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ESTUDIO DE CASO

# Mechanical resistance of a chemically-modified warm mix asphalt

## Resistencia mecánica de una mezcla asfáltica modificada con un aditivo químico

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## ABSTRACT

Warm Mix Asphalt (WMA) technology offers a wide range of potential for use in road construction projects. Although the main advantage of using WMA mixtures is environmental, there are also noteworthy technical and economic benefits. This paper discusses results for the laboratory evaluation of WMA mixtures and their subsequent comparison to traditional hot mix asphalts (HMA). WMA and HMA mixtures of nominal maximum aggregate size of 25 mm were employed in this study. The WMAs were obtained by means of a liquid chemical solution that foams the asphalt binder AC 60-70 (PG 58-22). Aspects studied include strength under monotonic and dynamic loading. Additionally, a battery of tests was performed: Marshall, resilient modulus, permanent deformation and indirect tensile strength. The research herein leads to the conclusion that the WMA chemical additive decreases mix temperatures by 30° C, which, in turn, translates into better mixture workability and volumetric composition. Furthermore, WMAs display higher levels of resistance to high service temperatures under monotonic and dynamic loading.

***Keywords:*** chemical additive, foamed asphalt, hot mix asphalt, mechanical behavior, warm mix asphalt.

## RESUMEN

La tecnología de las mezclas asfálticas tibias (WMA por sus siglas en inglés) brinda una amplia oportunidad de éxito en la construcción de capas asfálticas para carreteras. Su principal ventaja es de carácter ambiental, aunque también ofrece ventajas técnicas y económicas. El artículo presenta los resultados experimentales de un estudio ejecutado con el fin de evaluar la resistencia mecánica de una mezcla asfáltica tibia, fabricada empleando un aditivo químico líquido que espuma el asfalto. Para tal fin, se evaluó sobre la mezcla la resistencia bajo carga monotónica empleando el ensayo Marshall y el de tracción indirecta, el cambio en la composición volumétrica, la rigidez bajo carga cíclica y la resistencia a la

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deformación permanente. Como granulometría de referencia se utilizó la de la mezcla densa en caliente MDC-25 (INVIAS, 2013) y como ligante, cemento asfáltico tipo CA 60-70. En conclusión, se reporta que el aditivo empleado es capaz de reducir la temperatura de la mezcla asfáltica en caliente de referencia MDC-25 en 30°C, generando una mezcla tibia con composición volumétrica similar y de mayor rigidez y resistencia bajo carga monotónica y cíclica.

***Palaras clave:*** aditivo químico, asfalto espumado, mezcla asfáltica en caliente, mezcla asfáltica tibia, resistencia mecánica.

## INTRODUCTION

The four main categories used to describe asphalt mixtures are based on the temperatures used for their production in specialized asphalt plants: cold mix asphalt – CMA (temperatures lower than 60°C), half-warm mix asphalt – HWMA (temperatures between 60°C and 100°C), warm mix asphalt –WMA (temperatures between 100°C and 140°C) and hot mix asphalt - HMA (temperatures between 140°C and 190°C) (Rubio, Martínez, Baena & Moreno, 2012; Rondón & Reyes, 2014). WMA mixtures, achieved using a variety of techniques, can reduce mixing and compaction temperatures required for HMAs without significantly altering mechanical properties. According to Bonaquist (2011) and Sterling (2012), the minimum decrease in the mixture manufacturing temperature in an asphalt plant must be 28°C (compared to an HMA) for a mixture to be designated as WMA. The reduced mixing and compaction temperatures is accompanied by a decrease in the energy required for mixture production and a decrease in atmospheric emissions (Romier, Audeon, David, & Martineau, 2006; Kristjansdottir, Muench, Michael & Burke, 2007; (Wasiuddin, Selvamohan, Zaman, & Guegan, 2007; Biro, Gandhi, & Amirkhanian, 2009; Tao & Mallick, 2009a; Bonaquist, 2011). According to You & Goh (2008), WMA mixtures generate less pollutant emissions during manufacture and construction processes regarding the HMA mixtures; energy savings approach 30%.

Using a life-cycle assessment (LCA) model (Blankendaal, Schuur, & Voordijk, 2014), report WMA mixtures represent a 33% less negative environmental versus HMA mixtures. Prowell, Frank, Osborne, Kriech, & West (2014) and West, Rodezno, Julian, & Prowell (2014) reported an average reduction in mix temperature of 27°C for WMAs, which lead to average fuel savings of 22,1%. According to Robjent & Dosh (2009), this fuel reduction can be placed between 20% and 35%, but, sometimes, reaches 50% or greater. Estakhri, Cao, Álvarez, & Button (2009) further explain the benefits of WMAs, this time turning to significant reductions in CO2, SO2 , volatile organic compounds, CO, NOx and ash; reduction levels are 30%-40%, 35%, 50%, 10%-30%, 60%-70% and 20%-25%, respectively, compared to these levels for HMA mixtures.

Based on Building for Environmental and Economic Sustainability model (BEES 4.0), Hassan (2010) found that, in comparison to HMA mixtures, WMA mixtures generate 24%, 18%, and 15% less air pollution, fossil fuel consumption and total negative environmental impact, respectively. During road construction processes that rely on WMA mixtures, worker exposuring to breathable fumes is significantly reduced, thus directly improving worker health and safety as well as the environment (Prowell et al., 2014; West, Rodezno & Prowell, 2014).

From the perspective of aging, lower oxidation levels are exhibited for the short-term aging of asphalt binders is generally reported, a product of the lower temperatures used during the manufacture, extension and compaction processes of the WMA mixture; this may result in increased resistance to fatigue, low-temperature top-down cracking (TDC) and oxidation (Zhao, Xiao, Amirkhanian, & Putman, 2012; Goh, Hasan & You, 2013; Hossain & Zaman, 2013; Vidal, Moliner, Martínez & Rubio, 2013).

A number of studies, carried out both in situ and in the laboratory, provide evidence that WMA mixtures exhibit properties comparable —and even superior— to those of HMA mixtures (Kim, Zhang & Ban, 2012; Tan, Guo, Xu & Zhang, 2012; Zhao, Xiao, Amirkhanian & Putman, 2012; Behl, Kumar, Sharma & Jain, 2013; Topal et al., 2014). Regarding mixture use in construction, it has been consistently noted that the viscosity of the asphalt binder used to manufacture WMA mixtures is lower than that of the binder used for HMA mixtures (You & Goh, 2008), which results in an earlier road inaugurations and improved workability (Vasconcelos, Bhasin & Little, 2010; Capitão, Picado-Santos & Martinho, 2012; Wang et al., 2013; Goh, Hasan & You, 2013). What is more, the additives employed to develop WMAs allow for longer mixture transport distances prior to extension and compaction (Robjent & Dosh, 2009) and allow extension and compaction to be performed in colder environments (Tao, Huang, Du & Yan, 2009). As a result of these factors, WMA technology is deployed to manufacture emergency roads in regions subject to natural disasters(Howard et al. 2014).

Another widely reported advantage of WMA technology comes in the form of recycling; that is, the production of recycled mixtures, recycled or reclaimed asphalt pavement (RAP) (Morea, Marcozzi & Castaño, 2012; Wu & Zeng, 2012; Doyle & Howard, 2013; Rossi et al., 2013; Hajj, Souliman & Cortez, 2014; Nejad, Azarhoosh, Hamedi & Roshani, 2014; Yu, Leng & Wei, 2014; West, Rodezno, Julian & Prowell, 2014) Researchers such as (Ameri, Hesami & Goli, 2013) discuss using technology to produce WMA mixtures with comparable, or even superior, properties to those of HMA when the natural stone aggregate is replaced by ground-granulated blast-furnace slag (GGBS). For a state of the art on WMA technology, readers are directed to (Rondón & Reyes, 2015).

The WMA under study in the present paper was made with a liquid chemical additive used to foam the asphalt binder. The additive was introduced during the mixture of asphalt binder AC 60-70 (according to the ASTM D-5 penetration test) with a performance grade (PG) 58-22. To properly assess WMA performance, the gradation of a HMA was used as a sort of control (HMA-25). The number attached to the HMA represents the nominal maximum aggregate sizes of 25 mm, in line with the specifications found in (INVIAS, 2013). Marshall, resilient modulus, permanent deformation and indirect tensile strength (ITS) tests were conducted to evaluate strength under monotonic and dynamic loading, in addition to resistance to moisture damage.

## METHODOLOGY

### Materials

**Table 1.** Characterization of aggregate and asphalt binder

| Test | Method | Result |
|---|---|---|
| Specific Gravity (Coarse and Fine) | ASTM D 854–00 | 2,62 |
| Sand Equivalent Value | ASTM D 2419-95 | 76% |
| Liquid Limit, Plastic Limit | ASTM D 4318-00 | 0% |
| Plasticity Index | ASTM D 4318-00 | 0% |
| Fractured Particles | ASTM D 5821-01 | 87% |
| Shape – Flat Indices | NLT 354-91 | 9,5% |
| Soundness of Aggregates Using Magnesium Sulfate | ASTM C 88-99a | 12,9% |
| Abrasion in the Micro-Deval Apparatus | ASTM D6928-03 | 22,3% |
| 10% of Fines (Wet/Dry Ratio) | DNER-ME 096-98 | 83% |
| Abrasion in Los Angeles Machine | ASTM C 131-01 | 24,6% |

**Source:** Own work.

**Table 2.** Aggregate Gradation for Asphalt Mixtures

| SIEVE HMA-25 | | PERCENT PASSING |
|---|---|---|
| 25,0 mm | 1″ | 100 |
| 19,0 mm | 3/4″ | 87,5 |
| 12,5 mm | 1/2″ | 76 |
| 9,5 mm | 3/8″ | 68,5 |
| 4,75 mm | No. 4 | 51 |
| 2,00 mm | No. 10 | 37 |
| 0,425 mm | No. 40 | 19,5 |
| 0,180 mm | No. 80 | 12,5 |
| 0,075 mm | No. 200 | 6 |

**Source:** Own work.

**Table 3.** AC 60-70 Characteristics

| Test | Method | Unit | AC 60-70 |
|---|---|---|---|
| Neat Asphalt | | | |
| Penetration (25° C, 100 g, 5 s) | ASTM D-5 | 0,1 mm | 65 |
| Penetration Index | NLT 181/88 | - | -0,7 |
| Softening Point | ASTM D-36-95 | ° C | 52,5 |
| Absolute Viscosity (60°C) | ASTM D-4402 | Poises | 1752 |
| Viscosity at 135°C | AASHTO T-316 | Pa-s | 0,36 |
| Specific Gravity | AASHTO T 228-04 | - | 1,016 |
| Ductility (25°C, 5cm/min) | ASTM D-113 | cm | >105 |
| Solubility in Trichloroethylene | ASTM D-2042 | % | >99 |
| Water Content | ASTM D-95 | % | <0,2 |
| Flashpoint | ASTM D-92 | °C | 275 |
| Tests on Residue after RTFOT | | | |
| Mass Loss | ASTM D-2872 | % | 0,47 |
| Penetration of Residue after Loss by Heating, in % of Original Penetration | ASTM D-5 | % | 72 |

**Source:** Own work.

Aggregate properties are given in table 1, and table 2 provides data related to the gradation used in asphalt mixture fabrication. For results of characterization tests performed on the AC 60-70 asphalt binder, see table 3. In the tables, readers will find the acronyms RTFOT and PAV, which refer, respectively, to the Rolling Thin Film Oven Test and Pressure Aging Vessel. The former simulates short-term aging, while the combination of the two simulates long-term aging.

Although the actual name and properties of the additive are not mentioned here due to a pending technological development, select properties of AC 60-70 modified with the additive are displayed in figures 1 and 2. The additive, a liquid chemical product used to foam the binder (dubbed HUSIL by the authors), is not classified as dangerous or as a pollutant according to the Globally Harmonized System of Classification and Labelling of Chemicals - GHS (United Nations Economic Commissions for Europe - UNECE, 2013). An inorganic material that does not ignite, HUSIL's pH value ranges between 10 and 12. Furthermore, it is not considered carcinogenic or teratogenic. As for HUSIL's use as an additive, it was mixed/combined with AC 60-70 at 80°C for 5 minutes; 80°C was chosen on account of the fact that this temperature represents that at which the additive foams the bitumen.

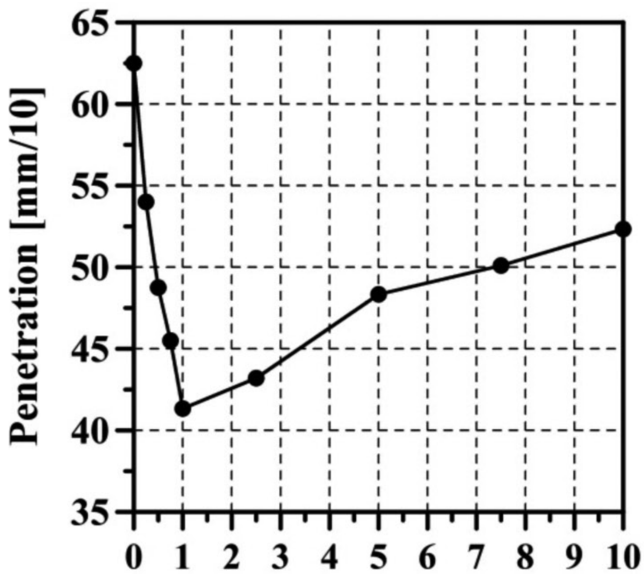


**Figure 1.** Evolution of the Penetration (ASTM D-5, 25° C, 100 g, 5 s) with HUSIL/AC

**Source:** Own work.

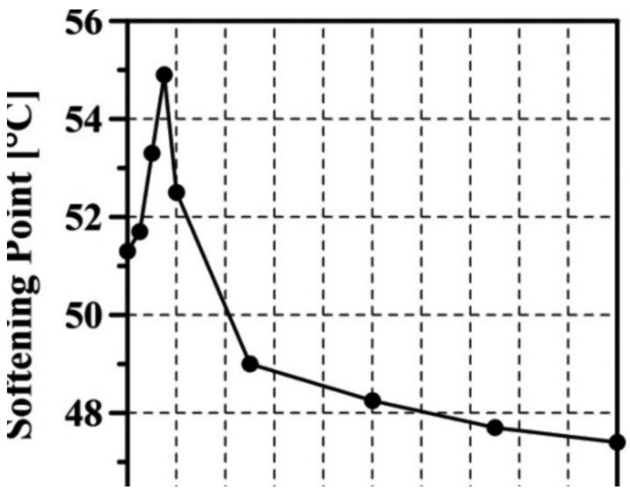


**Figure 2.** Evolution of the Softening Point (ASTM D-36-95) with HUSIL/AC

**Source:** Own work.

Figures 1 and 2 illustrate a noticeable increase in stiffness after 1% HUSIL is added (in relation to the binder's total mass). With increased stiffness comes an increased softening point and decreased penetration, results consistent with the rheological characterization at high and intermediate service temperatures using a dynamic shear rheometer - DSR (AASHTO T 315-05). Tables 4 and 5 depict rheological characteristics of AC 60-70 asphalt binder without additive (HUSIL/AC = 0%) and modified with HUSIL/AC = 1%, respectively. In these tables, $G^*$ and $\delta$ denote the shear modulus complex and phase angle, respectively. PG at high and intermediate service temperatures of AC 60-70 was 58ºC ($|G^*|/\sin\delta > 1,0$ kPa for un-aged asphalt binder and $|G^*|/\sin\delta > 2,2$ kPa for RTOFT-aged asphalt) and 22ºC ($|G^*|\sin\delta < 5000$ kPa for RTFOT + PAV-aged asphalt), respectively.

Modified asphalt binder (HUSIL/AC = 1%) exhibits better PG at high service temperatures (70ºC), which helps bolster resistance to permanent deformation in high-temperature climates. In the same vein, it becomes apparent that PG at intermediate service temperatures improves when HUSIL/AC = 1% (19º C). This is most likely attributable to the improved resistance to aging HUSIL offers the bitumen. On a side note, rheological characterization tests at low service temperatures were not conducted, for the present research focused on application in tropical countries, such as Colombia.

**Table 4.** AC 60-70 Rheological Characterization without Additive (HUSIL/AC=0%)

| Temperature [°C] | Frequency [rad/s] | δ [°] | G* [Pa] | \|G*\|/sinδ [kPa] | \|G*\| · sinδ [kPa] |
|---|---|---|---|---|---|
| AC 60-70 not aged – Neat asphalt | | | | | |
| 58 | 10 | 87 | 2470 | 2,473 | 2,467 |
| 64 | 10 | 88 | 1002 | 100 | 1,00 |
| 70 | 10 | 89 | 453 | 0,453 | 0,453 |
| AC 60-70 aged in RTFOT | | | | | |
| 52 | 10 | 83 | 11062 | 11,15 | 10,98 |
| 58 | 10 | 85 | 4276 | 4,29 | 4,26 |
| 64 | 10 | 87 | 1701 | 1,70 | 1,70 |
| AC 60-70 aged in RTFOT + PAV | | | | | |
| 16 | 10 | 44 | 14266000 | 20537 | 9910 |
| 19 | 10 | 45 | 10193000 | 14415 | 7208 |
| 22 | 10 | 47 | 6659000 | 9105 | 4870 |

**Source:** Own work.

**Table 5.** Rheological Characterization of Modified AC 60-70 (HUSIL/AC=1%)

| Temperature [°C] | Frequency [rad/s] | δ [°] | G* [Pa] | \|G*\|/sinδ [kPa] | \|G*\| · sinδ [kPa] |
|---|---|---|---|---|---|
| AC 60-70 modified with HUSIL/AC=1%, not aged | | | | | |
| 64 | 10 | 66,5 | 2358,3 | 2,57 | 2,16 |
| 70 | 10 | 69 | 1280,5 | 1,37 | 1,20 |
| 76 | 10 | 70 | 888,2 | 0,95 | 0,83 |
| AC 60-70 modified with HUSIL/AC=1%, aged in RTFOT | | | | | |
| 64 | 10 | 72,4 | 8685 | 9,11 | 8,28 |
| 70 | 10 | 76,3 | 4072 | 4,19 | 3,96 |
| 76 | 10 | 79,8 | 1899 | 1,93 | 1,87 |
| AC 60-70 modified with HUSIL/AC=1%, aged in RTFOT + PAV | | | | | |
| 16 | 10 | 31,5 | 11700000 | 22392 | 6113 |
| 19 | 10 | 32,6 | 8570000 | 15907 | 4617 |
| 22 | 10 | 33,9 | 6150000 | 11027 | 3430 |

**Source:** Own work.

## Control HMA design

After performing preliminary tests on the aggregate and asphalt binders, five briquettes were made (compacted at 75 blows per side using a standard Marshall hammer) with asphalt binder percentages of 4,5%, 5,0%, 5,5%, 6,0% and 6,5% in order to carry out the Marshall mix design procedure (AASHTO T 245-97, 04) on the control HMA (HMA-25 without additive, HUSIL/AC = 0%). Laboratory mix and compaction temperatures were set at 140ºC and 150ºC, respectively; these values were selected based on the criteria established by ASTM D6925, wherein the viscosities required to obtain mix and compaction temperatures for dense-graded HMAs are 85±15 SSF (170 cP) and 140±15 SSF (280 cP), respectively.

Optimum asphalt percentage was determined to be 5,3% for HMA-25. This percentage was established by looking at the average values for the following four asphalt contents: (1) asphalt binder content corresponding to maximum stability and flow (S/F) ratio; (2) asphalt binder content corresponding to maximum bulk specific gravity; (3) flow values between 2 and 3,5 mm; (4) asphalt binder content corresponding to designed air void percentage boundaries in the total mixture (between 3% and 6%). Bulk specific gravities and air void contents were measured in accordance with ASTM D2726.

## Experimental testing program

After arriving at the optimum asphalt content, modified (HUSIL/AC = 1%, 2%, 3%) and unmodified (HUSIL/AC = 0%) HMA-25 specimens were prepared at mix temperatures (T) of 140°C, 130°C, 120°C and 110°C. Five briquettes were made (compacted at 75 blows per side using a standard Marshall hammer) for each HUSIL/AC ratio and T. The previously mentioned briquettes help account for a handful of variables: mix temperature, HUSIL/AC ratio and HMA type. Likewise, they allowed researchers to conduct the Marshall tests. Procedurally speaking, the additive was combined with the asphalt binder (AC 60-70) during aggregate and bitumen mixing.

The HMA control mixture (without additive, HMA-25, HUSIL/AC = 0%, T = 150°C) and the WMA mixture (with additive, WMA-25, HUSIL/AC = 1%, T = 120°C) were analyzed using resilient modulus tests (ASTM D 4123-82) at three different temperatures (5ºC, 15ºC and 40ºC) and loading frequencies (2,5 Hz, 5 Hz and 10 Hz). Thus, stiffness under dynamic loading could be assessed. Together, the mixing temperature (120°C) and ratio HUSIL/AC = 1% for WMA were chosen with an eye towards decreasing the temperature needed for HMA by 30°, as well as taking modified asphalt binder characteristics and Marshall test results into account. In addition, permanent deformation tests (Spanish NLT-173-00 regulation) were performed at 60ºC with a contact pressure of 900 kPa. Both tests were run on the control HMA (HUSIL/AC = 0%, T = 150°C) and the WMA (HUSIL/AC = 1%, T = 120°C). Each resilient modulus test was carried out on nine samples (three for each temperature), while the permanent deformation tests were done on a total of three samples.

ITS (ASTM D 4867/D4867M-96) was tested to evaluate resistance under monotonic loading for the HMA (HUSIL/AC = 0%, T = 150°C) and WMA (HUSIL/AC = 1%, T = 120°C). Furthermore, ITS testing helped determine resistance to moisture damage by measuring wet/dry tensile shear ratios (TSR) expressed as percentages. Six samples for each HMA and WMA with air void percentages of 7±1% were tested (12 samples in total). Of the six samples for each mixture, three were tested in a dry state and three in a wet state (the target degree of saturation was 75–80%).

## RESULTS AND DATA ANALYSIS

Data related to air voids and the Marshall S/F ratio (Marshall Quotient – MQ in kg/mm) are shown in Figures 3 and 4. Figure 3 provides evidence of a typical increase in air voids inversely related to mix temperature; an inverse relationship of this nature often indicates diminished workability (i.e. greater difficulty to compact mixtures) brought about by increased binder viscosity. However, the additive boosted sample compactability, and reduced air voids. As the additive foamed the asphalt binder, it facilitated the coating of aggregates and binder. In addition, greater resistance under monotonic loading (S/F) was observed when HUSIL/AC = 1% (Figure 4). The increase in the Marshall S/F ratio was the work of the stiffer modified asphalt binder due to the additive's application (see Figures 1 and 2, tables 4 and 5). Not only did the additive increase binder stiffness, but it also enhanced mixture workability compactibility and led to less air voids. When HUSIL/AC = 1% was used and the mix temperature reduced by 30°C (from 150°C to 120°C), WMA-25 developed resistance under monotonic loading (S/F) similar to that of the control HMA-25, with the latter group relying on a mixing temperature of 150°C, air voids between 4% and 6% and the HUSIL/AC ratio at 0%.

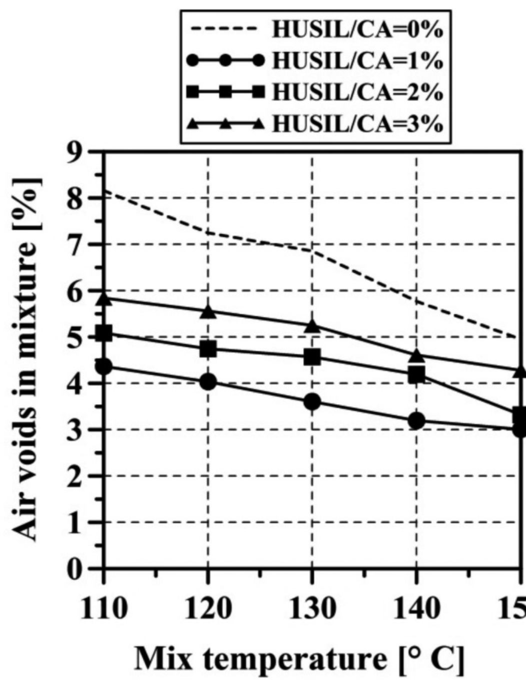


**Figure 3.** Evolution of Air Voids for Modified (HUSIL/AC = 1%, 2%, 3%) and Unmodified (HUSIL/AC = 0%) Mixtures

**Source:** Own work.

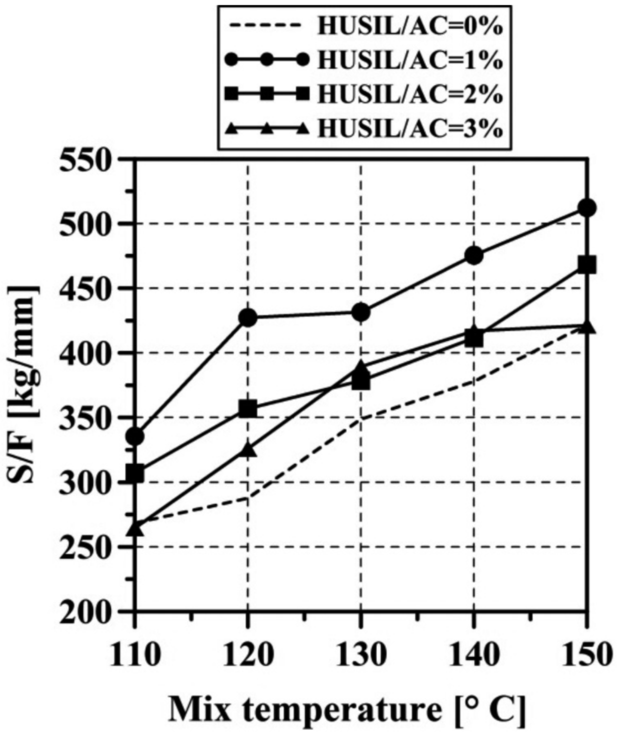


**Figure 4.** Evolution of Stability and Flow Ratio for Modified (HUSIL/AC = 1%, 2%, 3%) and Unmodified (HUSIL/AC = 0%) Mixtures

**Source:** Own work.

Figures 5, 6 and 7 furnish readers with information regarding the evolution of the resilient modulus. WMA mixtures (HUSIL/AC = 1%, mix temperature T = 120°C) saw resilient modulus increases compared to the control HMA mixture (HUSIL/AC = 0%, mixing temperature T = 150°C) for temperatures of 5°C, 15°C and 40°C. This demonstrates that the WMAs are better suited to resist permanent deformation. Figure 8 encompasses rutting performance results. Based on all rutting data measured, WMA mixture proved to be a better choice than the control HMA mixture. On account of the simultaneous interaction between stiffer modified binders and better aggregate interlock (less air voids) in WMAs, it should come as no surprise that WMA-25 mixture lasted until 120 minutes for the rutting test, with 3 mm less rut depth than the control HMA-25 mixture.

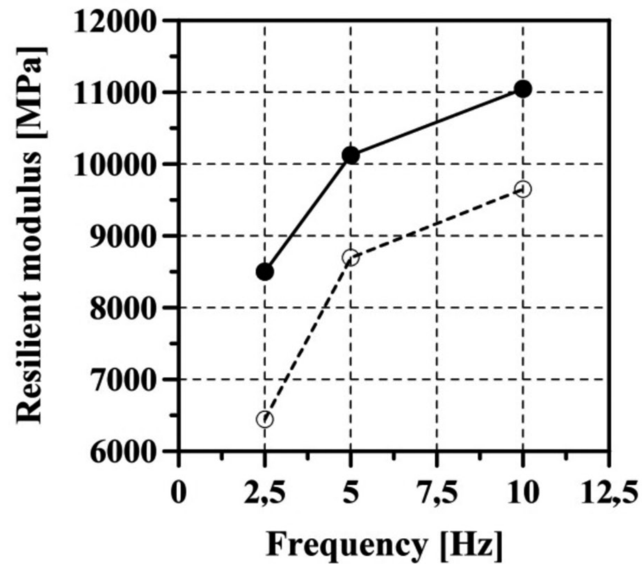


**Figure 5.** Evolution of the Resilient Modulus at 5°C (HMA-25 and WMA-25)

**Source:** Own work.

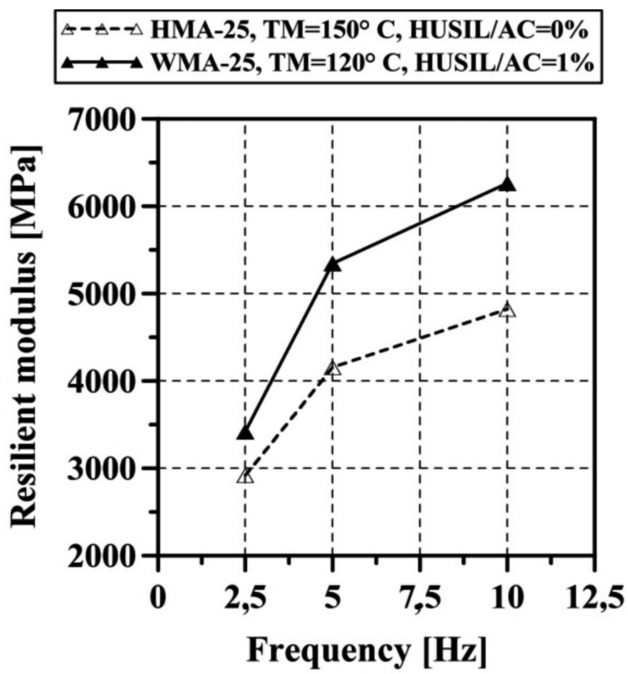


**Figure 6.** Evolution of the Resilient Modulus at 15°C (HMA-25 and WMA-25)

**Source:** Own work.

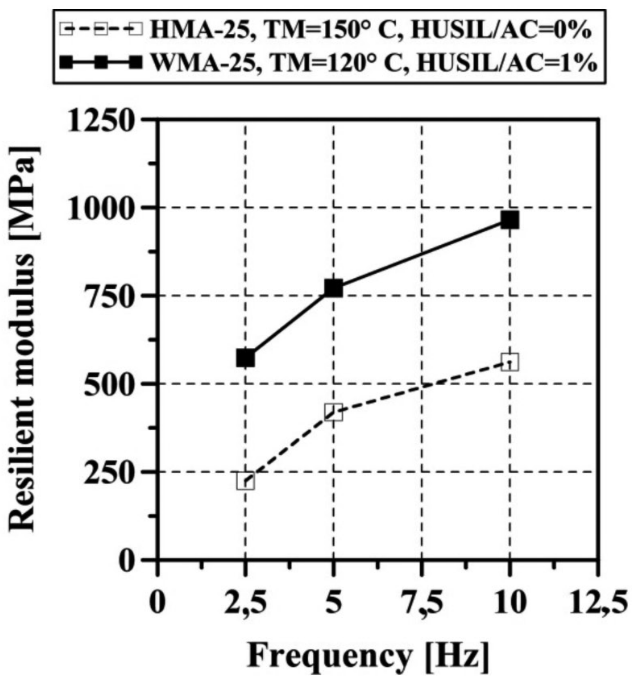


**Figure 7.** Evolution of the Resilient Modulus at 40° C (HMA-25 and WMA-25)

**Source:** Prepared by authors.

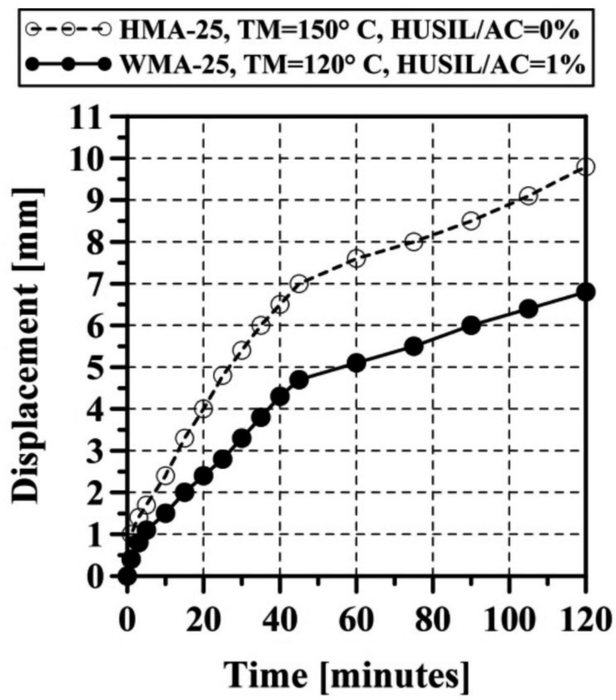


**Figure 8.** Results for Permanent Deformation Test (HMA-25 and WMA-25)

**Source:** Own work.

**Table 6.** Resistance to Moisture-Induced Damage

| Mixture | Air Voids [%] | Standard | Sample Condition | | TSR (S2/S1) [%] |
|---|---|---|---|---|---|
| | | | Dry S1 [kPa] | Moist S2 [kPa] | |
| HMA-25 (HUSIL/AC = 0%, T = 150° C) | 6,8 | AASHTO T 283-03 | 2785 | 2109 | 75,7% |
| WMA-25 (HUSIL/AC = 1%, T = 120° C) | 6,6 | | 2811 | 2276 | 81% |

**Source:** Own work.

Table 6 contains information on resistance to moisture-induced damage. The ITS test results showed no significant difference between the HMA and WMA mixtures. In the unconditioned state (dry), the control WMA developed slightly greater ITS under monotonic loading. Additionally, the WMA had higher TSR and improved moisture damage resistance, i.e. neither additive had any detrimental effect on susceptibility to water even though the mixtures were produced at lower temperatures. Moreover, the WMA mixture had the highest ITS in a conditioned state (wet). Therefore, the higher tensile strength values of WMA mixtures can be attributed to the tensile modified binder's performance.

## CONCLUSIONS

The present study evaluates a WMA mixture by looking at its mechanical strength under monotonic and dynamic loading and resistance to moisture damage. The WMA was prepared with a liquid chemical additive used to foam the asphalt binder. In order to assess experimental WMA performance, Marshall, resilient modulus, rutting and indirect tensile strength tests were carried out, and a comparative analysis between traditional HMA and the WMA was performed. Armed with laboratory results, the following conclusions can be drawn:

Even when additive content is low (HUSIL/AC = 1%), significant changes are generated in the binder's properties: stiffness and PG increase at high service temperatures. Additionally, PG at intermediate service temperatures exhibits improvement when HUSIL is used.

HUSIL significantly reduces mixture temperatures (by 30°C). It is worth noting that additive not only lowers temperatures and improves workability in the compaction process, but it also stiffens the asphalt binder.

Based on results from Marshall, resilient modulus, rutting and ITS tests, it can be said that the WMA mixture (mixed at 120°C) displays greater resilient modulus numbers, as well as strength under monotonic loading, versus the control HMA mixture (T = 150°C) at high service temperatures. Furthermore, WMA mixtures exhibit slight improvements in terms of resistance to moisture damage and rutting (when compared to control HMA).

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