Moisture susceptibility of warm mix asphalt

Mehmet Bayazit\textsuperscript{a}, Prabir Kumar Das\textsuperscript{b}, Yuksel Tasdemir\textsuperscript{a}\textsuperscript{*}

\textsuperscript{a}Engineering and Architecture Faculty, Bozok University, Yozgat, Turkey
\textsuperscript{b}Division of Highway and Railway Engineering, KTH Royal Institute of Technology, SE-10044 Stockholm, Sweden

Received 2 December 2013; accepted 31 July 2014

In this study, moisture susceptibility characteristics of wax modified bitumens and warm mix asphalt (WMA) mixtures are determined. The asphalt mixtures are prepared with 50/70 penetration grade unmodified bitumen and modified bitumens with three different types of additives (Fischer Tropsch wax, montan wax and polyethylene wax) by weight of 6%. The moisture susceptibility characteristic of the four bitumens is determined with Sessile drop method and that for asphalt mixtures is determined with Nicholson stripping test on loose asphalt mixtures and Modified Lottman test on compacted asphalt mixtures. Furthermore, Marshall stability with different blow numbers of WMA mixtures are determined. The findings from all of these tests suggest that due to the Fischer Tropsch wax and montan wax modification the asphalt mixture become more moisture susceptible which correlates with the surface energy characterization. Interestingly, polyethylene wax modification shows positive moisture performance.

**Keywords:** Warm mix asphalt, Moisture susceptibility, Modified Lottman test, Sessile drop method

One of the major causes of air pollution during the construction of transportation infrastructures is the emission of greenhouse gases into the atmosphere. In case of asphalt pavement construction especially with hot mix asphalt (HMA), a high mixing and compaction temperature is required throughout the construction process to maintain sufficient workability. This high mixing and compaction temperature causes emission which is a major drawback in both environmental and working environment point of view. This emission is proportional to the temperature thus lowering the temperature may reduce the pollution, however, this will also reduce the workability. Thus, it is important to have a technology which can give the same level of workability as HMA at a lower temperature. It has been found that warm mix asphalt (WMA) can be used to replace HMA because it is produced at 20-40°C lower temperature than the HMA but provides the same level of workability.\textsuperscript{3} Besides aforementioned environmental benefits, WMA provides other advantages such as: better working conditions because of the absence of harmful gases, lower energy consumption in mix production, quicker turnover to traffic, longer hauling distances and extended paving season.\textsuperscript{1} Furthermore, lower void content due to improved compaction should make the pavement more durable.\textsuperscript{2} Therefore in the recent years, WMA is gradually becoming more popular material in asphalt paving industry. Rising energy prices, global warming concern, and more stringent environmental regulations have resulted in an interest in WMA technologies as a mean to decrease the energy consumption and emissions.\textsuperscript{3}

In general, WMA is produced using commercial wax such as FT-paraffin, montan and polyethylene wax as an additive in asphalt mixing plant. Despite of having environmental benefits, one of the big concerns of using WMA is the durability. Thus, several researchers have investigated the effect of using WMA on pavement distresses caused by traffic loading and environmental effects, mainly fatigue cracking, rutting, low temperature cracking and moisture damage.\textsuperscript{2,4-11} A detail review on WMA technology by considering all these aspects can be found in the literatures.\textsuperscript{12,13}

According to previous studies, addition of waxes may slightly increase the moisture susceptibility of asphalt mixtures through decreasing the adhesion between bitumen and aggregate.\textsuperscript{14-17} Nevertheless, some other investigations have reported an improvement in moisture sensitivity when using waxes in decreasing the construction temperatures.\textsuperscript{11,14,18-20} Also, numerical reports

\*Corresponding author (E-mail: yuksel.tasdemir@gmail.com)
concluded there are inconsistent results in terms of moisture susceptibility of WMA mixtures\textsuperscript{11,14,21,22}. Hence, there is still lack of knowledge in moisture susceptibility of WMA and a number of challenges to overcome. The short of experience with WMA tends to raise logical doubts and uncertainties about their use, because they are still at a stage of experimentation and standardization\textsuperscript{1}. By developing a clear understanding of the moisture susceptibility of WMA, one can engineer the WMA technique that will result in improved durability and eventually better performing pavements.

**Research Motivation**

Moisture damage is defined as the progressive functional deterioration of a pavement mixture by loss of the adhesive bond between the bitumen and the aggregate surface and/or loss of the cohesive resistance within the bitumen principally due to presence of water\textsuperscript{23}. Loss of adhesion causes stripping and raveling whereas, loss of cohesion causes pore pressure damage and premature cracking\textsuperscript{24}. Failure of asphalt pavement due to moisture damage causes a considerable expenditure of funds for repair and rehabilitation every year\textsuperscript{25}. Thus, moisture damage is becoming one of the key concerns along all of the pavement distresses\textsuperscript{23-32}. The methods of treatment to reduce moisture damage include use of good aggregate, pretreatment of aggregates and use of additives such as anti stripping agent, hydrated lime, polymer modification of the bitumen etc.

The decreasing production temperature of WMA can cause adhesion failure as moisture may remain in aggregates\textsuperscript{33,34}. The interplay between bitumen property and aggregate mineralogy plays a vital role on moisture damage performance of asphalt mixture. Thus, non stripping aggregate was chosen particularly in this study to eliminate any contradictions may arise due to aggregate mineralogy issue. The mixing and compaction temperatures were also carefully determined and controlled during specimen preparation.

In this study, the wettability of wax modified bitumen was characterized by surface energy theory utilizing Sessile drop method. The moisture susceptibility of wax modified asphalt mixtures were investigated with Nicholson Stripping and Modified Lottman tests. Moreover, Marshall stability of the wax modified mixtures were also determined to evaluate effect of waxes modification. Finally, the analyses of the obtained results can provide fundamental knowledge on the moisture susceptibility of WMA to the asphalt community.

**Materials**

**Bitumen and additives**

In this study, low penetration grade (50/70) bitumen obtained from Turkish Petroleum Refineries was used as control bitumen and denoted as LP. The bitumen was modified with three different types of wax additives, such as: FT-paraffin, montan and polyethylene wax which were denoted as S, MW and PW, respectively. Characteristics of the additives obtained from the manufactures are given in Table 1. Only one level of content (6%) was used in this study, and chosen in order to obtain, if possible, significant effects in the asphalt mixture testing.

FT-paraffin and montan wax are the most commonly used WMA additives which are used in production stage of asphalt pavements and mastic asphalt to reduce the mixing temperature and thereby energy consumption and emissions\textsuperscript{35}.

FT-paraffin wax (also known as Sasobit) produced by Fischer Tropsch synthesis have carbon chain lengths ranging from C45 to C100. The longer carbon chains in the FT-paraffin wax lead to a higher melting point. The smaller crystalline structure of the FT-paraffin wax reduces brittleness at low temperatures as compared to bitumen paraffin waxes. Due to its ability to lower the viscosity of the bitumen during the asphalt mixing process and lay down operations, it is known as flow improver.

**Table 1 – Information regarding additives used in this study**

<table>
<thead>
<tr>
<th>Additive</th>
<th>Characteristics</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sasobit,</td>
<td>Congealing point</td>
<td>100 (°C)</td>
</tr>
<tr>
<td>(FT paraffin</td>
<td>Penetration at 25°C</td>
<td>&lt;1 (dmm)</td>
</tr>
<tr>
<td>wax)</td>
<td>(ASTM D 1321)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Penetration at 65°C</td>
<td>7 (dmm)</td>
</tr>
<tr>
<td></td>
<td>(ASTM D 1321)</td>
<td></td>
</tr>
<tr>
<td>Romonta</td>
<td>Solidification point</td>
<td>95-105 (°C)</td>
</tr>
<tr>
<td>Asphaltan B,</td>
<td>Dropping point</td>
<td>110-120 (°C)</td>
</tr>
<tr>
<td>(Montan wax)</td>
<td>(Romonta test method W 1.1)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Viscosity at 120°C</td>
<td>20-200 (mPas)</td>
</tr>
<tr>
<td></td>
<td>(Romonta test method W 7.1.1)</td>
<td></td>
</tr>
<tr>
<td>Luwax A,</td>
<td>Melting point</td>
<td>98-108 (°C)</td>
</tr>
<tr>
<td>(Polyethylene</td>
<td>(microscope or DSC)</td>
<td></td>
</tr>
<tr>
<td>wax)</td>
<td>Congealing point</td>
<td>92-100 (°C)</td>
</tr>
<tr>
<td></td>
<td>Penetration value at 23°C</td>
<td>1-2 (dmm)</td>
</tr>
<tr>
<td></td>
<td>(ASTM D 1321)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Viscosity at 120°C</td>
<td>950-1550 (mm²/s)</td>
</tr>
<tr>
<td></td>
<td>(ASTM D 2126)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Density at 23°C</td>
<td>0.91-0.93 (g/cm³)</td>
</tr>
<tr>
<td></td>
<td>(ASTM D 792)</td>
<td></td>
</tr>
</tbody>
</table>
decrease in viscosity allows working temperatures to be lowered down by 18-54°C. FT-paraffin has a congealing temperature of about 102°C and is completely soluble in bitumen at temperatures higher than 120°C. At temperatures below its melting point, reportedly forms a crystalline network structure in the bitumen that leads to the added stability. FT-paraffin addition of ranged from 0.8 to 4 percent by mass of bitumen is considered optimal\(^{33,36}\). Whereas, the addition of more than 4% FT-paraffin may cause low temperature cracking problem in asphalt pavements\(^{35,37,38}\).

Montan wax derives from fossilized vegetables and re-obtain by solvent extraction of certain types of lignite and brown coal. This wax is a combination of non glyceride long chain carboxylic acid esters, free long chain organic acids, long chain alcohols, and other organic compounds with a complex structure\(^{39}\). It has a more complicated structure than FT-paraffin wax. Montan waxes have been specially modified so that adding with bitumen increases its softening point and also improve asphalt mixture adhesion properties. Montan wax can be used as a flow improver for bitumen and found in different names depending upon the sources. In this study, Asphaltan B has been used as montan wax which congealing point is about 100°C\(^{35}\).

On the other hand, polyethylene wax is not commonly used as a flow improver or modifier in asphalt mixtures as Sasobit or montan wax. However in previous studies, adding polyethylene wax had shown considerable stiffening effect on the rheological behavior and increased rutting resistance of bitumen at medium and higher temperatures\(^2,9\). Therefore it is a great interest to investigate the behavior of this wax and compared performance with the other two waxes.

Bitumen was modified by adding 6% of wax additives by weight of bitumen. Approximately, 300 g of 50/70 control bitumen samples were heated about 3 h at 150°C. After 6% wax by weight of the bitumen was added in the heated bitumen, this modified samples were then heated 30 min at 150°C. Both modified and unmodified samples were shaken about 90 s in preheated blocks in order to homogenize bitumen-wax blends. No compatibility and homogeneity problems were observed during mixing.

**Aggregates and asphalt mixtures**

In the present study, crashed aggregates with maximum size of 19 mm were obtained from Astas quarry of Yozgat/Turkey and used to prepare asphalt mixtures. The mineralogy of the aggregates contains 96.01% CaO, 1.29% SiO\(_2\), 0.753% Al\(_2\)O\(_3\), 0.744% MgO and 0.597% Fe\(_2\)O\(_3\). The presence of high percentage of calcite component (CaO) confirms limestone type of aggregate. Due to its mineralogy, limestone type of aggregate has a long history by providing better bonding with bitumen. A dense graded asphalt mixture according to Turkish road standards was prepared\(^{40}\). The gradation curve of the aggregate is shown in Fig. 1.

The asphalt mixtures were prepared in the laboratory. The optimum bitumen content was found 5.25% by weight of aggregate based on the Marshall Mix Design procedure with 75 blows\(^{41}\). The mixing and compaction temperatures for producing specimens were selected in a way that the viscosities are 170±20 and 280±30 cSt, respectively\(^42\).

**Experimental Methodology for Bitumen**

**Conventional tests**

The standard test methods were used to characterize the control and wax modified bitumen samples, which include softening point (EN 1427), penetration (EN 1426) and Brookfield viscosity (EN 13302). A Brookfield rotational viscometer was used to determine viscosity of unmodified and modified bitumen. The Brookfield viscosity was determined by measuring the torque required to maintain a constant rotational speed of a cylindrical spindle while submerged in bitumen maintained at 135°C and 165°C. These conventional tests provide a preliminary idea of stiffness of the bitumen.

**Dynamic mechanical analysis (DMA)**

Dynamic mechanical analysis (DMA) was performed using a rheometer (AR 2000ex from TA instruments). A temperature sweep with 2°C increments (from 30°C to 100°C) was applied to characterize the temperature dependency of bitumen.
parameters at a frequency of 10 rad/s and variable strains. Parallel plates with diameter 25 mm and gap of 1 mm were used. A sinusoidal strain was applied and the actual strain and torque were measured. From this test, dynamic shear modulus ($G^*$) and phase angle ($\delta$) were determined to investigate any change in rheological properties due to wax modification.

**Surface energy characterization**

Surface energy is a fundamental material property which can be used as an indicator of adhesiveness and wettability of bitumen. Bitumen with greater wetting ability is desirable because it will better coat the surface of an aggregate and leave fewer places for moisture damage to occur in the future. A drop of liquid on a solid surface will either spread and form a thin layer or remain as a drop. This liquid drop has a contact angle between the surface of the liquid and the surface of the solid. The value of contact angle depends on the liquid-solid surface adhesive force and the cohesion in the liquid and thus, is a function of surface energy of the liquid and the surface energy of solid, as shown in Fig. 2. Therefore, contact angle measurement can provide useful information on the wettability of bitumen and its adhesiveness. Theoretically, a lower contact angle provides good adhesiveness, wettability and high surface energy.

For surface energy measurements, the static contact angles between three liquids and four different types of solid bitumen surfaces were measured at room temperature (23°C) using the Sessile drop method. Approximately 30 mg of hot bitumen was carefully placed on a rectangular glass slide (50 mm × 24 mm × 1.5 mm) and it was spread out with a blade to form a relatively even and smooth surface. Then the bitumen film was cooled to room temperature and covered to prevent dust pick-up. After that the sample was annealed at 25°C for a minimum of 24 h before measurement. After setting up the instrument, the contact angle of a 4 µL drop of water, form amide and diode-methane was measured. The three types of liquids have completely different surface tensions and provide a basis of calculation of surface energy. Once the contact angle is measured for three different known liquids then the Young-Laplace equation can be used to calculate surface energy of the bitumen:

$$\sigma_{sv} = \sigma_{sl} + \sigma_{lv} \cos \theta$$

(1)

where, $\sigma_{sv}$, $\sigma_{sl}$ and $\sigma_{lv}$ are the interfacial tension between solid-vapor, solid-liquid and liquid-vapor interfaces, respectively.

**Experimental Methodology for Asphalt Mixtures**

**Nicholson stripping test**

AASHTO T 182-84 “Test method for coating and stripping test of bitumen aggregate mixture” is utilized to evaluate the degree of stripping of WMA mixtures. As per the specifications, the aggregates were taken between 9.5 mm and 6.3 mm sieve. They were washed in distilled water and dried at 135°C - 149°C. From these aggregates, 100±1 g aggregate was placed in oven at 140°C for an hour and the four types of bitumen were placed in oven at 145°C for 3 hours. After the heating of bitumen and aggregate, 5.5±0.2 g heated bitumen was poured on to heated aggregate and mixed vigorously with the spatula for 2 min so that all the aggregate particles were coated with bitumen. The coated aggregate was cured for 2 h in the original container at 60°C. The loose mixture was then transferred to glass container and immersed in distilled water for 18 h at room temperature and visually inspected under water to estimate the degree of stripping and surface area of aggregate particles on which still the bitumen coating remains.

**Modified Lottman test**

AASHTO T-283 (Modified Lottman) test is used as a tool to determine moisture susceptibility characteristics of the asphalt mixture. The Modified Lottman test is one of the most commonly used procedures for determining HMA moisture susceptibility. According to the test procedure, the loose asphalt mixtures were placed in oven at 60°C for 16 h for curing. After curing and prior to compaction, the mixtures were kept in an oven at compaction temperatures for 2 h. Then, the mixtures were placed in a preheated mold and the specimens were prepared with 7±1% air voids. Totally, 24 specimens were produced and divided into two groups. The first group (12 specimens) was subjected to conditioned, and the second group (12 specimens) was remained unconditioned. For conditioning, the specimens were placed in the vacuum container and
filled the container with distilled water. After 5 min, vacuum was applied with pressure of 13-67 kPa for next 10 min. Then the bulk specific gravity of specimens was determined according to AASHTO T-166 procedure and degree of saturation of the specimens was recorded. The volume of water was obtained between 55% to 80%. The saturated specimens were covered with parafilm, then placed in plastic bag containing 10 mL distilled water and lastly, sealed it. The bags containing the specimens were placed in freezer at -18°C for 16 h. After the samples were removed from the freezer, the specimens were placed in water bath at 60°C for 24 h. Finally conditioned and unconditioned specimens were placed in water bath at 25°C for 2 h. To determine the tensile strength of the specimens, the indirect tensile strength tests were conducted with a loading rate of 50.8 mm/min. The tensile strength was calculated according the following equation:

\[ S_t = \frac{2000 \times P}{\pi t x D} \]  

where \( S_t \) is tensile strength (kPa), \( P \) is maximum load (N), \( t \) is thickness of the specimens (mm), and \( D \) is diameter of the specimens (mm). The ratio of the tensile strength (TSR) was then calculated from the following equation:

\[ \text{TSR} = \frac{S_{t2}}{S_{t1}} \]  

where \( S_{t1} \) and \( S_{t2} \) are the average tensile strength of the unconditioned and conditioned specimens, respectfully. According to the specification, if the tensile strength ratio is lower than 0.8, the samples are susceptible to moisture damage.

**Marshall stability test**

The Marshall specimens were prepared using the four different types of unmodified and modified bitumen (cf. Table 2). Compactions of specimens were done by a Marshall compactor with 50 and 75 blows on each side of the cylindrical samples. The specimens were kept at room temperature overnight before testing. After the samples were waited, they were immersed in water about 30 min at 60°C. Then the samples were placed in Marshall stability test equipment and loaded at a constant rate of 50.8 mm/min until it fails. This failure load was used to determine Marshall stability. Marshall stability is defined as the maximum load carried by a compacted specimen. Since this stability is a measure of the mass viscosity of the asphalt mixture thus it generally gets affected by the viscosity profile of used bitumen. Failure in asphalt mixtures may occur within the bitumen (cohesive failure) or at the aggregate-bitumen interface (adhesive failure). It can be considered that adhesive bond strength controls the failure mechanism in the Marshall Stability test\(^{48,49}\).

Additionally, Marshall Quotient (MQ) was also determined which is a ratio of stability and flow, and can be used to indicate the stiffness of the mixes\(^{21}\). A higher value of MQ generally represents a higher rutting resistance of the asphalt mixture and vice versa.

**Results and Discussion**

**Test on bitumen**

*Conventional test results*

Conventional test results are given in Table 2. As shown in the table, the addition of wax S and wax MW reduced penetration and increased softening point, indicating the stiffening effect. Whereas, in case of PW modified bitumen, the penetration value increased significantly but somehow the softening point remains similar. Interestingly, softening points of the all wax modified bitumen are higher than the unmodified bitumen.

In Table 3, the viscosities of all the four bitumen at 135°C and 165°C, and the mixing-compaction temperatures of the mixtures are given by using the viscosity values of 170±20 and 280±30 cSt, respectively\(^{50}\). The viscosities were reduced at 135°C and 165°C due to the addition of both wax S and wax MW, whereas increased for the addition of wax PW. These findings are identical with the penetration and softening point test results. It can be also seen that the mixing and compaction temperature became lower by

---

**Table 2 – Conventional test results of bitumens**

<table>
<thead>
<tr>
<th>Bitumen</th>
<th>Penetration (dmm)</th>
<th>Softening point (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LP</td>
<td>60</td>
<td>49</td>
</tr>
<tr>
<td>LP+6% S</td>
<td>29</td>
<td>92</td>
</tr>
<tr>
<td>LP+6% MW</td>
<td>42</td>
<td>86</td>
</tr>
<tr>
<td>LP+6% PW</td>
<td>40</td>
<td>52</td>
</tr>
</tbody>
</table>

**Table 3 – Mixing and compaction temperatures of mixtures and viscosity of bitumens**

<table>
<thead>
<tr>
<th>Bitumen</th>
<th>Viscosity at 135°C, (cSt)</th>
<th>Viscosity at 165°C, (cSt)</th>
<th>Mixing Range, °C</th>
<th>Compaction Range, °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>LP</td>
<td>463.8</td>
<td>128</td>
<td>159-165</td>
<td>146-151</td>
</tr>
<tr>
<td>LP+6% S</td>
<td>296.3</td>
<td>88.5</td>
<td>148-155</td>
<td>134-140</td>
</tr>
<tr>
<td>LP+6% MW</td>
<td>277.5</td>
<td>87.5</td>
<td>146-153</td>
<td>131-138</td>
</tr>
<tr>
<td>LP+6% PW</td>
<td>516.5</td>
<td>149.5</td>
<td>163-170</td>
<td>149-155</td>
</tr>
</tbody>
</table>
the addition of both wax S and wax MW, whereas higher or remained same by the addition of wax PW.

**Dynamic mechanical analysis measurement**

In Figure 3, DMA results showed stiffening effects at medium and high temperatures due to addition of wax S and wax PW. Adding wax PW indicated greater effect on complex modulus and phase angle than that of wax S. As shown in the figure, the phase angle decreases the most between 70°C to 90°C for binder samples containing wax PW. A corresponding plateau effect appears for the complex modulus. At temperatures in the range of 45°C to 85°C, typical of high pavement service temperatures, the main distress mechanism is rutting, and therefore, dynamic modulus and phase angle are relevant. For rutting resistance, a high complex modulus value is favorable because it represents a higher total resistance to deformation. A lower phase angle is favorable as well because it reflects a more elastic (recoverable) component of the total deformation.

The findings certainly indicate the increment in rutting resistance of bitumen modified by wax PW.

**Surface energy measurement**

The measured contact angle and surface energy is tabulated in Table 4. It can be seen that the contact angle between water and four types of bitumen decreases due to the wax modifications. Interestingly, the total surface energy decreases due to the wax S and wax MW modification whereas increases for wax PW. A reduced surface energy indicates low adhesive quality bitumen which indicates more susceptible to moisture damage and vice versa. This indicates the addition of wax S and wax MW decreases the adhesiveness of the unmodified bitumen and thus become more moisture sensitive. While wax PW modification increases surface energy, which indicated this modification makes the bitumen surface hydrophilic and thus improves the adhesiveness and wettability. Since these findings are completely based on bitumen investigation, it would be interesting to study the mixture moisture susceptibility and compared to it.

**Tests on mixtures**

**Nicholson stripping test**

The loose mixtures were visually inspected after immersing in distilled water for 24 h. As can be seen in Fig. 4, the percentage of the total visible area of the aggregate which remains coated was determined above 95%. This indicates that the asphalt mixtures prepared using limestone aggregate have high resistance to stripping since the bond strength between asphalt and aggregate is strong.

**Modified Lottman test**

The indirect tensile strength ($S_t$) of all the unconditioned and conditioned specimens was

![Fig. 3 – Effect on complex modulus and phase angle (frequency 10) unmodified and modified with 6 % waxes bitumen](image1)

![Fig. 4 – Nicholson stripping test results](image2)
calculated utilizing Eq. (2) and plotted for all the four different asphalt mixtures, in Fig. 5. As can be seen for unconditioned specimens, the $S_t$ of the wax modified asphalt mixtures is higher than the unmodified one. This increment in tensile strength due to wax modification may be related with the observed stiffening effect from bitumen test results. While after conditioning the tensile strength of the specimens reduces due to moisture damage however the ranking this time differs from the unconditioned case. To investigate the effect of moisture damage furthermore, the tensile strength ratio (TSR) of control mixture, wax PW, wax MW and wax S modified mixtures was recorded as 0.94, 0.88, 0.83 and 0.78, respectively (Fig. 5). Mixture with a higher value of TSR has lower risk of moisture susceptibility and will have a good long term performance. One may observe that the TSR value of the unmodified bitumen mixture is higher than the wax modified bitumen mixtures. The second highest TSR value obtained for wax PW modified mixture and interestingly the mixing-compaction temperature was also high for this specific mixture (c.f. Table 3). From these observations, it can be concluded that the reduction of TSR in wax modified mixtures may be due to the decreased production temperature the moisture remains in the aggregate and thus causes adhesion failure.

**Marshall stability test**

The Marshall stabilities and Marshall Quotient (MQ) values were obtained by averaging of three specimens and the obtained results are given in Table 5. As shown in the Table 5, Marshall stability of unmodified mixture increased with blow numbers, however wax modified asphalt mixtures almost not changed. In case of 75 blows, the unmodified and wax PW modified asphalt mixtures showed better stability than the wax S and wax MW modified mixture. The presence of wax S and wax MW in the asphalt mixtures resulted in, decreased adhesive bond strength which leads to decreased stability values of the mixtures. Hence, wax S and wax MW modified mixture could be more moisture susceptible.

Flow values of the wax modified specimens were lower than that of the unmodified specimens. It was seen that all the specimens with wax modified have higher MQ values than unmodified specimens. MQ increased 30-41% and 7-45% compared with control specimens under 50 and 75 blows, respectively. Among all of them wax PW showed the highest effect. This represents the wax modified mixtures especially wax PW modified mixtures, have higher rutting resistance than unmodified mixtures. Similar results were obtained from Dynamic mechanical analysis.

**Conclusions**

This study was carried out on unmodified and modified (FT-paraffin wax, montan wax and polyethylene wax) bitumen and asphalt mixtures to determine their mechanical properties and the characteristics of moisture susceptibility. Based on the obtained test results and analyses, the following conclusions can be drawn:

(i) According to conventional bitumen test results, the addition of wax S and wax MW showed stiffening effect whereas wax PW showed softening effect. Adding wax MW and wax S in the bitumen decreased viscosity whereas wax PW increased viscosity of bitumen. This indicates wax MW and wax S modification reduced the mixing and compaction temperature but not the wax PW. Thus, using wax PW as a WMA additive might not be resulted as beneficial as wax S and wax MW.
The rheological properties of bitumen were obtained from DMA analyses where wax additives showed better performance in rutting than the unmodified one. In this case, wax PW was found to be the most rutting resistant. The similar results were found from the Marshall stability test where Marshall Quotient was used as a performance indicator.

The analysis of surface energy showed that the addition of wax S and wax MW decreases the surface energy and thus reduces adhesiveness and become more sensitive to moisture damage. Whereas, wax PW showed opposite effect.

The moisture susceptibility of asphalt mixtures were determined by Nicholson stripping and modified Lottman test. According to Nicholson test result, the unmodified and wax modified mixtures were found to be resistant to stripping. Whereas in the Lottman test, it was obtained that unmodified and wax PW modified asphalt mixtures shows better resistance to moisture damage than the other two which had lower mixing and compaction temperature. This implies that due to decreasing production temperature cause adhesion failure as moisture may remain in the aggregate.

In case of unconditioned asphalt mixture, the indirect tensile strength increases with the wax modification and wax S showed the best load carrying capacity.

In the Marshall stability test it was obtained that the stability of unmodified bitumen samples increased approximately 20% whereas wax modified bitumen samples almost not changed with increasing compaction number. Moreover, it was observed that the wax S and wax MW modified mixture is more moisture susceptible.

In this study only the moisture damage performance of WMA was investigated without considering the effect of aggregate mineralogy. Thus, plug in the aggregate mineralogical investigation will add another dimension. However, from this study, it has been found that with the wax additives the asphalt mixture become more moisture susceptible.

References