Laboratory and Field Study of a WMA Mixture Produced with a New Temperature Reduction Additive

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ABSTRACT

Several temperature reduction technologies, called warm-mix asphalt (WMA), have been recently developed in the asphalt paving industry. Part of these technologies is based on the use of additives to modify the viscosity or the workability of the binder incorporated in the asphalt mixture. This WMA technology does not demand significant changes to be carried out on the asphalt plant, in order to produce the mixtures.

The additive used in this study has been developed in Korea in the last few years and some pavement trials have been successfully constructed to assess the properties of the final mixture. It comprises a wax-based composition including crystal controller and adhesion promoter that adjust the wax crystallization and improve the low temperature properties of the binder.

The present study involves the use of the mentioned additive in an ongoing research project in Portugal, including the construction of a field trial where a warm-mix asphalt (WMA) produced with this additive was applied. A conventional hot-mix asphalt (HMA) was also studied in the laboratory and paved in the field trial for comparison purposes.

The mix design was carried out in the laboratory for the conventional HMA and a similar composition was adopted for the WMA (with the incorporation of 3% additive in the bitumen), in order to analyze the influence of the additive on the fundamental properties of the resulting mixture. The temperature reduction used in the WMA was determined by means of a compactability test, according to the European Standard EN 12697-10.

Several specimens were produced in the laboratory for each mixture, prior to the field trial, and they were tested to assess their water sensitivity, rut resistance, stiffness modulus and fatigue resistance. The test results of laboratory mixtures were compared against those of specimens collected from the field. Based on the study carried out, it can be concluded that both mixtures showed similar properties (either in the lab or on the field) and that the additive used allowed a temperature reduction of about 25°C (a higher reduction could possibly be considered, but since this was the first experience in Portugal with this additive, a more conservative reduction was taken). The application temperatures were controlled for both mixtures through the use of a thermographic camera in order to evaluate the differences between WMA and HMA mixtures.
INTRODUCTION

Hot-mix asphalt is produced at temperatures between 140°C and 160°C, and even higher mixing temperatures can be used to produce some mixtures, namely asphalt rubber and polymer-modified asphalt mixtures. These temperatures ensure that the aggregate is dry, the asphalt binder coats the aggregate, and the mixture has a suitable workability (so that it can be transferred into storage silos, transported, applied, and compacted on site). Warm-mix asphalt (WMA) technology is now available to decrease the production temperatures of asphalt mixtures, by improving the workability of the mixture at construction temperatures while reportedly maintaining or improving pavement performance.

A number of new processes and products are available to reduce the temperature at which the asphalt mixtures are produced and compacted, apparently without compromising the performance of the pavement. These contain the use of various physical-chemical means (usually additives), including surfactants and paraffin wax additives (1), two phase bitumen introduction in the mixtures (2), foamed bitumens (3) or emulsions (4). These technologies are usually classified as WMA mixtures when produced slightly above 100 ºC (5), and they can reduce the production temperatures by as much as 40 percent (6). Reducing the production and application temperatures will provide several benefits, including reduced emissions, fumes, and odors, a cooler work environment, and evident energy savings (7). However, it is essential that the overall performance of WMA is truly as good as HMA. On a life-cycle basis, if WMA does not perform so well, there will not be long-term environmental benefits or energy savings. Thus, several authors have been studying the performance of the WMA additives, binders and mixtures (7, 8, 9), in order to improve their behavior.

In Korea, the Korea Institute of Construction Technology (KICT) and Kumho Petrochemical Co. LTD. have jointly developed a new WMA additive which is named low energy and low carbon-dioxide asphalt pavement (LEADCAP).

As shown in Figure 1, the developed additive is an organic WMA additive, which has a wax-based composition including a crystal controller and an adhesion promoter. The crystal controller adjusts the wax crystallization at the low temperature, preventing the binder to show a brittle behavior and the adhesion promoter acts as an effective bonding agent between aggregates and asphalt binder (10). As a result, this additive should help improving crack resistance at low temperature and enhancing the moisture susceptibility of WMA mixtures.

The LEADCAP additive has a melting point below a normal HMA production temperature and can be added to the asphalt mixture (plant-mixed type process) or to the asphalt binder (pre-mixed type process) allowing for the production and placement of the mixture at about 30 ºC below the temperatures of conventional HMAs. This additive is typically added at the rate of 1.5% to 4.0% by weight of asphalt binder (11).

FIGURE 1 LEADCAP WMA additive.

To investigate the workability and compactability of WMA mixtures using LEADCAP additive in the field, the first WMA field trial section was constructed on Sinryeong-Gono Interstate Highway in Korea on October 13, 2008 (12, 13), as shown in Figure 2. Since then, several WMA field trial sections using LEADCAP additive were successfully constructed in Korea, Japan, Portugal, Italy (14) and, more
recently, United States (15) and Thailand. This paper presents in more detail the results obtained in the Portuguese trial.

**FIGURE 2** WMA field trials using LEADCAP additive in Asia and Europe.

Table 1 summarizes the emissions and fuel consumption data collected from the 2nd WMA field trial. As can be observed, the decreased production temperatures led to energy savings of 32%, which resulted in 32% reduction of CO₂, 18% reduction of CO, 24% reduction of SO₂, and 33% reduction of NOₓ. These results indicate how effective the LEADCAP additive was in reducing the energy consumption and the emissions to the atmosphere, when producing WMA mixtures (12).

**TABLE 1** Collections of emissions and fuel consumption during the production of WMA and HMA mixtures in the plant (2nd field trial in Korea)

<table>
<thead>
<tr>
<th>Content</th>
<th>Asphalt Mixture</th>
<th>Reduction Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>WMA with LEADCAP</td>
<td>Control HMA</td>
</tr>
<tr>
<td>Fuel use (liter/ton)</td>
<td>6.3</td>
<td>9.3</td>
</tr>
<tr>
<td>CO₂ (kg/ton)</td>
<td>19</td>
<td>28</td>
</tr>
<tr>
<td>CO (ppm)</td>
<td>850</td>
<td>1040</td>
</tr>
<tr>
<td>SO₂ (ppm)</td>
<td>160</td>
<td>210</td>
</tr>
<tr>
<td>NOₓ (ppm)</td>
<td>20</td>
<td>30</td>
</tr>
</tbody>
</table>

Although the field pavement trials constructed with this additive are still limited, it was concluded that the WMA mixture achieved a comparable air void as the HMA mixture at a significantly lower temperature. The energy savings and the air quality improvements obtained with the WMA mixture using LEADCAP additive were observed, but long-term performance and durability of WMA pavement should be further investigated (13, 14).

In the following sections, the results of the tests performed on laboratory prepared and field collected samples are presented. Particular attention was paid to the application temperatures that have a significant influence on the final mixture properties.

**LABORATORY PERFORMANCE OF STUDIED MIXTURES**

**Laboratory Mix Design**

*Conventional Hot-Mix Asphalt*

The mix design of the conventional HMA mixture was carried out according to the Marshall Mix Design Method. Figure 3 presents the gradation envelope for the HMA mixture, imposed in the Specifications for
a surface course mixture (AC 14 Surf 35/50), and the design gradation curve obtained through the combination of the several granite aggregates and limestone filler in order to fulfil the envelope limits.

![Figure 3](image-url)

**FIGURE 3** Gradation of the aggregate used in the conventional HMA and WMA mixtures.

During the Marshall Mix Design, five mixing batches were prepared and specimens were compacted with 75 blows in each side (according to the Portuguese Specifications) and with different binder contents (with a variation of 0.5% between them), in order to obtain the optimum binder content. The medium binder content used in the studied mixture was 5.0%. The maximum density of the mixing batches was assessed and all the volumetric characteristics of the Marshall specimens (voids content, VMA and volume of bitumen and aggregates) were calculated. Finally, all specimens were tested by using the Marshall Test procedures, recording the load and deformation values during the tests. In general, it was observed that the characteristics of the designed mixture were in conformity with the Portuguese Specifications, and the optimum binder content obtained was 4.8%.

An additional study was carried out to validate the mix design, comprising water sensitivity tests (Indirect Tensile Strength Ratio, ITSR, according to the EN 12697-12 standard) and wheel tracking tests (Wheel Tracking Slope, WTS$_{air}$, according to the EN 12697-22 standard) on three sets of specimens (one set with the optimum binder content previously determined, and the other two with a variation of ± 0.5%). The results obtained in this study, confirming the previous value of 4.8%, are presented in Figure 4.

![Figure 4](image-url)

**FIGURE 4** Mix design validation test results.
**Warm-Mix Asphalt**

For this project, the rate of 3.0% additive by weight of asphalt binder was selected to produce an asphalt binder equivalent to a PG 70-22 that was used in the laboratory and field experiences.

For the WMA mixture, no particular mix design procedure was carried out. Thus the bitumen content, aggregate type and gradation considered were the same used for the HMA, for comparison purposes.

The production temperature of the HMA mixture used in the laboratory was based on the recommendations of EN 12697-35 standard, according to the type of bitumen used. Thus, for a 35/50 penetration grade bitumen, the mixture production temperature used was 165°C. In order to determine the adequate temperature reduction for the WMA mixture, different tests were performed, including dynamic viscosity (using the rotating spindle apparatus, EN 13302), according to the procedure presented by Silva et al. (9), and compactability tests (according to the EN 12697-10 standard, using the impact compactor).

As can be observed in Figure 5, the viscosity test results were almost inconclusive, as the results of temperature obtained for the mixing viscosity range were very similar to those of the original bitumen. This similarity is also confirmed by the penetration and softening point test results presented in Table 2. Therefore, the temperature reduction was defined in essence according to the compactability test results. These tests were carried out on WMA mixtures produced at 140°C and 130°C (respectively, 25°C and 35°C below the temperature of the conventional mixture) in order to compare the voids content and the water sensitivity of the WMAs and the HMA, as presented in Figure 6.

![Figure 5: Dynamic viscosity test results of studied binders.](image)

**TABLE 2  Penetration and Softening Point of the studied binders**

<table>
<thead>
<tr>
<th>Binder</th>
<th>Penetration (0.1 mm)</th>
<th>R&amp;B (ºC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional</td>
<td>37.3</td>
<td>53.1</td>
</tr>
<tr>
<td>Modified with 3%LEADCAP</td>
<td>37.2</td>
<td>55.9</td>
</tr>
<tr>
<td>Difference</td>
<td>-0.1</td>
<td>2.8</td>
</tr>
</tbody>
</table>

Based on the results presented on Figure 6, it was possible to conclude that the temperature of 130°C was not adequate to assure a performance equivalent to that of the conventional mixture. Therefore, a more conservative temperature reduction (25°C), corresponding to a production temperature of 140°C was used in the laboratory for the WMA mixture.
FIGURE 6 Water sensitivity and voids content results of mixtures after the compactability tests.

Laboratory Performance of Studied Mixtures

As could be confirmed in the previous section, the water sensitivity test results of both HMA and WMA mixtures are similar (respectively, 68.3% and 62.5% of retained strength after a conditioning period in water). However, in order to confirm if the WMA mixture would perform as well as the HMA mixture, a more comprehensive series of tests was carried out, which include rut resistance, stiffness modulus and fatigue cracking resistance tests. The results obtained in this study are presented in the following subsections.

Rut Resistance

The resistance to permanent deformation can be assessed by means of wheel tracking tests, under high temperatures. In this study, the mixtures were subjected to a repeated load application in a controlled temperature (60°C) condition. The tests were carried out according to the EN 12697-22 standard, using 10,000 loading cycles. The results of both mixtures are plotted together in Figure 7 for comparison.

FIGURE 7 Wheel tracking test results of studied mixtures (60°C).
As can be observed from Figure 7, the WMA additive has significantly improved the permanent deformation performance of the mixture, resulting in a wheel tracking slope (0.13 mm per 10³ cycles) of less than half of the result obtained for the HMA mixture (0.45 mm per 10³ cycles).

**Stiffness Modulus**
The stiffness modulus and phase angle were obtained for the two mixtures using the four-point bending beam test, with a repetitive sinusoidal loading configuration, as specified in the EN 12697-26 standard. Frequency sweep (0.1 to 10 Hz) tests were carried out at 20ºC, and the results are presented in Figure 8.

![Stiffness modulus and phase angle of both mixtures](image)

**FIGURE 8** Stiffness modulus and phase angle of both mixtures.

From the analysis of Figure 8, it can be concluded that the additive exhibited a slight softening effect on the WMA mixture, which can be observed by the reduction on the stiffness modulus (about 800 MPa reduction for frequencies above 1 Hz), and by the small increase on the phase angle. Nevertheless, the difference is not considered significant.

**Fatigue Resistance**
The fatigue cracking resistance of the mixtures was obtained by four-point bending tests, which were carried out on strain control and with a repetitive sinusoidal loading configuration (EN 12697-24). Nine specimens were tested at 20ºC for each mixture, using a frequency of 10 Hz and three different tensile strain levels. The number of cycles corresponding to a 50% reduction of the initial stiffness (failure criterion) was recorded as the fatigue life of each specimen. Thus, the fatigue lines of the WMA and HMA mixtures are presented in Figure 9.

![Four point bending fatigue test results of the studied mixtures](image)

**FIGURE 9** Four point bending fatigue test results of the studied mixtures.
As can be observed from Figure 9, the fatigue performance of both mixtures is identical, although it appears that the WMA mixture is showing a slightly higher fatigue life, probably as a result of its lower stiffness modulus. In summary, it was concluded that the HMA and WMA laboratorial prepared samples had similar properties, which was next evaluated in a pavement trial section.

PAVEMENT TRIAL SECTION

Production and Application of Studied Mixtures

Prior to the production of the WMA mixture, the additive was introduced in the bitumen tank and left under circulation for a period of about four hours in order to obtain a homogeneous blend. However, at the end of that period, a visual inspection was carried out and some agglomeration of additive at the top of the bitumen was still visible. In order correct that situation, manual agitation was applied to the bitumen in the tank and it was subjected to an extra two hours of circulation. When the visual aspect of the binder was satisfactory, some binder samples were collected and the mixture started to be produced at 140ºC. The results obtained from the characterization of the binder samples collected during the production stage are presented in Table 3. In the case of the modified binder, the results are the average of six samples collected throughout the mixture production. The difference observed between both types of binder (conventional and modified with LEADCAP additive) is similar to that obtained in the laboratory, which demonstrates the efficacy of the modification process.

**TABLE 3** Penetration and Softening Point of the binders used in the trial section

<table>
<thead>
<tr>
<th>Binder</th>
<th>Penetration (0.1 mm)</th>
<th>R&amp;B (ºC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional</td>
<td>39.6</td>
<td>50.4</td>
</tr>
<tr>
<td>Modified with 3% WMA additive</td>
<td>39.8 (±1.3)</td>
<td>52.8 (±1.0)</td>
</tr>
<tr>
<td>Difference</td>
<td>0.2</td>
<td>2.4</td>
</tr>
</tbody>
</table>

As expected, a significant reduction on the amount of fumes emitting from the WMA mixture was observed, in comparison with the HMA mixture, as can be observed from Figure 10 during the discharge of the mixture to the truck.

![Figure 10](image)

**FIGURE 10** Fumes observed at the discharge of the HMA (a) and WMA (b) mixtures for the trucks.
During the application and compaction of the mixtures on the pavement trial, the temperature was monitored and samples of mixture were collected for quality control. Also after concluding the works, slabs were cut from the pavement trial and further laboratory tests were carried out as presented in the following Section.

Thermographic Analysis of the Pavement Trial

In order to monitor the temperature of the mixtures during the application and compaction of the studied mixtures, a thermographic camera and a conventional thermometer were used. The results obtained on both devices were in the same order of magnitude. The temperature reduction observed between the production and the application was around 30°C (production temperature of 165°C minus compaction temperature of 135°C) for the HMA and 20°C (production temperature of 140°C minus compaction temperature of 120°C) for the WMA, as can be concluded from the analysis of Figures 11 and 12.

FIGURE 11  Temperature variation along a line transverse to the spreading direction, immediately after the beginning of the HMA application.

FIGURE 12  Temperature variation along a line transverse to the spreading direction, immediately after the beginning of the WMA application.

COMPARISON BETWEEN LABORATORY PREPARED AND TRIAL SECTION MIXTURES

Performance of Both Types of Mixtures

As previously mentioned, several slabs were cut from the pavement trial in order to extract specimens for determination of their performance in comparison to the laboratory prepared mixtures.

The volumetric properties of the specimens were determined and a significantly higher voids content was observed on both mixtures (between 7 and 8%), which was later associated to a problem
detected in the asphalt plant that was modifying the gradation curve of the final mixture. Nevertheless, the comparison between the HMA and WMA mixture is still valid as both were produced with the same aggregate and under the same conditions.

The water sensitivity and rut resistance test results are presented in Table 4. The differences between the results are inconclusive, as the HMA has shown a lower water sensitivity but the WMA has shown a higher rut resistance. This may be an effect of the presence of the additive in the WMA mixture.

**TABLE 4  Water sensitivity and rut resistance of the mixtures applied on the trial section**

<table>
<thead>
<tr>
<th>Mixture</th>
<th>WMA</th>
<th>HMA</th>
</tr>
</thead>
<tbody>
<tr>
<td>ITS (%)</td>
<td>57.6%</td>
<td>71.4%</td>
</tr>
<tr>
<td>WTS&lt;sub&gt;AIR&lt;/sub&gt; (mm/10&lt;sup&gt;3&lt;/sup&gt; cycles)</td>
<td>0.20</td>
<td>0.47</td>
</tr>
</tbody>
</table>

According to the results presented in Table 4 and Figure 7, it can be concluded that the WMA mixture has performed better than the HMA mixture in terms of rut resistance, both with lab produced and field mixtures.

The stiffness and fatigue cracking resistance of the studied mixtures are presented in Figures 13 and 14. In comparative terms, the field mixtures have shown a slightly worse performance, which is related to the mentioned high voids content of those mixtures. Nevertheless, the WMA mixture outperformed the HMA, due to the contribution of the additive. The phase angle results were similar to those obtained in the laboratory because this result is not much influenced by the voids content.

**FIGURE 13** Comparison between the stiffness modulus and phase angle of the mixtures produced in the laboratory and the mixtures applied on site.

**FIGURE 14** Comparison between the fatigue resistance of the mixtures produced in the laboratory and the mixtures applied on site.
The fatigue test results obtained for the field mixtures are clearly worse than the lab prepared mixtures. However, in both cases, the additive did not have a detrimental effect in the performance of the mixtures. As can be observed from Figure 14, the fatigue performance of the WMA mixtures is similar to that of the HMA mixtures both in the laboratory and in the field.

CONCLUSIONS

According to the results presented in this paper, the main conclusions that can be drawn are the following:

- The WMA additive used in this study does not affect the lower service temperature properties of the binder and, consequently, of the bituminous mixture, while improving the properties of the binder at higher service temperatures, e.g., increasing the softening point;
- The use of the studied additive allowed a reduction of 25ºC on the production temperature of the mixture;
- The fundamental properties of the WMA mixture were similar to those obtained for the HMA mixture, which indicates that the additive is effective on reducing the production temperature without compromising the mixture performance;
- An asphalt plant problem with the sieves in the batching system resulted in an inadequate aggregate gradation on the field mixtures, but the comparison between the WMA and HMA mixture was still valid since both mixtures were prepared in similar conditions. Thus, it was found that the fundamental properties of the WMA trial mixture were also similar to those obtained for the HMA trial mixture.

REFERENCES


