types of dry resin polymer powder

3.5. Construction of Specimens

Design and mixing of asphalt mixtures was done using standard Marshall Design with 75 strokes on each side of cylindrical specimens. Samples were compressed and tested according to standard methods. Optimal bitumen content for limestone and granite aggregates was 5.5 and 5%, respectively.

3.6. Number of Specimens

In this study, dry resin material was used as bitumen modifier in two different percentages relative to bitumen weight (2 and 4% bitumen weight). For this purpose, 8×15 specimens (120 specimens) should be made. Moreover, optimal bitumen content was measured for the specimen with unmodified bitumen and limestone and granite aggregates. For each bitumen percentage, 3 specimens were made with two iterations and Marshall Test was performed; totally, 60 specimens were tested.

Table 5. Number of asphalt mixture specimens for testing optimal bitumen and moisture sensitivity

Type of aggregate	Type of bitumen	Test	Objective	Number of specimens
Granite	Unmodified bitumen	Marshal	Determine optimal bitumen content	30
Limestone	Unmodified bitumen	Marshal	Determine optimal bitumen content	30
Granite	Unmodified bitumen	Indirect tensile ratio	Determine moisture sensitivity	15
Limestone	Unmodified bitumen	Indirect tensile ratio	Determine moisture sensitivity	15
Granite	Bitumen modified with 2% dry resin polymer	Indirect tensile ratio	Determine moisture sensitivity	15
Limestone	Bitumen modified with 2% dry resin polymer	Indirect tensile ratio	Determine moisture sensitivity	15
Granite	Bitumen modified with 4% dry resin polymer	Indirect tensile ratio	Determine moisture sensitivity	15
Limestone	Bitumen modified with 4% dry resin polymer	Indirect tensile ratio	Determine moisture sensitivity	15
Granite modified with hydrated lime	Unmodified bitumen	Indirect tensile ratio	Determine moisture sensitivity	15
Granite modified with hydrated lime	Unmodified bitumen	Indirect tensile ratio	Determine moisture sensitivity	15

3.7. Experiments on Asphalt Specimens

In this study, Marshall mixing design tests based on ASTM D1559, Marshall Strength test, moisture damage sensitivity test AASHTO T283, measurements of bituminous surface free energy components and measurement of surface free energy components of aggregates were used.

3.8. Marshall Mixing Test According to ASTM D1559 Standard

- In this study, Marshall mixing design was used to determine the optimum bitumen content.
- Selection of the type of aggregate used in the mixes based on the proposed aggregate in the regulations of pavement of roads in Iran.

- In the Marshall method, granular aggregates are mixed in proportion to the percentages of each granulation to 1200 g of rock materials.

These 1200 grams of specimens are placed in a temperature of 160-170 degrees for 24 hours to evaporate the water in the rock mass. Then the bitumen, which is heated to 135 ° C, is poured into five percent by weight, as a mixture of asphalt mixture, mixed with mortar and molded in Marshall molds, which have a diameter of 1/10 and a height of 25/6 cm. It is worth noting that the percentage of bitumen should be selected in such a way that the optimum amount of bitumen is within the range of percentages. Finally, the compression action is carried out by 75 impacts (for heavy traffic) Marshall Hammer, which weighs 4.5 kilograms and falls to a height of 45 centimetres.

3.9. Testing the Specific Gravity of the Actual Asphalt Samples

After the prototypes were made and after gradual cooling (at least after two hours), the samples were assisted. Hydraulic jacks are removed from the marshall mould. The diameter and height of each of the specimens were measured by a ruler and measured in three stages, and their mean as the diameter and height of the sample is reported. Then weigh each of the samples in air and in water, weigh the numbers and calculate the difference of these two weights, the sample size. Finally, the actual gravity of the asphaltic sample is calculated.

3.10. Marshall Strength Test

Marshall Specimens are placed in thermostat at 60 ± 10 ° C after determining the specific gravity for 30 to 40 minutes in a hot water bath. Care should be taken that the placement of samples in water should be such that all of them can be removed within 30 to 40 minutes and tested on them. A few minutes before removing the first sample of the warm water bath, the Marshall's jaw is placed in the oven and lubricated a few moments before the start of the test. Then the specimens are placed inside the jaw and applied. Finally, the relative strength and deformation values of each one are recorded. A view of the Marshall Strength Test is shown in Figure 3.

Figure 3. Shows the gauge and measuring device for the relative deformation of asphalt samples

3.11. Rice Test

To measure the percentage of free space of the asphaltic mixture, the test is called Rice test. In this test, samples taken from the Marshal machine are placed inside the oven to open well. Then, with a four-part operation, about 120 grams of the mixture are selected and poured into the arsenic where it’s dry and high water content is obtained. More than one-third of the volume of the erlon containing the asphalt sample is filled with water and, after closing the door, attaches to the vacuum device to remove air from asphalt particles. Finally, by removing all the air between the mixed particles, the eagle is separated from the device and the mark line is filled with water and its weight is measured. In Figure 4, the Rice test equipment is visible.

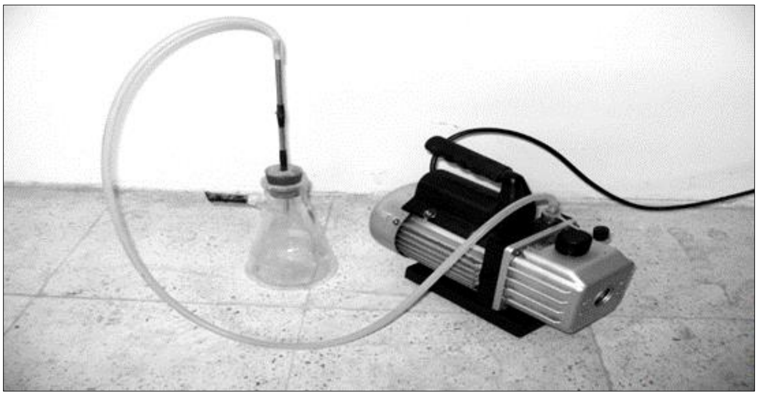

Figure 4. Rice Test Equipment

3.12. Sensitivity Test for Moisture Failure Using AASHTO T283

Resistance to weathering (moisture sensitivity) Asphalt mixtures have been evaluated by decreasing the amount of indirect tensile strength after the ice-melting cycle based on the AASHTO T283 standard.

The tensile strength of a gravel asphalt mix is determined by bitumen bonding and bituminous-aggregate adhesion. The tensile strength is expressed by the maximum load that the sample can withstand before rupture. Asphalt mixtures with higher tensile strengths can provide better resistance to fatigue and rupture. Therefore, any additive that can provide a higher tensile strength for asphalt mixtures in wet and dry conditions can improve the long-term performance of the asphalt mix. This test consists of loading on cylindrical samples with vertical compressive loading, which causes a tensile stress of approximately uniformity along the vertical diagonal plate. Rupture usually occurs in the shape of the separation along this page.

The most commonly used test is to examine the strength of asphalt mixtures against moisture damage and also to investigate the effect of anti-scaling materials. Sufficient materials are mixed to produce at least 6 samples of the hot mix as a percentage of the optimum bitumen specified in the previous section. More samples are needed when one of the samples is in trouble or the maximum specific gravity of the specimens is not specified. Before carrying out the original experiment, a number of tests are needed to find the number of impacts needed to compress the original samples to achieve a percentage of 7 ± 1 cavity. The percentage of air cavities is specified in accordance with the AASHTO T269 standard. When the number of bouts and specimens were compressed, the specimens were divided into two groups of dry specimens and specimens under wet conditions. Then, the specimens that are set to under the conditions are placed under vacuum conditions to reach a saturation degree of 55-80%. Saturated specimens are stored in a freezer at -18 ° C for 16 hours and kept in a water bath at 60 ° C for 24 hours. The remaining specimens are stored in dry conditions. All samples are brought to the same laboratory temperature (25 ° C) and an indirect tensile strength test is performed on the specimens. The test and loading procedure is shown in Figure 3-6. The loading rate in this experiment is 2 inches per minute (about 50.8 mm / min).

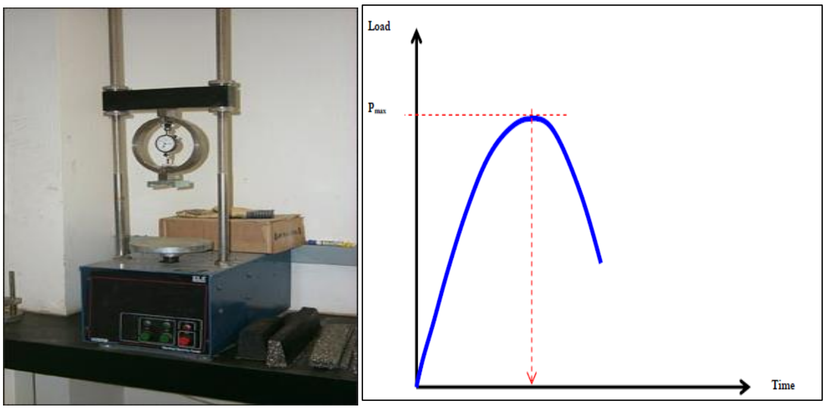

Figure 5. How to test and how to load in the indirect tensile strength test

4. Results and Discussion

4.1. Moisture Sensitivity Test in Specimens Modified with Dry Resin Polymer

Moisture Sensitivity Test by AASHTO T283*:* The results of indirect tensile strength of specimens in different ice-melt cycles are shown in Figures 2 and 3. Obviously, indirect tensile of the specimens is reduced by increasing the number of ice-melt cycles. The decrease in indirect tensile strength of specimens by increasing the number of ice-melt cycles can be attributed to the loss of mixture adhesion or bitumen bonding due to exposure of more samples to moisture. It can be concluded from the data presented in these two figures that addition of dry resin polymer as an anti-striping agent increases adhesion and bonding in the mixture and does not allow rapid displacement of bitumen on aggregate surfaces, which results in higher resistance of the mixture to moisture following ice-melt cycles than specimens without dry resin polymer additives.

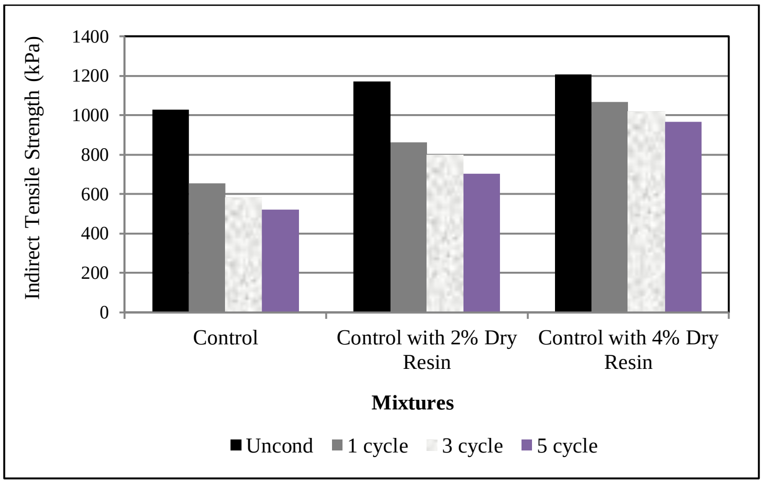

Figure 2. Relationship between ITS and percentage of dry resin polymer additives in different ice-melt cycles in specimens made with granite aggregate

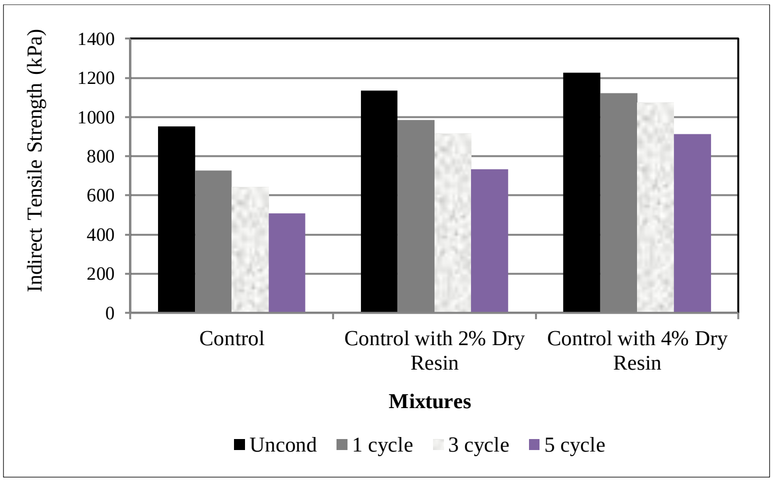

Figure 3. Relationship between ITS and percentage of dry resin polymer additives in different ice-melt cycles in specimens made with limestone aggregate

Figure 4 and Figure 5 represent TSR values for compounds made with a dry resin polymer in this study. It is known that increase in the number of ice-melt cycles reduces TSR. The specimens made with limestone and 4% dry resin polymer have the highest TSR (92%) in the first cycle, which is reduced to 75% at the end of the fifth cycle.

The results related to addition of dry resin polymer indicate that addition of these materials in all percentages used in this study has a positive effect on TSR value. Adding 2% of these materials leads to a significant increase in TSR value. However, this increase in 4% additive compared to 2% additive is not significant. This means that more than 2% increase in this material is not logical as it increases cost of the mixture and has a positive effect in increasing resistance to moisture damage compared to 2% specimens.

It can be concluded from Figure 4 and Figure 5 that addition of anti-strip agents increases adhesion and bonding in the mixture and does not allow rapid displacement of bitumen on aggregate surfaces, which results in higher resistance of the mixture to moisture following ice-melt cycles than specimens without additives.

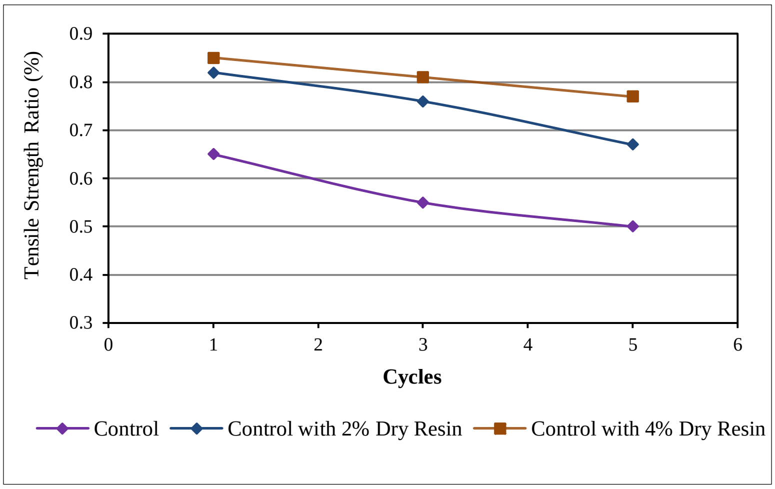

Figure 4. Relationship between TSR and percentage of dry resin polymer additives in different ice-melt cycles in specimens made with granite aggregate

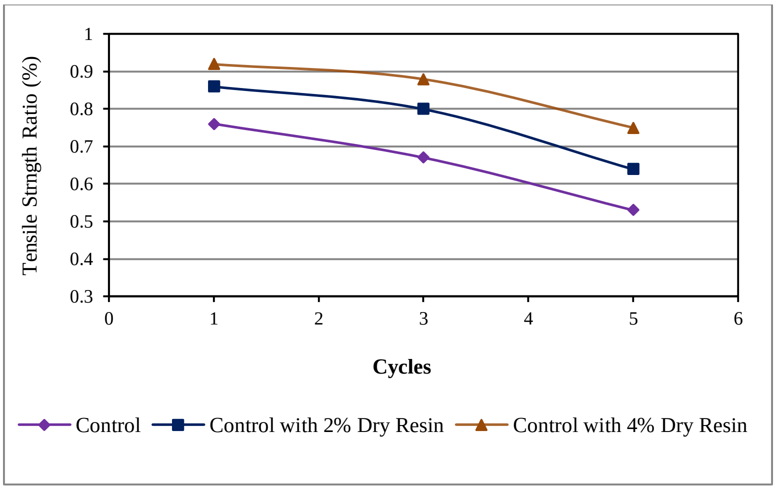

Figure 5. Relationship between TSR and percentage of dry resin polymer additives in different ice-melt cycles in specimens made with limestone aggregate

4.2. Microscale Study of Moisture Damage by Surface Free Energy

Bituminous Surface Free Energy Components: Surface free energy components of bitumen used in this study are measured by Wilhelm plate method. To measure surface free energy components of bitumen, three test fluids are required; the materials used, along with their surface energy components, are shown in the table below.

Table 6. Surface free energy components of basic and modified bitumen along with their contact angles with test fluids

Type of bitumen	Pure bitumen	Pure bitumen modified with 2% dry resin polymer	Pure bitumen modified with 4% dry resin polymer
Contact angle with water	127.14	124.22	121.36
Contact angle with glycerol	116.85	113.93	110.98
Contact angle with fomamid	114.18	110.60	107.18
Total free energy (erg/cm)	15.89	21.44	26.85
Non-polar free energy (erg/cm)	13.69	19.04	24.11
Polar free energy (erg/cm)	2.20	2.40	2.74
Acidic component of free surface energy (erg/cm)	2.58	2.09	1.92
Alkaline component of free surface energy (erg/cm)	0.47	0.69	0.98

Aggregate Surface Free Energy Components: surface free energy of aggregates is measured using USD. In this study, two types of granite and limestone aggregate were used. The results presented in Table 7 show that limestone, which is considered as alkaline aggregate, is expected to have a larger alkaline component of surface free energy than granite, and in contrast, granite has a larger acidic component than limestone aggregate.

Table 7. Free energy components of two types of aggregates used in this study

Type of aggregate	Total surface free energy	Non-polar component	Polar component	Alkaline component	Acidic component
Granite	325.06	204.29	120.77	317.36	11.49
Limestone	236.74	114.96	121.78	448.29	8.27

Adhesion Free Energy Components: As previously noted, adhesion free energy is positive and larger positive values indicate that a better adhesion is provided. The results of free surface energy of adhesion between bitumen and aggregates used in this study before and after modification using dry resin polymer are presented in Table 8.

As shown in Table 8, dry resin polymer leads to an increase in bitumen-aggregate adhesion free energy (closer to zero), which means that the system tendency to strip and achieve a stable state is reduced by the lowest energy. An increase in dry resin polymer content further reduces the tendency. In addition to adhesion free energy, primary energy required for striping is also important. Obviously, dry resin polymer additives significantly increase free energy of bitumen-aggregate adhesion. An increase in dry resin polymer leads to further increase and reduces potential striping.

Table 8. Adhesion free energy in dry and wet conditions

Type of aggregate	Type of bitumen	Bitumen-aggregate	Bitumen-aggregate in the presence of water	Water-aggregate	Bitumen-water
Granite	Basic bitumen	167.64	-92.07	347.62	67.00
	Bitumen modified with 2% dry resin polymer	181.87	-83.88		69.95
	Bitumen modified with 4% dry resin polymer	196.44	-75.42		73.84
Limestone	Basic bitumen	151.30	-103.80	343.00	67.00
	Bitumen modified with 2% dry resin polymer	159.57	-101.57		69.95
	Bitumen modified with 4% dry resin polymer	169.66	-97.58		73.84

4.3. Moisture Sensitivity Test of Specimens Modified with Hydrated Lime

To compare the effect of dry resin polymer with conventional anti-striping additives of hydrated lime, moisture sensitivity was tested in specimens containing hydrated lime. The results of ITS test are presented in Figures 6 and 7. By comparing these results and specimens containing dry resin polymer, it can be seen that hydrated lime has less adhesion compared to dry resin polymer in dry conditions. In wet conditions, ITS values of specimens containing hydrated lime and specimens containing bitumen modified with dry resin polymer are closely matched.

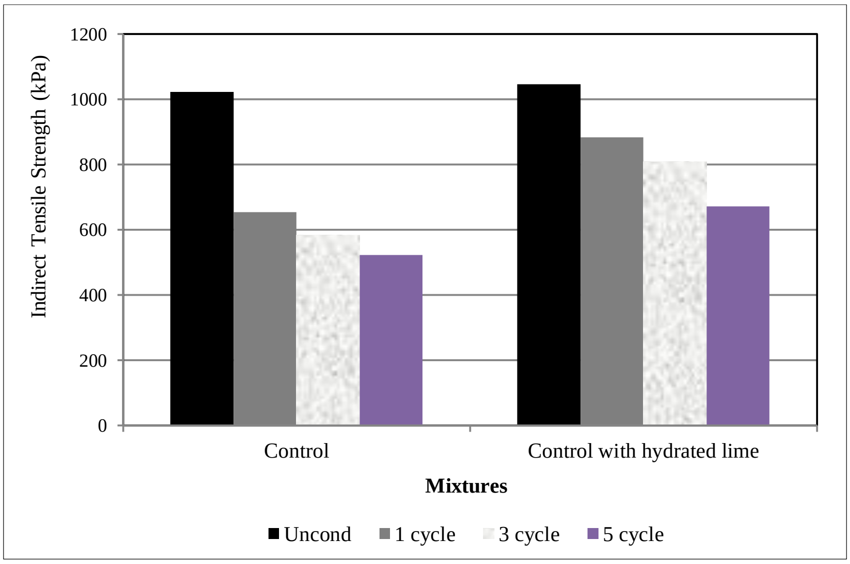

Figure 6. Relationship between ITS in different ice-melt cycles in specimens made with granite and hydrated lime aggregates

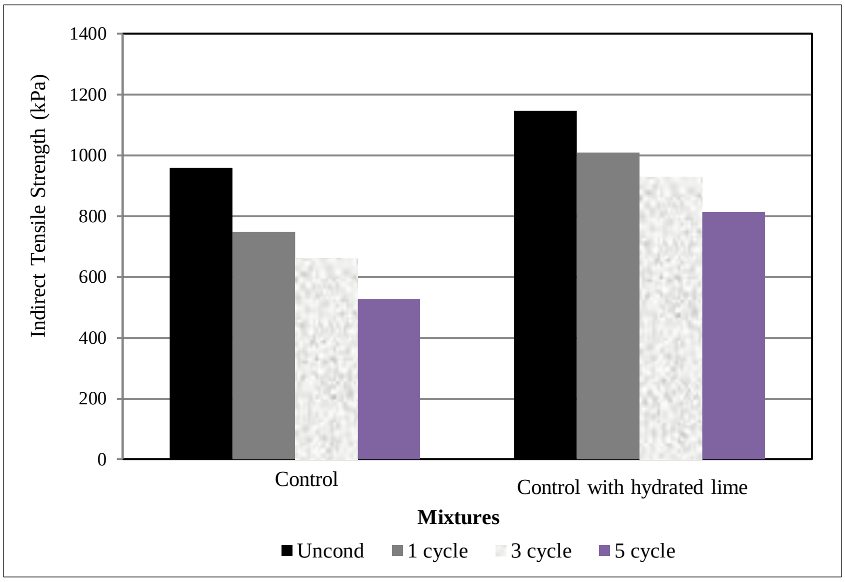

Figure 7. Relationship between TSR in different ice-melt cycles in specimens made with limestone and hydrated lime aggregates

TSR results of different specimens are presented in Figure 8 and 9. The results of these figures show that hydrated lime significantly improves moisture sensitivity of specimens made with granite aggregate. This anti-striping agent results in higher resistant mixture compared to specimens with dry resin polymer in the early ice-melt cycles; in the higher ice-melt cycles, however, this trend is reversed. In fact, it can be claimed that specimens made with dry resin polymer additive will have a better resistance to moisture damage in higher ice-melt cycles.

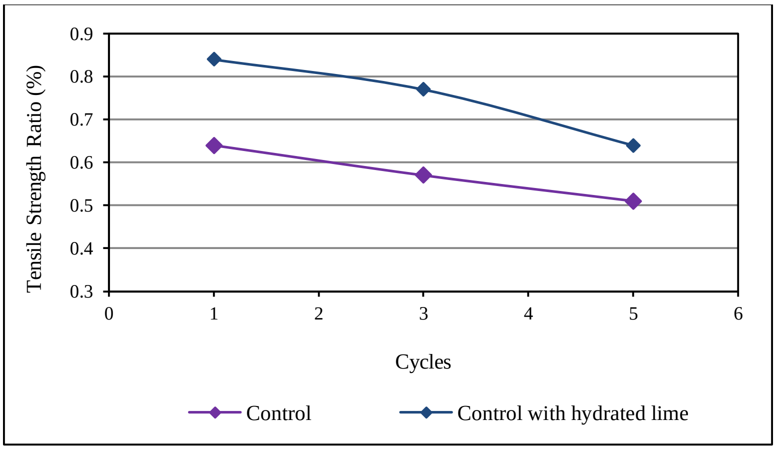

Figure 8. Relationship between TSR in different ice-melt cycles in specimens made with granite and hydrated lime aggregates

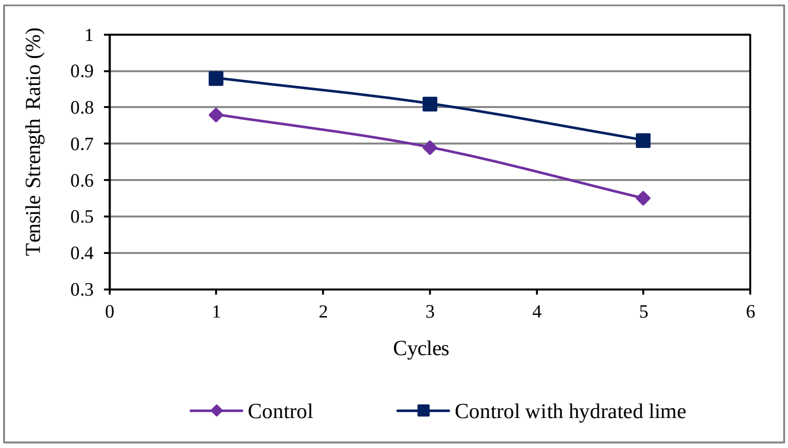

Figure 9. Relationship between TSR in different ice-melt cycles in specimens made with limestone and hydrated lime aggregates

The most important studies of moisture breakdown or water failure in asphalt mixtures are associated with known processes known as scavenging. The detachment is the process of removing bitumen from the aggregate surface, which is the reason for this increase in gravity between aggregate and water relative to aggregate and bitumen. Several factors determine the amount of moisture breakdowns that are used to improve this type of failure, with the use of anti-scrubbing additives most important. The main objective of the current study is to make an asphalt mixture resistant to moisture damage. Regarding the methods used to reduce moisture sensitivity noted above, this study tended to use suitable anti-striping materials and changes in materials of asphalt mixtures to resist them favourably against moisture damage. Numerous additives were considered in design process and primary tests; key factors such as reinforcement of asphalt mixture to moisture (which is the most important objective of this study), lack of deficiencies in other technical properties of the mixture, operational considerations, economic considerations and environmental considerations were the most important of these. Additives considered for modification of aggregates, such as hydrated lime, are added directly to aggregates to correct the surface charge of aggregates or to modify the bitumen in the interface of bitumen and aggregate. These additives are mainly used when coarse grains is susceptible to striping because it is easier to add them to coarse grains rather than fine grains. Choice of additive type varies based on: 1) effect on adhesion properties; 2) effect on mixture properties; 3) percentage required; 4) economic problems. Despite positive effect of hydrated lime, its use is associated with performance problems. Accordingly, this study tended to introduce new anti-striping agents and their microscale analysis on moisture damage. It was also attempted to compare moisture sensitivity of specimens modified with dry resin polymer and specimens modified with hydrated lime.

5. Conclusions

Here are the most important results of this study:

- Adding dry resin polymer increases adhesion and bonding in the mixture and does not allow rapid displacement of bitumen on the aggregate surfaces, which results in higher resistance of the mixture to moisture following ice-melt cycles than specimens without additives.
- The best percentage of anti-striping additives is different depending on the type of aggregate and bitumen and the tests used to determine moisture sensitivity can be used to determine optimal percentage of these materials. As the results of this study also showed, increasing dry resin polymer content from 2 to 4% did not have a notable effect on improving asphalt mixture resistance compared to specimens containing 2% dry resin polymer.
- Indirect tensile strength of specimens modified with dry resin polymer increased both under wet conditions and dry conditions.
- Addition of dry resin polymer significantly increases resistance to moisture damage and increases TSR value in the specimens modified with this material compared to specimens containing controlled aggregates.
- Dry resin polymer increased non-polar component of total surface free energy of bitumen.
- Dry resin polymer increases alkaline component and reduces acidic component of bituminous surface free energy, resulting in more adhesion between acidic aggregates and bitumen.
- Aggregates have high polar energy, because of which non-polar bitumen hardly covers aggregates. Correction with dry resin polymer changes the bitumen properties and increases its coating capability.
- Correction with dry resin polymer increases adhesion free energy, which increases bitumen-aggregate adhesion.
- Limestone relatively performs better against moisture, because changes in free energy of its adhesion to bitumen in the presence of water is lower than granite.
- As expected, hydrated lime improved resistance of asphalt mixtures to moisture.
- Performance of hydrated lime in early ice-melt cycles was better than dry resin polymer; this performance changed in higher cycles and specimens with dry resin polymer performed better against resistance damage based on AASHTO T283.

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