ON THE DEVELOPMENT OF A NEW TEST METHODOLOGY FOR MOISTURE DAMAGE SUSCEPTIBILITY OF ASPHALT CONCRETE

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ABSTRACT
In this contribution the development of a new moisture susceptibility test protocol is described in which the individual asphalt mix components (aggregates, aggregate-mastic interface and mastic) are evaluated for their physical and mechanical moisture susceptibility characteristics. In the paper, the principle and development consideration of the test procedure are described, which is built around the measurement of the tensile strength of mastic (bitumen, filler and sand) and aggregate-mastic samples as a function of moisture concentration at the location of the fracture plane.

The developed moisture conditioning procedure allows for an easy measurement of moisture uptake and release behavior of the components and can show distinct differences between the investigated mastic-aggregate combinations. Comparing the measured adhesive versus cohesive moisture susceptibility strength curves allows for a fundamental material selection that can assist in the mitigation of susceptibility to moisture damage in the field.

KEY WORDS: Mastic, aggregate-mastic bond, moisture damage
1. INTRODUCTION

Currently, the majority of transportation agencies try to control moisture induced damage failures in the field by specifying tests which mainly originate from the major moisture damage test development effort in the late 1980’s. Unfortunately, it is known that the predictability of moisture damage in the field by most of these test has not always been successful, [1]-[10].

Two main categories of moisture susceptibility tests are currently in use: the classical immersion tests and tests in which saturated samples are loaded. Most commonly used are the first category tests, in which the asphalt/aggregate mixtures are not subjected to mechanical loading as they are exposed to moisture, for instance the AASHTO T-283, the EN 12697-12 method A, the immersion-compression or the Duriez, Marshall retained stability test. The second type of test procedures was introduced to create damage in the asphalt mixture by applying a load to a saturated specimen. The combined action of moisture conditioning and mechanical loading can be applied via simulation tests such as the Hamburg wheel-tracking device or the Asphalt Pavement Analyzer, or the creation of pore pressures can be generated under more controlled mechanical loading using the Environmental Conditioning System as developed by SHRP.

Unfortunately, the semi-empirical nature of both test categories does not allow for any fundamental insight into the actual parameters which are dominant in the moisture susceptibility, and these tests can therefore –at the very best- lead to comparative studies under very specific boundary conditions. From the research by Azari et.al [11] it has recently been shown that the mix morphology, the chosen laboratory compaction methodology and moisture conditioning procedure can have significant effects on the outcome of the predicted moisture susceptibility using the AASHTO T-283 procedure, thus explaining some of the experienced inconsistencies.

Even though it often seems practical to use an ‘easy to perform’ test for moisture susceptibility assessment, erroneous conclusions can result from such tests and will not contribute to long-term sustainable and economically viable asphalt mix design. In this paper a new moisture susceptibility assessment methodology is presented.

2. DEVELOPED TEST PROCEDURE

2.1 Principle of test methodology

Moisture induced damage in asphalt mixtures may display a pronounced adhesive (in the aggregate-mastic bond) or cohesive (in the mastic) failure pattern [12]. One failure pattern, however, is not unrelated to the other, and depending on the circumstances, mixtures may experience a combination of both. In this research, direct tension tests are performed for various moisture conditioning times on specially developed mastic-aggregate and mastic
samples, giving the strength as a function of conditioning time, Figure 1(a). Computational simulations of moisture infiltration into the tested specimens estimate the amount of moisture in the specimens as a function of conditioning time, Figure 1(b), on the basis of the total uptake of moisture, as measured in the laboratory. By combining the results of the tension tests with computer simulations of moisture infiltration, a direct relationship for the influence of moisture on the engineering properties of the mix components can be determined, Figure 1(c).

![Figure 1 Overview of research approach](image)

Top: adhesive testing Bottom: cohesive testing

This relationship is independent of the geometry and moisture conditions of the mechanical test specimens, and can be directly utilized for comparison of moisture susceptibility between materials. Additionally, these relationships can be used to compare the cohesive mastic strength versus the adhesive aggregate-mastic strength, to allow for the subsequent determination of the time scale over which either failure pattern may become dominant in an asphalt mix.

2.2 Investigated materials

The developed test procedure is demonstrated for 6 mastic-stone combinations and 4 mastics which are frequently used in the Netherlands for open graded asphalt wearing courses. The moisture susceptibility performance in the field is therefore known for each combination and can serve as a validation of the developed test method. Two aggregates are used in this research, sandstone (greywacke) from the Bremanger quarry in Norway and granite from a Scottish
quarry. It is known from field performance that the sandstone has an overall better stripping resistance than the granite.

For the mastics, three different bitumen types are used: a Pen 70/100, a modestly polymer modified Cariphalte XS and a highly modified Sealoflex 5-50 (PA). For filler materials two different fine fillers are used (10-75 μm): lime filler (Wigras 60) and hydrated lime (Wigro 60K) are used, and for sand (150 μm - 1mm) a crushed Norwegian aggregate is used. In Table 1 the densities of these materials is summarized. From the bitumen, fine filler particles and crushed sand, 4 types of mastics are composed, Table 2.

Combining these 4 mastics with the 2 aggregates, 6 relevant mastic-stone combinations are made, Table 3.

From field performance, it is known that Combi 1 shows the worst resistance to stripping; the addition of hydrated lime has a positive effect against stripping; the sandstone behaves better than the granite and the polymer modified bitumen behave better than the non-modified bitumen.

### 3. ADHESIVE TESTING

3.1 Adhesive sample preparation procedure

For measuring the adhesive strength of the aggregate-mastic combinations, the aggregate substrates were sawn into round slabs with diameter 150 mm and
thickness of 20 mm, cleaned with distilled water and dried for 48 hours at 60°C, cooled down and heated before sample preparation. To prepare the mastic film, the mastic was heated to the relevant temperature of each bitumen and poured into a mall of 4 mm thickness, Figure 2. After cooling down of the samples, a (cold) steel stub which attaches to an MTS device is glued onto the mastic, using two-component superglue. All samples are left to cure for a prescribed time at 18 ± 2°C. The moisture conditioning of the samples is performed by placing the samples in a bath filled with distilled water on a flat layer of gravel. The moisture level is kept at a constant height of 1 mm below the aggregate top surface at a constant temperature of 18 ± 2°C. The mastic-stone samples were then conditioned for 0, 2, 4 and 6 weeks, after which they are immediately tested.

![Figure 2 Test specimens for measurement of adhesive moisture susceptibility [13]](image)

3.2 Adhesive bond strength test results

Each mastic-stone type and conditioning time was repeated 3 times. The aggregate-mastic bond strength of the samples was then determined using a hydraulic MTS device. To attach the samples to the loading stub, a special metal fixture is attached to the steel stub which was glued onto the sample, Figure 2. The bond strength is measured in a direct tension displacement rate of 0.05 mm/s and temperature of 18 ± 2°C.

In general, the repeatability of the experiment was fairly good, a few examples exempted (e.g. 2wk-combi 5), with a standard deviation for the bond strength of 0.02-0.10 MPa. The mean value of the bond strength and the bond energy are summarized in Table 4.

<table>
<thead>
<tr>
<th>COMBI</th>
<th>S [MPa]</th>
<th>W [Nmm/mm²]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0 wk</td>
<td>2 wk</td>
</tr>
<tr>
<td>1</td>
<td>1.28</td>
<td>0.97</td>
</tr>
<tr>
<td>2</td>
<td>1.79</td>
<td>1.29</td>
</tr>
<tr>
<td>3</td>
<td>1.15</td>
<td>1.09</td>
</tr>
<tr>
<td>4</td>
<td>0.94</td>
<td>0.77</td>
</tr>
<tr>
<td>5</td>
<td>1.15</td>
<td>0.89</td>
</tr>
<tr>
<td>6</td>
<td>1.24</td>
<td>0.97</td>
</tr>
</tbody>
</table>
All mastic-stone combinations had an initial (dry) bond strength of 0.9 - 1.8 MPa and a bond energy of 0.4 - 0.9 Nmm/mm². To compare the effect of the moisture infiltration on the bond strength of the mastic-stone samples, numerical moisture infiltration simulations were performed using the finite element software RoAM [14] to determine the moisture concentration at the interface at the time of testing. More details on this procedure can be found [13]. Defining moisture damage as

\[ d_S(\theta) = 1 - \frac{S(t)}{S_0} \]  

where \( S_0 \) is the original, undamaged bond strength measured at 0 hours conditioning time, \( S(t) \) is the measured bond strength after conditioning time \( t \) and \( \theta \) is the normalized moisture content. In Figure 3 the comparison is shown for the moisture susceptibility of the 6 aggregate-mastic combinations.

By comparing the moisture damage functions, it becomes clear that Combi 2 (with the sand stone) shows 5 - 10% higher adhesive moisture damage resistance than Combi 1 (with the granite). This is in agreement with the field behavior. Furthermore, it becomes clear that the hydrated lime gives an increase of 15 – 30% to the bond strength resistance and an increase of 15 – 40% to the bond energy resistance to moisture damage. In the case of bond strength reduction Combi 6 has the best behavior, followed by Combi 4 and Combi 3. Therefore, even though the non-stripping aggregate should always be preferred, in the case of no choice, it is worth using a modified binder to increase the moisture susceptibility of the mastic-stone bond.
4. COHESIVE TESTING

4.1 Cohesive sample preparation procedure
To determine the measurement of mastic strength as a function of moisture concentration, the test specimen geometry must allow for a uniform stress- and moisture concentration field at the failure location. To allow for the first, a direct tension test set-up is chosen. For the latter, attention must be given to the design of the pulling ring in combination with the moisture conditioning procedure. Given the visco-elastic nature of the mastic, it is important to have a controlled failure plane at the centre of the sample, [16], and avoid any interference from or failure at the pulling ring. To allow for relatively short moisture conditioning times, a smaller sample size is to be preferred, yet, the specimens must be large enough for an accurate failure strength measurement in the available load-cells. To take all these considerations into account, the geometry of the mastic samples is optimized, making use of a combination of finite element parametric analyses and laboratory trials. More details on this procedure can be found in [15].

![Figure 4 Mastic samples for cohesive strength testing](image)

Based on the above computational and laboratory analyses, the optimum mastic specimen geometry was determined to be a parabolic specimen with a geometry as shown in Figure 4(e). With the use of a steel contra-malt, special silicon molds are developed which were heated at the same mixing temperature (165 °C for mastic 1 and 2 and 185 °C for mastic 3 and 4 with the polymer modifiers) as the mastics at the time of pouring the samples in the mals, Figure 4 (a).
After cooling down, the samples were removed from the malts, Figure 4 (b) and placed in a moisture conditioning bath on a layer of sand. During the conditioning period, the samples were regularly rotated to avoid deformation and to encourage a uniform infiltration pattern. After various conditioning times, samples were glued onto the MTS and tested at a constant displacement rate of 0.8 mm/s at room temperature. All tested samples failed in the intended critical area, Figure 4 (d).

During the conditioning period, the increasing mass of the specimens was regularly measured to monitor the progress of the moisture infiltration, Figure 5. From this it was seen that significantly different diffusion behavior was found for the four mastic types. Using the finite element software RoAM [14] the infiltration of moisture into the samples was simulated hereby assuming that the moisture infiltration into the mastic is following a constant diffusion flow.

From this, it was found that the moisture diffusion rates of mastic 1, 2 and 3 was similar, but the maximum moisture uptake of mastic 1 and 3 are 2.5 - 3 times higher, respectively, than that of mastic 2. Mastic 4 showed a significantly different moisture absorption behavior, reaching its maximum moisture uptake after 30 days of conditioning, which is three times faster than the other mastics. Its maximum moisture concentration however was slightly more than that of mastic 2 and half that of mastic 1 and 3.

After the samples had reached full saturation, they were removed from the moisture bath. Four samples of each mastic type were immediately tested for their cohesive strength in the direct tension set-up and the remaining samples were given a water-proof coating on the side of the samples, leaving the top and bottom of the sample open and placed in a climate chamber with a relative humidity of 20% for drying. During this, the samples were regularly measured for their decrease in mass. By again simulating computationally the same conditions, using the measured overall mass decrease as input data, the decreasing moisture concentration in the critical area of the specimens could be determined.

![Figure 5 Moisture uptake mastic specimens](image-url)
4.2 Cohesive strength results
To assess the mastic strength as a function of moisture concentration, the mastic samples were tested at fully saturated and two different partially saturated conditions after 35 and 113 days of drying. From the test results it was seen that the strength measurements are very repeatable and consistent results are obtained, Table 5(a). From this it can also be noted that mastic 3 had the highest tensile failure force, whereas it was seen that this mastic had the highest net moisture absorption. In Table 5(b) the mean values (average from 4 specimens) of the measured tensile strengths are given. From the data is can be seen that mastic 1 and mastic 4 have an increasing strength with an increasing drying time, which is in accordance with the expectation. Mastic 2 and 3, however, show an opposite trend: decreasing mastic strength as drying time increases. Since the measured strength values are related to the moisture concentration at the critical cross-section, the measured overall mass loss was used in the finite element analyses with RoAM.

<table>
<thead>
<tr>
<th>Drying Time</th>
<th>Mastic 1</th>
<th>Mastic 2</th>
<th>Mastic 3</th>
<th>Mastic 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 days</td>
<td>0.639</td>
<td>0.644</td>
<td>1.057</td>
<td>0.677</td>
</tr>
<tr>
<td>35 days</td>
<td>0.645</td>
<td>0.592</td>
<td>0.853</td>
<td>0.785</td>
</tr>
<tr>
<td>113 days</td>
<td>0.689</td>
<td>0.540</td>
<td>0.873</td>
<td>0.765</td>
</tr>
</tbody>
</table>

The analyses showed that mastic 1 had lost a significant amount of moisture at the critical cross-section after 35 (θ=0.8) and 113 days (θ=0.6) of drying. Mastic 2 and 3 seemed to retain most of their moisture at the critical cross-section and have only lost moisture at the top and bottom of the specimens during this drying period. Mastic 4 showed a rapid decrease of moisture within the first few days, reaching θ=0.8 at the critical cross-section, after which no additional moisture evaporation seemed to occur. From this, it is plausible to conclude that when moisture does not diffuse within the mastic (i.e. is chemically bound within the material) it has time to diminish the material properties, thus reducing the strength. From the 35 to 113 days drying data of mastic 3, however, this trend can not be seen.

5. CONCLUSIONS AND RECOMMENDATIONS
Based on the measured cohesive strength of the mastics and the calculated moisture concentration at the critical cross-section, it is already possible to
make a preliminary comparison between the measure adhesive aggregate-mastic bond and the cohesive mastic strength, Figure 6.

For the given test conditions (temperature and displacement rate), the following preliminary conclusions can be drawn: For an asphalt mixture using either of the stones with mastic 1 would lead to a cohesive failure at lower moisture concentrations. Higher moisture concentrations (>8.7 \(10^{-6}\) g/mm\(^3\)) would lead to an adhesive (bond) failure before breaking the mastic. In the case of a mixture of mastic 2 and the sandstone aggregate a cohesive failure seems to occur for all moisture concentrations. For a mixture with mastic 3 and the sandstone an adhesive failure seems to occur at all moisture concentrations. In the case of mastic 4 with either of the aggregates, the reverse of mastic 1 seems to occur: lower moisture concentrations may promote an adhesive failure and higher concentration (>5.0 \(10^{-6}\) g/mm\(^3\)) will induce a cohesive (mastic) failure, even though not enough data was generated to be conclusive about the trend of the curve.

Assuming that a cohesive failure should be preferred, given its potential healing propensity, and assuming moisture will infiltrate into the mixture and may in time reach relatively high concentrations, based on the above it would therefore be recommended to select combi 5 or 6 to reduce the susceptibility to moisture damage. The influence that mix morphology, the actual micro- and macro-texture of the aggregates and the environmental conditions may have on these conclusions will be discussed in the following section, along with some additional recommendations for the continuation of this research.

For the continuation of this research the following recommendations can be made:
- the influence of the micro-texture of the aggregate surfaces as created in the adhesive test samples should be investigated;
- the developed test procedure should be repeated for various temperatures and displacement rates;
- computational analyses can be performed, incorporating the actual mixture morphology and climatic conditions, utilizing the measured fundamental moisture susceptibility, to give a realistic estimate of the time frame over which moisture damage can be expected in the field;
- in addition to damage due to an increased moisture concentration, erosion of mastic from the mixture as a consequence of water pressures should be included to cover all moisture induced damage processes.

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