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Behavior of a warm mix asphalt using a chemical additive to foam the asphalt binder

Comportamiento de una mezcla asfáltica tibia usando un aditivo químico para espumar el asfalto

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ABSTRACT: A relatively recent development in asphalt pavement technology, warm mix asphalt (WMA) offers a number of benefits. Although its most important advantage is environmental in nature, it also shows technical and economic benefits. This paper presents and discusses results for the laboratory evaluation of a WMA, which were compared to traditional hot mix asphalts (HMA). Two samples of WMA and two samples of HMA with nominal maximum aggregate sizes of 10 mm and 19.0 mm were evaluated. A liquid chemical solution was used to make WMA (Patent pending for this additive). The purpose of this additive was to induce foaming of the asphalt binder AC 60-70 (PG 58-22). Moisture susceptibility and strength under monotonic and dynamic loading were studied. In addition, a set of tests were performed: Marshall, resilient modulus, permanent deformation and indirect tensile strength. The research led to the conclusion that the WMA chemical additive decreases mix temperatures by 30° C, which in turn, translates into better workability and volumetric composition. Furthermore, the WMA showed higher levels of resistance to both moisture damage and high service temperatures under monotonic and dynamic loading.

RESUMEN: La principal ventaja de emplear mezclas asfálticas tibias (WMA, por sus siglas en inglés) es de carácter ambiental, aunque ofrecen adicionalmente ventajas técnicas y económicas. El artículo presenta y discute los resultados de una fase experimental ejecutada con el fin de comparar el comportamiento que experimenta una mezcla WMA con respecto a una mezcla densa en caliente tradicional (HMA, por sus siglas en inglés). Dos mezclas WMA y dos HMA se fabricaron empleando como tamaño máximo de partícula 10 mm y 19 mm. Las mezclas WMA se modificaron con un aditivo líquido que espuma el asfalto. El aditivo actualmente se encuentra en proceso de patente. El asfalto base utilizado para la fabricación de las mezclas fue CA 60-70 (PG 58-22). Sobre las mezclas se midieron la resistencia bajo carga monotónica y dinámica, así como la resistencia al daño por humedad, empleando ensayos Marshall, módulo resiliente, deformación permanente y resistencia a la tracción indirecta. Como conclusión general se reporta que el aditivo químico disminuye la temperatura de la mezcla en 30°C, así mismo contribuye con una adecuada trabajabilidad y composición volumétrica de la mezcla WMA. Adicionalmente, las mezclas WMA experimentan mayor resistencia bajo carga monotónica y dinámica a altas temperaturas de servicio, así como mayor resistencia al daño por humedad.

1. Introduction

Warm Mix Asphalt (WMA) technology was introduced in Europe in 1995 [1]. It offers many environmental benefits. Firstly, WMA technology reduces mixing and compaction temperatures; thus, less energy is required for mixture production, which decreases atmospheric emissions [2]. That is, the use of WMA technology is accompanied with less fuel consumption and factory emissions [3, 4]. For instance, [5, 6] reported that an average decrease of 27° C in mix production temperature results in an average fuel savings of 22%, affecting greenhouse gas emission (e.g. CO_2) in an undoubtedly positive fashion. [4] places this fuel reduction between 20% and 35%, though, on some occasions, it has been reduced up to 50%.

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Secondly, research has also shown WMAs to decrease emissions of CO_2, SO_2, volatile organic compounds, CO, NOx and ash by 30–40%, 35%, 50%, 10–30%, 60–70% and 20–25%, respectively, when compared to traditional Hot Mix Asphalts (HMA). A third environmental benefit of WMAs is that it is possible to manufacture asphalt mixtures with recycled rubber (from tires or other polymers) [7-12]. Moreover, this technology can be used for manufacturing

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open or porous mixtures [13, 14] and reclaimed asphalt pavement mixtures, which are commonly referred to as RAPs [15-19].

Having discussed the environmental advantages of WMAs, the focus turns to their technical and economic benefits. Numerous laboratory and *in situ* studies provided evidence of the comparable—and even superior—properties exhibited by WMAs in comparison with HMAs [20, 21]. Lower oxidation levels in the short-term aging of the asphalt binders are generally observed as a result of the lower temperatures used during mixture manufacture, extension and compaction. The outcome is an enhanced resistance to aging, stripping, fatigue and low temperature top-down cracking (TDC) [22-25]. In many cases, viscosity of the asphalt binder used for WMAs production is less than the one used for HMAs; therefore, the risk of compaction-related issues is lessened. Also, as less cooling time is needed before laying the material or placing the next layer, less time is needed to open the road for use [26-28].

Several researchers have reported that instead of reducing the viscosity, some additives improve mixture workability by enhancing lubrication between the asphalt binder and stone aggregate [2] at the microscopic level. Lubrication represents a significant aspect as it helps counteract the internal friction generated in mixtures by the high shear stress values brought about during mixture and compaction [23]. Also, some additives allow longer lapses of time between mixture, extension and compaction, greater transport distances [4], as well as "pave the way" for extension and compaction in colder environments [29]. Therefore, taken together these features of WMAs technology, it could be excellent for the construction of emergency roads in regions hit by natural disasters [30].

Foamed asphalt technology in the production of WMAs has been practiced for more than 50 years. It started as a way to produce cold mix asphalts (CMA). Traditionally, it consists of applying pressurized water jets to hot asphalt binder, mainly used either for the stabilization of non-treated granular materials or the manufacture of cold and recycled mixtures. Cold water (1% to 2% of asphalt mass) and pressurized air are combined in an expansion chamber and then used to treat high-temperature asphalt cement (160–180° C) to induce foaming. As a result, the volume rapidly expands (approximately 15 times), the binder viscosity decreases and improved adhesion and coating between asphalt and stone aggregate is observed.

Although foamed asphalt technology includes greater mixture workability during the manufacturing process it has also some disadvantages. For instance, the application of cold water may induce some flaws related to low resistance to moisture damage [31]. Thus, it is necessary to mix it with adhesion and anti-stripping additives. A primary alternative to induce foaming is the introduction of synthetic zeolites or chemical materials into the stone aggregate.

Aspha-Min® and Advera® (developed by Hubbard Group & PQ Corporation) represent two of the most commonly used additives around the world. As [32] reported, Aspha-Min® is made with sodium aluminosilicate; the additive is generally used in 0.3% proportion to the asphalt mixture's total mass. According to the manufacturers of Aspha-Min®, this additive reduces mix temperatures by more than 10° C and saves 30% on asphalt plant energy consumption. Furthermore, [33, 34] found that in comparison to HMAs, emissions of organic compounds, carbon monoxides, nitrogen oxides and sulfur dioxides were lowered by at least 50%, 60%, 20% and 83%, respectively when WMA foaming is carried out with Aspha-Min®.

Advera®, another hydrothermally crystallized synthetic zeolite (thin hydrated sodium aluminosilicate powder), with water constituting between 18% and 22% of its mass, is added to asphalt in a 0.25% proportion with respect to WMAs total mass [35]. [21] argued that WMAs produced with synthetic zeolites respond better under cyclic loading (*i.e.* better resistance to rutting and fatigue) in comparison to those manufactured with natural zeolites. Other additives or industrial processes used to induce foaming in the asphalt manufacturing process are AccuShear, Aquablack foam, AquaFoam, Double Barrel Green/Green Pac, ECOFOAM-II, Low Emission Asphalt (LEA), Meeker Warm Mix foam, Terex foam, Tri-Mix foam, Ultrafoam GX, WAM-Foam and LT Asphalt. Research carried out by [36] suggests that foamed WMAs reduce CO, CO_2 and NOx by 10% and energy consumption by 24% compared to HMAs while maintaining resistance to induced-moisture damage.

The present paper studied the performance of two WMAs produced using a liquid chemical as an additive to foam the asphalt binder. This additive is unique and unpatented. 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 the WMAs performance, the gradations of two HMAs (HMA-10 and HMA-19) were used as control. The number attached to the HMAs represents the nominal maximum aggregate sizes of 10 mm and 19.0 mm, respectively in line with the specifications found in [37]. Marshall, resilient modulus, permanent deformation and indirect tensile strength tests were conducted to evaluate strength under monotonic and dynamic loading in addition to their resistance to moisture damage.

2. Experimental methodology

2.1. Materials

The study was carried out on two samples each of HMAs and WMAs. Tables 1 and 2 provide the aggregate properties and data related to the gradation used in fabricating the asphalt mixtures, respectively. Results of characterization tests performed on the AC 60-70 asphalt binder are shown in Table 3. The Rolling Thin Film Oven Test (RTFOT) was used to simulate short-term aging, while a combination of the RTFOT and Pressure Aging Vessel (PAV) was used to simulated long-term aging.

Table 1 Aggregate characterization

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 by use of Magnesium Sulfate	ASTM C 88-99a	12.9%
Abrasion in 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%

Table 2 Asphalt mixture aggregate gradation

Sieve		Percent passing	
		HMA-10	HMA-19
19.0 mm	3/4”	100	100
12.5 mm	1/2”	100	87.5
9.5 mm	3/8”	100	79.0
4.75 mm	No. 4	76.0	57.0
2.00 mm	No. 10	52.0	37.0
0.425 mm	No. 40	22.5	19.5
0.180 mm	No. 80	14.0	12.5
0.075 mm	No. 200	7.5	6.0

The additive used to foam the binder (called 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 – [38]). HUSIL is an incombustible inorganic material with pH values ranging between 10 and 12. Also, it is not considered carcinogenic or teratogenic. Although the actual name and properties of the additive are not provided here due to a pending patent, some properties of AC 60-70 modified with the additive are presented in the following figures. In that way, to modify AC 60-70, HUSIL was added at 80° C during the manufacturing process for 5 minutes, with 80° C being the temperature at which the additive induces foaming in the bitumen. Figures 1, 2 and 3 show a noticeable increase in stiffness when 1% HUSIL is added (in relation to the binder's total mass). The increase in stiffness is accompanied by an increase in the softening point and a decrease in penetration.

These results are 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 δ denote the shear modulus complex and phase angle, respectively.

Performance grade (PG) at high and intermediate service temperatures of AC 60-70 was 58° C ($|G^*|/\sin\delta$ > 1.0 kPa

Table 3 AC 60-70 characteristics

Test	Method	Unit	AC 60-70
Un-aged (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 a 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 the residue after loss by heating, in % of the original penetration	ASTM D-5	%	72

for un-aged asphalt binder and |G^*|/sinδ > 2.2 kPa for RTOFT-aged asphalt) and 22º C (|G^*|sinδ < 5000 kPa for RTFOT + PAV-aged asphalt), respectively. Modified asphalt binder (HUSIL/AC = 1%) exhibited better PG at high service temperatures (70ºC), which helps to increase resistance to permanent deformation in high-temperature climates. It becomes evident that PG at intermediate service temperatures improves when HUSIL/AC = 1% (19º C). This is most likely attributed to the improved resistance to aging that HUSIL provides to the bitumen. It should be noted that rheological characterization tests were not performed at low service temperatures since the research mainly focuses on application in tropical countries (such as Colombia).

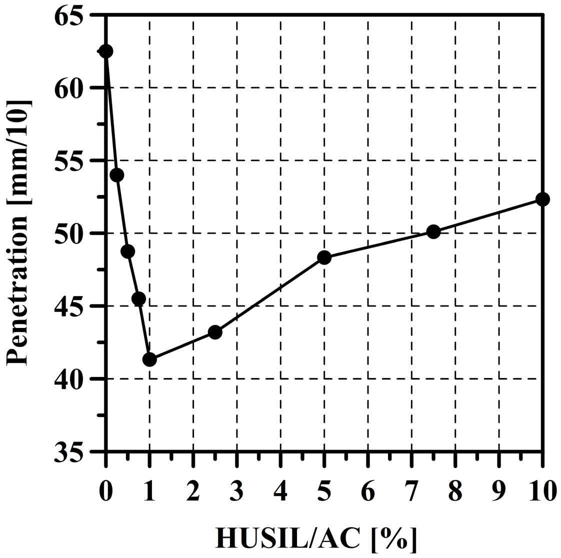

Figure 1 Penetration evolution (ASTM D-5, 25° C, 100 g, 5 s) with HUSIL/AC

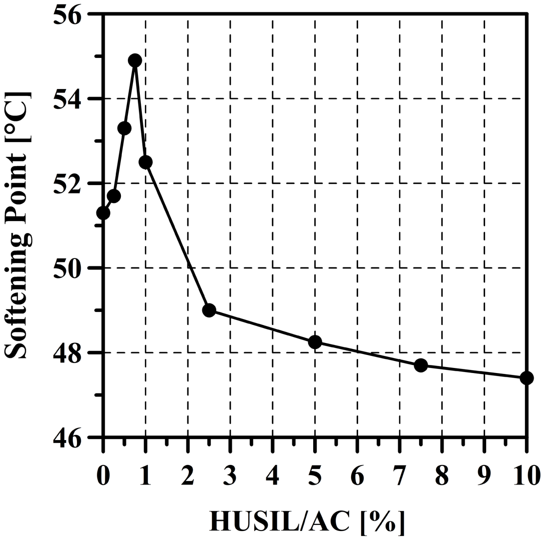

Figure 2 Softening point evolution (ASTM D-36-95) with HUSIL/AC.

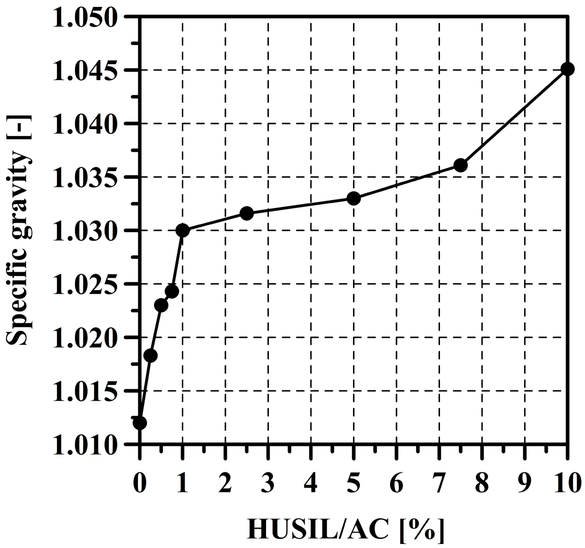

Figure 3 Specific gravity evolution (AASHTO T 228-04) with HUSIL/AC

In terms of the chemical characterization, a Fourier Transform-Infrared Spectroscopy was developed following standard test method ASTM D7418-12 with a Nicolet iS50 FT-IR by Thermo Scientific. The spectra showed that oxidation effects due to short term aging (related to aging caused by mixing and compaction process) in this modified asphalt were negligible. Wavenumbers related to oxidation were 1030 and 1700 cm^{-1}, which describe Sulfoxide (S=O) and Carbonyl (C=O) functional groups respectively, that are formed by aging. Figure 4 shows that on modified asphalts by HUSIL no peak is observed, which means that oxygen does not bond with sulfurs or carbons and, hence, oxidation was minor or non-existent.

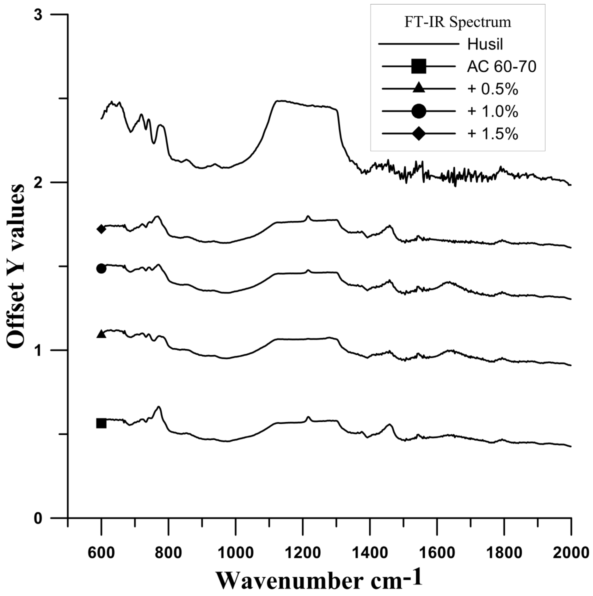

Figure 4 FT-IR spectra of HUSIL and AC 60-70 and AC 60-70 modified with HUSIL

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 un-aged (neat asphalt)					
58	10	87	247	2.47	2.47
64	10	88	1002	1.00	1.00
70	10	89	453	0.45	0.45
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

Table 5 AC 60-70 rheological characterization with additive (HUSIL/AC = 1%)

Temperature [° C]	Frequency [rad/s]	*δ* [°]	*G** [Pa]	|*G**|/sin*δ* [kPa]	|*G**| · sin*δ* [kPa]
AC 60-70 modified with HUSIL/AC = 1% (un-aged/neat)					
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

2.2. Control HMA design

After performing preliminary tests on the aggregate and asphalt binders, five samples were prepared (compacted at 75 blows per side using a standard Marshall hammer) with asphalt binder contents of 4.5%, 5.0%, 5.5%, 6.0% and 6.5% created in order to perform the Marshall mix design procedure (AASHTO T 245-97, 04) on the control HMAs (HMA-10 and HMA-19 without additive, HUSIL/AC = 0%). Laboratory mixing and compaction temperatures were set at 140°C and 150°C, respectively; these values were selected based on the criteria established by the ASTM D6925 standard, wherein the viscosities required to obtain mixing and compaction temperatures for dense-graded HMAs are 85±15 SSF (170 cP) and 140±15 SSF (280 cP), respectively.

Optimum asphalt percentage turned out to be 5.8% for HMA-10 and 5.3% for HMA-19. To determine optimum content, average values of the following three asphalt contents were taken: (1) asphalt binder content corresponding to maximum stability and flow (S/F) ratio; (2) asphalt binder content corresponding to maximum bulk specific gravity; and, (3) asphalt binder content corresponding to designed air void percentage boundaries in the total mix (set between 3% and 6%). Bulk specific gravities and air void contents were measured in accordance with ASTM D2726.

2.3. Experimental testing program

After establishing optimum asphalt content, modified (HUSIL/AC = 0.75%, 1%, 2%, 3%) and unmodified (HUSIL/AC = 0%) HMA-10 and HMA-19 specimens were prepared at mixing temperatures (T) of 140° C, 130° C, 120° C and 110° C. Five samples were made (compacted at 75 blows per side using a standard Marshall hammer) for each HUSIL/AC ratio and T. The aforementioned samples aided in accounting a handful of variables: mixing temperature, HUSIL/AC ratio and HMA type. Likewise, it helped conduct the Marshall tests. As part of the procedure, the additive was combined with the asphalt binder (AC 60-70) during aggregate and bitumen mixing.

HMAs (without additive, HUSIL/AC = 0%, T = 150° C) and WMAs (with additive, HUSIL/AC = 1%, T = 120° C) were analyzed using resilient modulus tests (ASTM D 4123-82) at three different temperatures (5°C, 15°C and 40°C) and loading frequencies (2.5 Hz, 5 Hz and 10 Hz). Thus, stiffness under dynamic loading was assessed. The mixing temperature (120° C) and HUSIL/AC ratio of 1% for WMAs were selected with focus on decreasing the temperature needed for HMAs by 30°.The modified asphalt binder characteristics ad Marshall test results were also taken into account. In addition, permanent deformation tests (Spanish NLT-173-00 standard) were performed at 60°C with a contact pressure of 900 kPa. The resilient modulus test was conducted on nine samples (three tests on each of the three temperature levels), while the permanent deformation tests were performed on three samples.

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

3. Results and data analysis

Figures 5-8 gather data relating to air voids and the Marshall S/F ratio (Marshall Quotient – MQ in kg/mm). Values in these figures represent the mean of five samples. Figures 5 and 7 provide evidence of a typical increase in air voids that is inversely related to mixing temperature. This relationship often indicates diminished workability (*i.e.* greater difficulty to compact mixtures) brought about by the binder's increased viscosity. However, in the presence of the additive, sample compactability was boosted, and less air voids were observed in comparison to the HMAs control (HUSIL/AC = 0%). As the additive foams the asphalt binder, it facilitates the coating of aggregates and binder.

In the same way, greater resistance under monotonic loading (S/F) was achieved with HUSIL/AC = 1%. The increase in the Marshall S/F ratio is the work of the stiffer modified asphalt binder stemming from the additive's application (see Figures 1 and 2, and Tables 4 and 5). The additive not only increased binder stiffness but also enhanced mixture workability and compactibility, indicating a dip in air void content. When HUSIL/AC = 1% was used and the mixing temperature was reduced by 30° C (from 150° C to 120° C), both WMA mixtures (WMA-10 and WMA-19) developed similar resistance under monotonic loading (S/F) in contrast to the HMAs that relied on a mixing temperature of 150° C, air voids between 4% and 6% and the HUSIL/AC ratio at 0%.

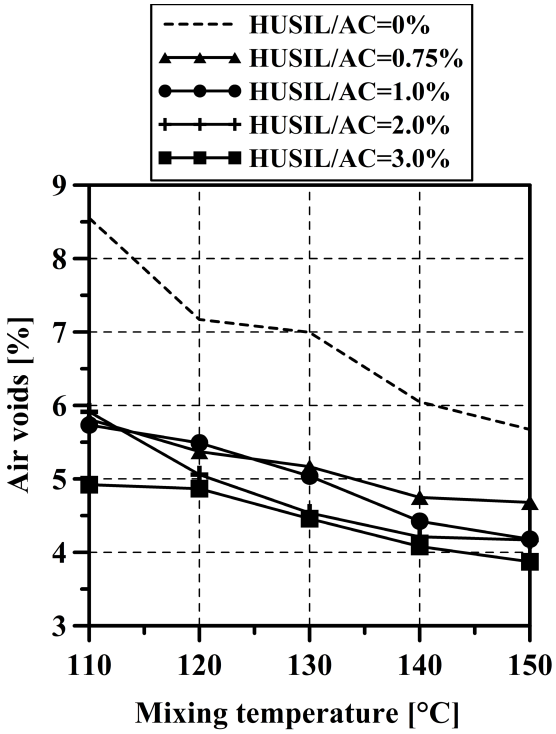

Figure 5 Air void evolution for modified (HUSIL/AC = 0.75%, 1%, 2%, 3%) and unmodified (HUSIL/AC = 0%) HMA-10 mixtures

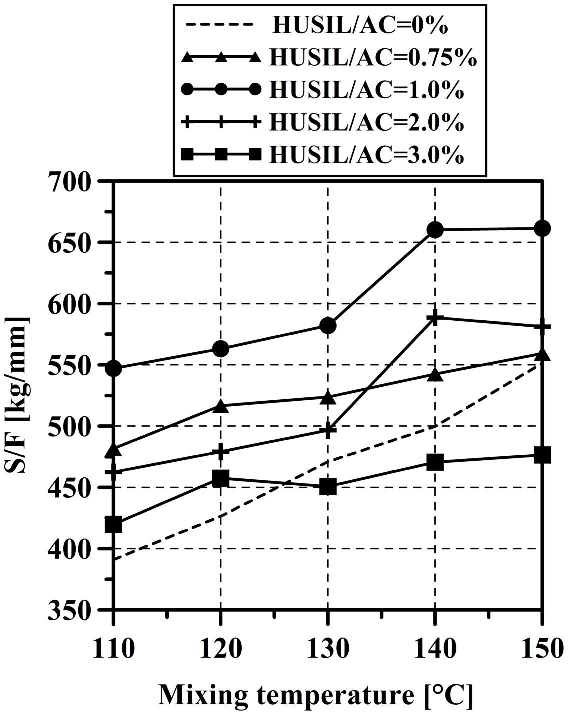

Figure 6 Stability and flow ratio evolution for modified (HUSIL/AC = 0.75%, 1%, 2%, 3%) and unmodified (HUSIL/AC = 0%) HMA-10 mixtures

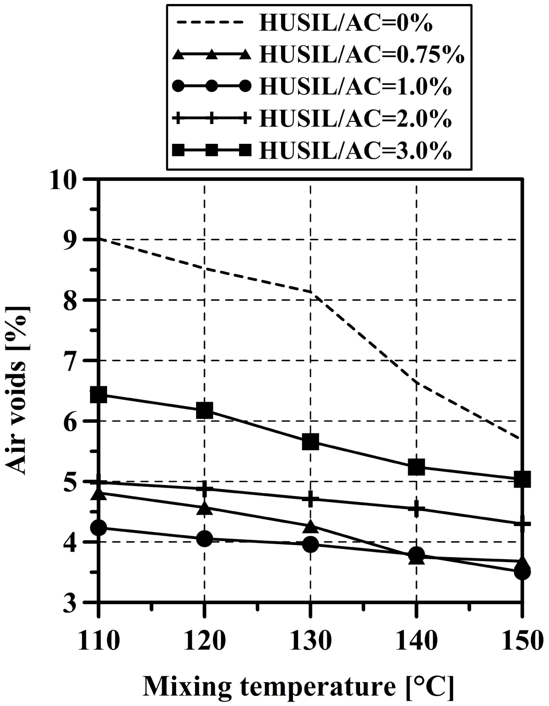

Figure 7 Air void evolution for modified (HUSIL/AC = 0.75%, 1%, 2%, 3%) and unmodified (HUSIL/AC = 0%) HMA-19 mixtures

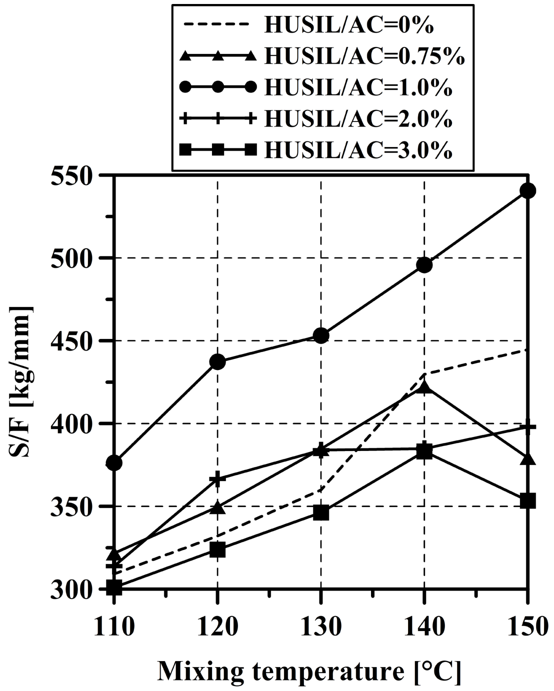

Figure 8 Stability and flow ratio evolution for modified (HUSIL/AC = 0.75%, 1%, 2%, 3%) and unmodified (HUSIL/AC = 0%) HMA-19 mixtures

Figures 9-14 inform on the evolution of the resilient modulus. WMAs(HUSIL/AC = 1%, mixing temperature T = 120° C) showed a higher resilient modulus values compared to the HMAs control (HUSIL/AC = 0%, mixing temperature T = 150° C) for temperatures of 15° C and 40° C. Hence, the WMAs were better for resisting permanent deformation. The WMA-10 resilient modulus increased—on average—3% and 13% when compared to HMA-10 at temperatures of 15° C and 40° C, respectively. The data exhibited a 9% increase for the corresponding comparison between WMA-19 and HMA-19 at the same temperatures (15° C and 40° C). For test temperatures at 5° C, WMAs slightly decreased their resilient modulus values (around 1.5%), which proved to be beneficial in terms of reduced cracking and increased fatigue resistance when subjected to low service temperatures.

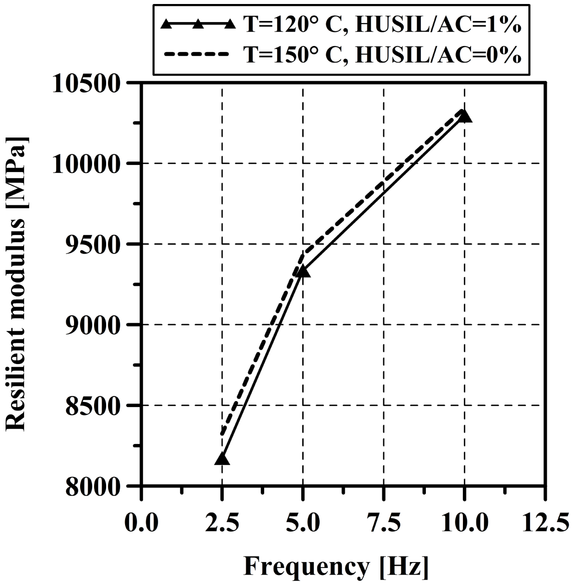

Figure 9 Resilient modulus evolution at 5° C (HMA-10 and WMA-10)

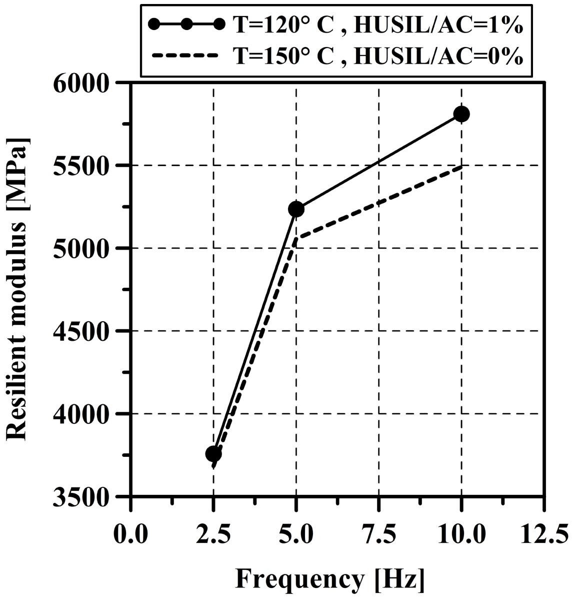

Figure 10 Resilient modulus evolution at 15° C (HMA-10 and WMA-10)

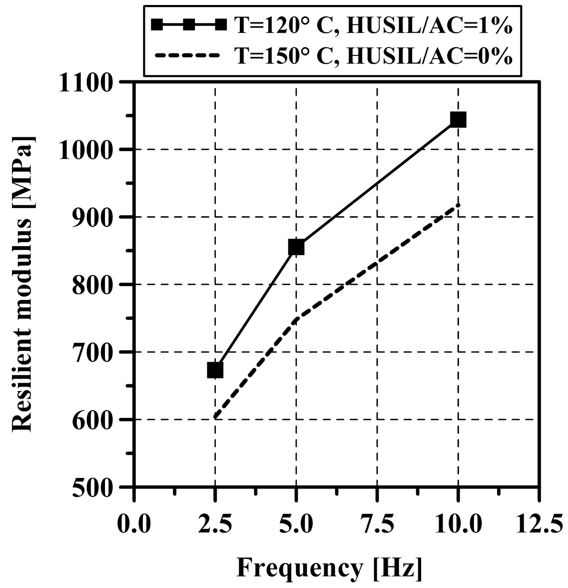

Figure 11 Resilient modulus evolution at 40° C (HMA-10 and WMA-10)

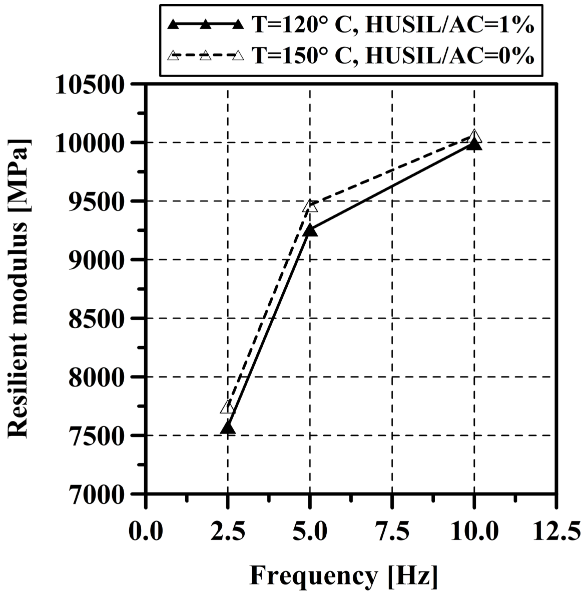

Figure 12 Resilient modulus evolution of at 5° C (HMA-19 and WMA-19)

Figures 15 and 16 show rutting performance results. Based on all rutting data measured, WMAs proved less rut depth than the control HMAs. Due to the simultaneous interaction of stiffer modified binders and better aggregate interlock (less air voids) in WMAs, it is not surprising that WMA-10 and WMA-19 mixtures reached 120 minutes for the rutting test, with 1.5 mm and 2.1 mm less rut depth than the control HMA-10 and HMA-19 mixtures, respectively.

Average indirect tensile strength values for control HMA-10 (HUSIL/AC = 0%, T = 150° C) in the dry and wet states were 2792 kPa and 2106 kPa, respectively (tensile shear ratios = WS/DS = 75.4%). For HMA-19, these values reached 3184 kPa and 2388 kPa, (tensile shear ratios=WS/DS=75%). Table 6 shows a slight increase in strength of WMAs (HUSIL/AC = 1%, T = 120° C) under monotonic loading. This slight increase in TSR is a response of the increased resistance to moisture damage that the HUSIL provides. Therefore, the higher tensile strength values of WMAs stem from the tensile modified binder's performance.

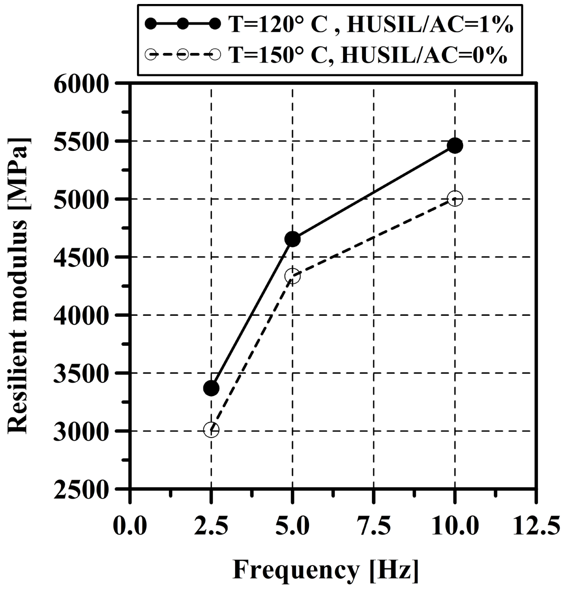

Figure 13 Resilient modulus evolution at 15° C (HMA-19 and WMA-19)

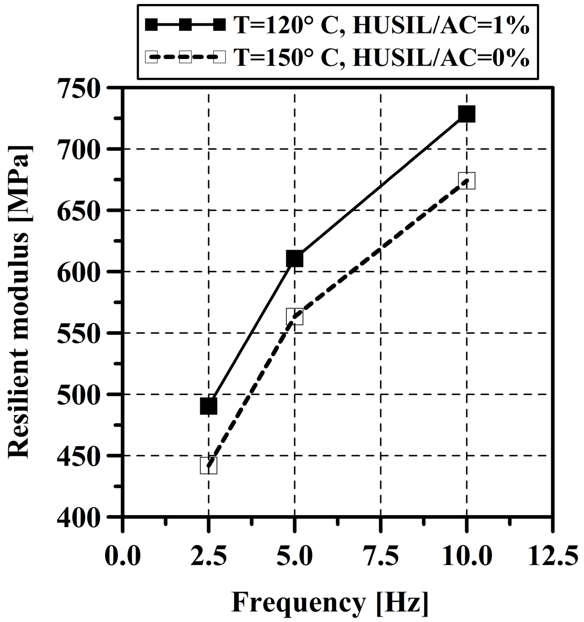

Figure 14 Resilient modulus evolution at 40° C (HMA-19 and WMA-19)

Table 6 Indirect tensile strength test results.

Mixture	Dry strength (DS) [kPa]	Wet strength (WS) [kPa]	TSR (WS/DS) [%]
WMA-10	3413	2652	77.7
WMA-19	3203	2460	76.8

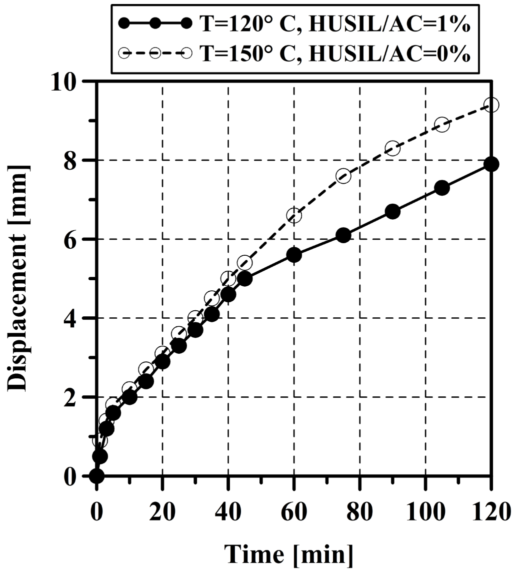

Figure 15 Permanent deformation test results (HMA-10 and WMA-10)

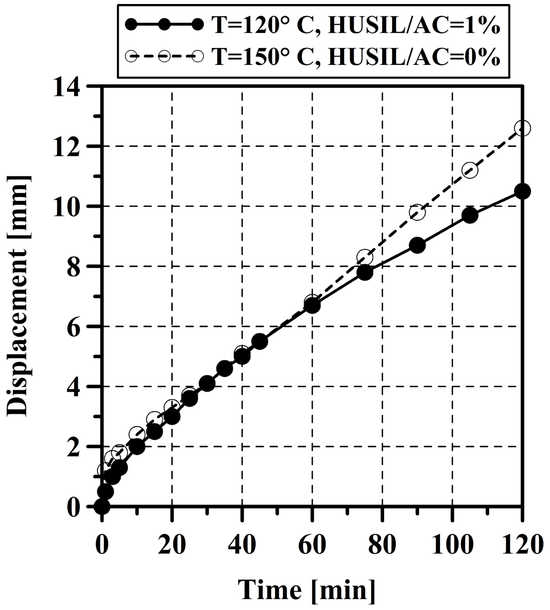

Figure 16 Permanent deformation test results (HMA-19 and WMA-19)

4. Conclusions

Even with low additive content (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 was improved and the oxidation produced by the mixing process (Short-Term Aging) was negligible or non-existent.

HUSIL significantly reduced mixture temperatures (by 30° C), improved the workability during the compaction process and enhanced stiffness of the binder.

Based on results from Marshall, resilient modulus, rutting and indirect tensile strength tests, WMAs (mixed at 120° C) displayed higher resilient modulus values, as well as strength under monotonic loading, in comparison to control HMAs (mixed at 150° C) at high service temperatures. Furthermore, WMAs exhibited slight improvements in terms of resistance to moisture damage and rutting (when compared to control HMAs).

vg

5. References

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