Behavior of Gilsonite-Modified Hot Mix Asphalt by Wet and Dry Processes

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Abstract: In tropical countries, roads built with asphalt layers must be made with bituminous mixtures containing asphalt that is reasonably stiff to increase resistance against permanent deformations, i.e., rutting. When the available asphalt is not stiff enough, an alternative is to modify it using Gilsonite. This article presents the laboratory results of tests performed on samples of Gilsonite-modified hot mix asphalts modified by wet and dry processes. Gilsonite increases the stiffness and improves the performance grade of a virgin binder at high temperatures of service. Additionally, Gilsonite-modified hot mix asphalts developed a greater strength and stiffness under monotonic and dynamic loading. **DOI: 10.1061/(ASCE)MT.1943-5533.0001339.** *© 2015 American Society of Civil Engineers.*

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Introduction

Literature Review

According to Saganome (1999), natural asphalts are bituminous materials in the solid state that are composed of high molecular weight hydrocarbons in layers that extend from a few centimeters to tens of meters in thickness. These materials exhibit a great variety of stiffness properties, such that their melting points can extend from 100°C to above 300°C. Natural asphalts exhibit high softening points (above 90°C) and are known worldwide as asphalt-hardening materials (Ameri et al. 2011b; Butt 2009; Lenfant 2012) because of their high content of asphaltenes. One of the natural asphalts that is most commonly used to modify the properties of hot mix asphalt is Trinidad Lake asphalt (TLA). According to Kim et al. (2013), TLA is a high-viscosity asphalt that provides high resistance against permanent deformation and durability to asphalt mixtures that use it as one of their components. According to Timm et al. (2014), TLA was used for the first time in 1595 by Sir Walter Raleigh to caulk his ships. The first documented use in roads appears in 1815 in Port of Spain, and this material has been used as an asphalt binder in the paving of multiple roads in the United States (Widyatmoko et al. 2005). Currently, this natural asphalt can be obtained in the form of pellets and exhibits a typical penetration of 0.1–0.4 mm at 25°C, specific gravity of 1.4, and softening point of 93–98°C.

Tropical countries, for example, in South America, are characterized as having climates with high temperatures. In these countries, roads built with asphalt layers must be made with bituminous mixtures containing asphalt that is stiff enough to increase resistance against permanent deformations, i.e., rutting. Despite this requirement, in countries such as Colombia, the stiffest asphalt cement (AC) that is produced is AC 60–70 [performance grade (PG) 58-18]. This asphalt is not stiff enough to resist the rutting phenomenon in high-temperature regions. An alternative to stiffen the asphalt is to modify the asphalt using Gilsonite (G).

In Colombia, there are numerous Gilsonite-type natural asphalt deposits. Deposits are primarily identified in the departments of Boyacá, Caquetá, Caldas, Cundinamarca, Tolima, Santander, and Cesar. Gilsonite is one of the higher purity natural asphalts and has a low fixed carbon and low sulfur content. Rondón and Reyes (2012) used this material to produce an asphalt concrete mixture and evaluated its properties under monotonic and dynamic loading. The results obtained from their study demonstrated that the asphalt mixtures modified with Gilsonite using a wet process, i.e., adding Gilsonite to the asphalt cement, generated stiffer asphalt concrete mixtures, leading to the conclusion that these mixtures would perform well in warm climates. The Marshall stability and stiffness values of the modified mixtures were greater for any percentage of asphalt and Gilsonite compared with the reference mixture, i.e., without Gilsonite. The resilient moduli of the modified mixtures were superior to those obtained for the reference mixtures, and greater increases were obtained when the temperature of the test increased. These results indicated that Gilsonite, as an asphalt modifier, can be used to improve the stiffness characteristics and resistance against permanent deformations of mixtures that are used in warm climates. Liu and Li (2008) reported a similar conclusion when they modified Alaska asphalt cement with Gilsonite using the wet process in percentages between 3 and 12%, with respect to the asphalt total weight. Esfeh et al. (2011) reported that adding Gilsonite to asphalt helps to increase the viscosity, decrease the penetration, and stiffen the binder. Ameri et al. (2011a), on the basis of tests of rheological characterization, reported that modification of two asphalts (PG 58-22 and PG 64-22) with Gilsonite in percentages of 4, 8, and 12%, with respect to the asphalt mass, improved the performance grade of both asphalts at a high service temperature; however, these additions decreased the performance grade

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at low temperatures. Because the asphalt modified with Gilsonite exhibits brittle behavior at low service temperatures, generation of cracks can occur. Anderson et al. (1999) reported a similar conclusion. Ameri et al. (2011b) and Feng et al. (2010, 2011) reported that the asphalts modified with Gilsonite improved the response at high and intermediate service temperatures. Furthermore, Ameri et al. (2011b) reported an increase in the resistance against permanent deformation and in the fatigue resistance of Gilsonite-modified hot mix asphalt, and Feng et al. (2010, 2011) reported an increase in the resistance against moisture damage. Yilmaz et al. (2013) reported a significant increase in the stiffness under cyclic loading, resistance against permanent deformations, and fatigue resistance of hot mix asphalts when 3% Gilsonite was added with respect to the mixture weight, albeit causing them to exhibit a more brittle and less elastic behavior. In this study, Gilsonite replaced part of the filling mineral. On the basis of rheological characterization tests on asphalts modified with styrene-butadiene-styrene (SBS), Kök et al. (2011) reported that Gilsonite can be used to reduce the production cost and compaction of asphalt mixtures. In addition, on the basis of the Marshall testing method, dynamic modulus testing, indirect tensile strength testing, and dynamic creep testing performed on Gilsonite-modified hot mix asphalts, Kök et al. (2012) also reported an increase in the stiffness under cyclic loading in the resistance against moisture damage in freeze-thaw cycles and in the resistance against permanent deformation. In addition, these researchers reported that the mixtures modified with Gilsonite decreased the optimum asphalt content in the design of the mixture by 1%, decreasing the production cost of the asphalt mixture. On the basis of a resistance and durability analysis of road structures, bridges, and tunnels constructed with TLA-modified asphalt layers, Charles and Grimaldi (1997) reported that when using this technique, these structures require less maintenance and offer the possibility of reducing design thicknesses. Cholewińska and Iwański (2011) modified an asphalt with a penetration of 50–70 (0.1 mm) with Gilsonite with percentages of 5, 10, and 15%, with respect to the asphalt total mass. These authors reported a significant decrease in penetration and an increase in the viscosity and softening point of the modified asphalt as the Gilsonite content was increased. On the basis of the modification of two Gilsonite-modified hot mix asphalts added to the standard asphalt in percentages of 4, 6, and 8%, with respect to the mass of bitumen, Wong and Michael (1990) reported an increase in the resistance against permanent deformation. However, these authors mention that it is not clear if the Gilsonite is considered an antistripping agent. On the basis of studies performed on asphalt AC 30 modified with Gilsonite and six other different additives, Tia et al. (1994) reported that the modified asphalt develops greater resistance against aging.

Research Objective

The research objective of this article is to present a comparison of Gilsonite-modified hot mix asphalt modified behavior by wet and dry processes. In studies performed on the subject, both modification processes have usually been studied separately. The results of an experimental phase designed to evaluate the resistance under monotonic and dynamic loading of a Mezcla densa en Caliente-19mm (MDC-19) hot mix asphalt [Instituto Nacional de Vías (INVIAS) 2013] modified with a G-type natural asphalt from Cesar (Colombia) by wet and dry processes are presented. The acronym MDC refers to the acronym of hot mix asphalt (HMA) in Spanish. The AC used for the mixture fabrication was AC 60–70. The Gilsonite was added to the asphalt and the aggregate of the asphalt mixture at a high temperature, in which modification was done by wet and dry processes, respectively. Marshall tests

Table 1. Characterization of Aggregate and Asphalt

Test	Method	Result (%)
Specific gravity (coarse and fine)	ASTM D854-00 (ASTM 2002)	2.62
Sand equivalent value	ASTM D2419-95 (ASTM 1995b)	76
Liquid limit, plastic limit	ASTM D4318-00 (ASTM 2000b)	0
Plasticity index	ASTM D4318-00 (ASTM 2000b)	0
Fractured particles	ASTM D5821-01 (ASTM 2006)	87
Shape, flat indices	NLT 354-91 (NLT 1991)	9.5
Soundness of aggregates by use of magnesium sulfate	ASTM C88-99a (ASTM 1999b)	12.9
Abrasion in the microdeval apparatus	ASTM D6928-03 (ASTM 2003)	22.3
10% of fines (wet/dry ratio)	DNER-ME 096-98 (1998)	83
Abrasion in Los Ángeles machine	ASTM C131-01 (ASTM 2001)	24.6

Table 2. Aggregate Gradation for Asphalt Mixtures

	Percentage passing
Sieve number (mm)	MDC-19
3/4 (19.0)	100
1/2 (12.5)	87.5
3/8 (9.5)	79.0
4 (4.75)	57.0
10 (2.0)	37.0
40 (0.425)	19.5
80 (0.180)	12.5
200 (0.075)	6.0

Table 3. AC 60–70 Characteristics

Test	Method	AC 60–70
Neat asphalt		
Penetration (25°C, 100 g, 5 s)	ASTM D5 (ASTM 2013b)	65 (0.1 mm)
Penetration index	NLT 181/88 (NLT 1988)	–0.7
Softening point	ASTM D36-95 (ASTM 2000a)	52.5 degrees Celsius
Absolute viscosity (60°C)	ASTM D4402 (ASTM 2015c)	175.2 kg/ms (1,752 P)
Viscosity at a 135°C	AASHTO T 316 (AASHTO 2013)	0.36 Pa·s
Specific gravity	AASHTO T 228-04 (AASHTO 2009)	1.016
Ductility (25°C, 5 cm/min)	ASTM D113 (ASTM 1999a)	>105 cm
Solubility in trichloroethylene	ASTM D2042 (ASTM 2015b)	>99%
Water content	ASTM D95 (ASTM 2013c)	<0.2%
Flashpoint	ASTM D92 (ASTM 2013a)	275 degrees Celsius
Tests on the residue after the RTFOT		
Mass loss	ASTM D2872 (ASTM 2012)	0.47%
Penetration of the residue after loss by heating in percentage of the original penetration	ASTM D5 (ASTM 2013b)	72%

Table 4. AC 60–70 Rheological Characterization Using DSR

Type of asphalt	Temperature (degrees Celsius)	Frequency (rad/s)	δ (degrees)	G^* (Pa)	$\lvert G^* \rvert / \sin\delta$ (kPa)	$\lvert G^* \rvert \sin\delta$(kPa)
AC 60–70 not aged, neat asphalt	58	10	87	2,470	2.473	2.467
	64	10	88	1,002	1.00	1.00
AC 60–70 aged in RTFOT	58	10	85	4,276	4.29	4.26
	64	10	87	1,701	1.70	1.70
AC 60–70 aged in RTFOT + PAV	19	10	45	10,193,000	14,415.1	7,207.6
	22	10	47	6,659,000	9,105.0	4,870.0

Note: PAV = pressure asphalt vassel.

[AASHTO T 245-97 (AASHTO 2008)] and wet-dry indirect tensile tests [ASTM D4867/D4867M-96 (ASTM 1996)] were performed to evaluate the mechanical strength under monotonic loading of the reference, i.e., without Gilsonite, and modified asphalt mixtures. Resilient modulus testing [ASTM D4123-82 (ASTM 1995a)] and permanent deformation tests [NLT 173-00 (2000)] were performed for the dynamic characterization.

Methodology

Materials Characterization

Table 1 lists the values obtained from the characterization tests of the aggregate, and Table 2 shows the gradation used for the fabrication of the asphalt mixtures. The results of the characterization tests performed on the AC 60–70 asphalt are presented in Table 3. Table 4 shows the rheological characterization of the AC 60–70 asphalt at high and intermediate service temperatures using a dynamic shear rheometer (DSR) [AASHTO T 315-05 (AASHTO 2005b)]. Table 5 presents the rheological characterization of the asphalt at a low service temperature using a bending beam rheometer (BBR) [AASHTO T 313-05 (AASHTO 2005a)]. The performance grade at high and intermediate service temperatures was 58°C, where $\lvert G^* \rvert / \sin\delta > 1.0$ kPa for the unaged asphalt and $\lvert G^* \rvert / \sin\delta > 2.2$ kPa for the asphalt aged in rolling thin film oven tests (RTFOTs), and 22°C, where $\lvert G^* \rvert \sin\delta < 5{,}000$ kPa for the asphalt aged in RTFOT, respectively. At a low service temperature, the PG is -18°C. The asphalt binder stiffness at 60 s $\cdot\, S(t) < 300$ MPa, and the slope of the master stiffness curve at 60 s $\cdot$ m > 0.30.

Table 5. AC 60–70 Rheological Characterization Using BBR

Parameter	Temperature (degrees Celsius)	Result
$S(t)$	−18	223.2 MPa
m		0.33
$S(t)$	−22	338.6 MPa
m		0.29

The Gilsonite was obtained from a mine located in the department of Cesar (Colombia). A description of the Gilsonite can be found in INVIAS (1997). This material exhibits a specific gravity of 1.32, penetration [25°C, 100 g, 5 s, ASTM D5 (ASTM 2013b)]

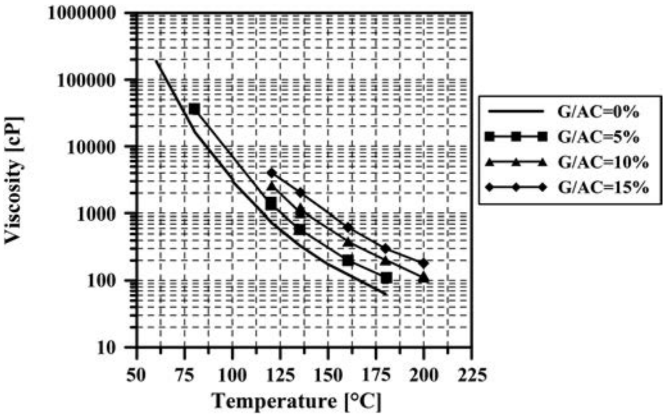

Fig. 2. Evolution of viscosity with temperature

Fig. 1. Gilsonite before and after milling (images by Hugo Alexander Rondón Quintana)

of 0, and a softening point of 95°C [ASTM D36-95 (ASTM 2000a)] and contains bituminous bright black particles that pass through sieve No. 40 in a gradation test when sieving after being milled (Fig. 1).

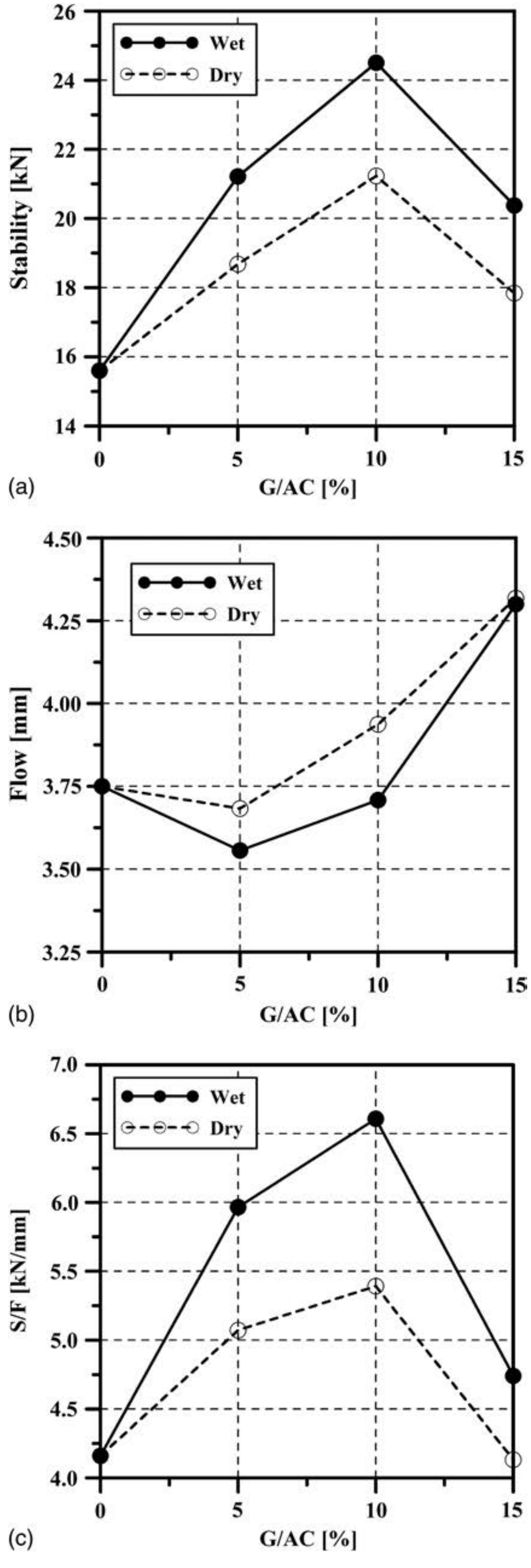

Fig. 3. (a) Evolution of stability *S* with G/AC ratio; (b) flow F with G/AC ratio; (c) S/F with G/AC ratio

Design of the Reference Asphalt Mixture

After performing tests on the aggregate and the asphalt binders, five briquettes were made, which were compacted at 75 blows per side for each asphalt, with percentages of 4.5, 5.0, 5.5, 6.0, and 6.5 to perform the Marshall mix design procedure [AASHTO T 245-95 (AASHTO 2004)] on the reference MDC-19 mixture (without Gilsonite). The temperatures of compaction and mixing in the laboratory were 140 and 150°C, respectively. These values were selected on the basis of the criteria established by the ASTM D6925 (ASTM 2015a) standard, in which the viscosity required to obtain the temperatures of fabrication and compaction of the dense-graded hot mix asphalts was 170 ± 20 and 280 ± 30 MPa · s, respectively. The optimum asphalt percentage was 5.3%.

Preparation of Modified Mixtures

Using the optimum asphalt percentage (5.3%), new briquettes were fabricated by adding the Gilsonite to the MDC-19 asphalt mixture through wet and dry processes in G/AC ratios of 5, 10, and 15%, with respect to the asphalt total mass. When using the wet process, the additive, Gilsonite, was added at a high temperature to the asphalt. For the wet method applied in this study, the Gilsonite was added to the asphalt at a temperature of 160°C for 20 min. This temperature was selected because at higher temperatures, the asphalt could experience aging because of the loss of chemical compounds by oxidation, and at lower temperatures, the mixing becomes more difficult, in particular when the Gilsonite content is high. For the dense MDC-19 mixture, ASTM D6925 (ASTM 2015a) [a viscosity of 0.17 Pa-s (170 cP)] recommends approximate mixing temperatures of the asphalt modified with the aggregate of 166, 187, and 205°C for $\mathrm{G/AC} = 5$, 10, and 15%, respectively (Fig. 2). These mixing temperatures were not used because for modified asphalts, the determination of these temperatures is not reliable when following the criteria recommended by ASTM D6925 (ASTM 2015a) primarily because the behavior of these materials is strongly dependent on the shear rate (non-Newtonian fluids). Thus, the temperatures obtained using this method are, in general, very high and unrealistic, degrading the original properties of the binder when oxidizing and aging it (Shenoy 2001; Bahia et al. 2006; Tang and Haddock 2006; West et al. 2010). Therefore, a temperature of 160°C was selected as the mixing temperature of the asphalt modified with the aggregate. The

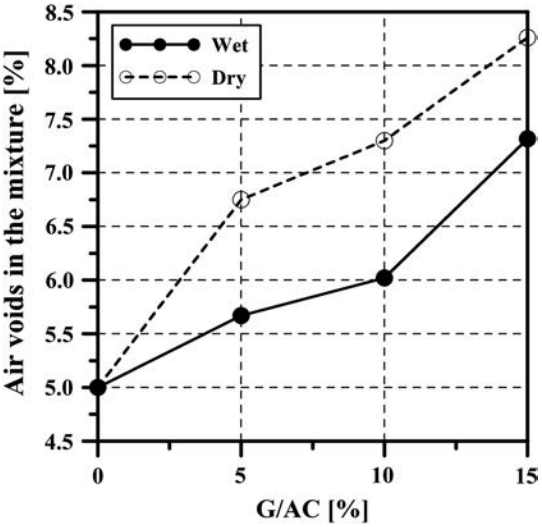

Fig. 4. Evolution of air voids in mixture with G/AC ratio

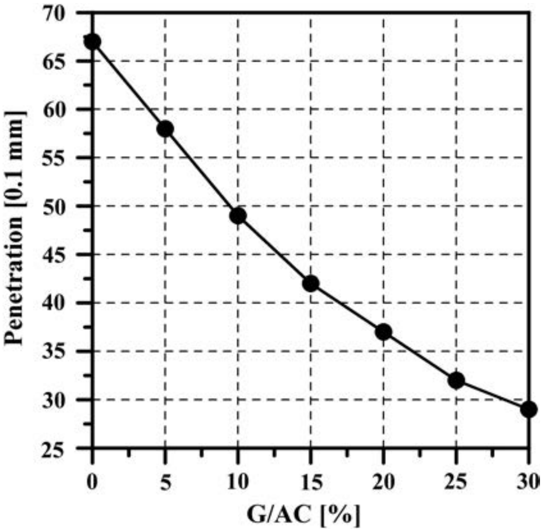

Fig. 5. Evolution of penetration with content of G/AC

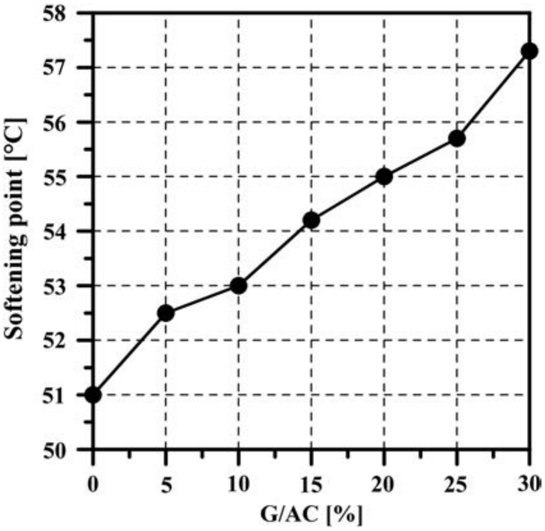

Fig. 6. Evolution of softening point with content of G/AC

aggregate was preheated at 110°C for 20 h, and the temperature of the aggregates was not elevated (superheated). Using the wet process, the Gilsonite was mixed with the asphalt and the aggregate at 160°C. This mixing temperature was empirically selected such that an adequate coating of the aggregate with the asphalt was obtained without generating either runoffs or collapse of the briquettes. Besides, it was desirable to use temperatures at which the aggregate could not suffer any fracture during its compaction in the laboratory to avoid asphalt overoxidation and high environment polluting emissions resulting from the preparation of the mixtures and to facilitate the mixing procedure, in particular, for high Gilsonite content conditions. When was used the dry process, the additive (Gilsonite) was added directly at 160°C to the aggregate, i.e., all components, i.e., asphalt, aggregate, and Gilsonite, were mixed at the same time and the additive was not previously mixed with asphalt. Additionally, in the dry process, the Gilsonite did not replace any part of the aggregate in the asphalt mixture because Gilsonite when heated becomes only asphalt without the presence of other components, e.g. solid fine particles or aggregate.

Experimental Phase

The Marshall testing [AASHTO T 245-97 (AASHTO 2008)] and indirect tensile testing [ASTM D4867/D4867M-96 (ASTM 1996)] were performed to evaluate the resistance under monotonic loading of the reference MDC-19 mixtures (G/AC = 0%) and the mixtures modified by wet-dry processes (G/AC = 5, 10, and 15%). The latter test was also used to evaluate the resistance against moisture damage. For each G/AC ratio, five samples were tested using the Marshall method. A total of six samples, with air void percentages of 7 ± 1%, were tested for each G/AC ratio using the indirect tensile test. A total of three samples of each asphalt mixture were tested in an unconditioned state, and the other three were tested in a moisture-conditioned state, with a target degree of saturation of 75–80%.

Resilient modulus tests [ASTM D4123-82 (ASTM 1995a)] at three different temperatures (10, 20, and 40°C) and loading frequencies of (2.5, 5, and 10 Hz) were performed to evaluate the behavior under dynamic loading. In addition, permanent deformation tests [NLT 173-00 (2000)] performed at 60°C and a contact pressure of 900 kPa were performed. Both tests were performed on the MDC-19 reference mixtures (G/AC = 0%) and those modified by the wet and dry processes (G/AC = 10%). The ratio G/AC = 10% was selected within the modified mixtures because with this content of G, the samples exhibited greater resistance under monotonic loading in the Marshall test (Fig. 3). Each resilient modulus test was performed on nine samples (three for each temperature), whereas the permanent deformation tests were performed on three samples.

Penetration [ASTM D5 (ASTM 2013b)] and softening point tests [ASTM D36-95 (ASTM 2000a)] were performed on the modified asphalts (G/AC = 5, 10, 15, 20, 25, and 30%) to help understand the response exhibited by the mixtures in the strength and stiffness tests. A total of three samples were used for each test and G/AC ratio. Furthermore, rheological characterization of the modified asphalt, G/AC = 10%, was performed at high and low service temperatures using a DSR [AASHTO T 315-05 (AASHTO 2005b)] and BBR [AASHTO T 313-05 (AASHTO 2005a)], respectively. The temperatures in the rheological test were selected on the basis of the AASHTO standard and performance graded binder specification (MP1) to determine the appropriate binder for pavement performance in terms of rutting and fatigue cracking. In these tests, three samples were used for each temperature and

Table 6. Rheological Characterization of AC 60–70 Modified

Type of asphalt	Temperature (degrees Celsius)	Frequency (rad/s)	δ (degrees)	G^* (Pa)	$\lvert G^*\rvert/\sin\delta$ (kPa)	$\lvert G^*\rvert\sin\delta$ (kPa)
AC 60-70 modified with G/AC = 10%, not aged	64	10	66	2,322.3	2.54	2.12
	70	10	68	1,174.2	1.27	1.09
AC 60–70 modified with G/AC = 10%, aged in RTFOT	70	10	68	2,144	2.31	1.99
	76	10	69	1,121	1.20	1.05
AC 60–70 modified with G/AC = 10%, aged in RTFOT + PAV	19	10	43	10,278,360	15,070.92	7,009.8
	22	10	45	7,033,810	9,947.29	4,973.7

10 measurements of the shear modulus (G^*) and phase angle (δ) were made in each test.

Results

Marshall and Indirect Tensile Tests

Figs. 3(a–c) show the evolution of the stability (S), flow (F), and S/F ratio, respectively, of the MDC-19 mixture as a function of G added by wet and dry processes, and Fig. 4 show the evolution with the air voids. Figs. 3(a and c) show increases between 30 and 59% in the stability and S/F ratio when the MDC-19 mixture was modified with $\mathrm{G/AC} = 10\%$ using dry and wet processes, respectively. For $\mathrm{G/AC} = 5\%$, the flow value decreases slightly [Fig. 3(b)] in both processes (wet and dry), allowing an increase in the S/F ratio. For the wet process, when $\mathrm{G/AC} = 10\%$ was used, the value of flow was similar to the MDC-19 of the control (without Gilsonite), and for the dry process, a slight increase was observed. Because the modified mixtures were produced at the same temperature, the increase in flow values at high contents of Gilsonite is perhaps because of the combination of (1) increase of air voids and (2) loss of workability and coating of aggregates. From $\mathrm{G/AC} = 10\%$, the results indicate that the S/F of the mixture greatly decreased because of the significant increase in air voids (Fig. 4) and flow [Fig. 3(b)]. Notably, Fig. 3 reveals that the mixtures experience the greatest increase in stiffness and mechanical strength for the ratio $\mathrm{G/AC} = 10\%$, despite the increase in air voids (Fig. 4). This increase in the mechanical strength under monotonic loading is primarily because of the increase in the asphalt viscosity (Fig. 2) and stiffness when that asphalt is modified with Gilsonite (Figs. 5 and 6; Table 6). The increase in the air voids is because of the loss of handling and workability of the mixture in the laboratory because of the increase in the asphalt viscosity (Fig. 2) as the content of G increases. The greater the resistance under monotonic loading that is observed in the mixtures modified by the wet method because of the lower content of voids developed in the modified mixture in the wet process (Fig. 4), the easier the coating of the aggregates and workability at the time of mixing and compaction of the samples compared with the procedure performed using the dry process.

Figs. 5 and 6 present the results of the evolution of the penetration and the softening point. The figures indicate that when Gilsonite is added to AC 60–70, a binder of stiffer consistency

Table 7. Rheological Characterization of AC 60–70 Modified Using BBR

Parameter	Temperature (degrees Celsius)	Result
$S(t)$	−12	281.8 MPa
m		0.31
$S(t)$	−18	348.1 MPa
m		0.27

Table 8. Results from an Indirect Tensile Stiffness Modulus Test

	US (kPa)		MS (kPa)		TSR (MS/US) (%)	
	Way of modification					
Mixture	Dry	Wet	Dry	Wet	Dry	Wet
$\mathrm{G/AC} = 5\%$	1,156.6	1126.7	969.0	966.7	83.8	85.8
$\mathrm{G/AC} = 10\%$	1,243.8	1281.4	1,015.3	1,106.7	81.6	86.4
$\mathrm{G/AC} = 15\%$	1,185.9	1266.5	1,009.7	1,056.7	85.1	83.4

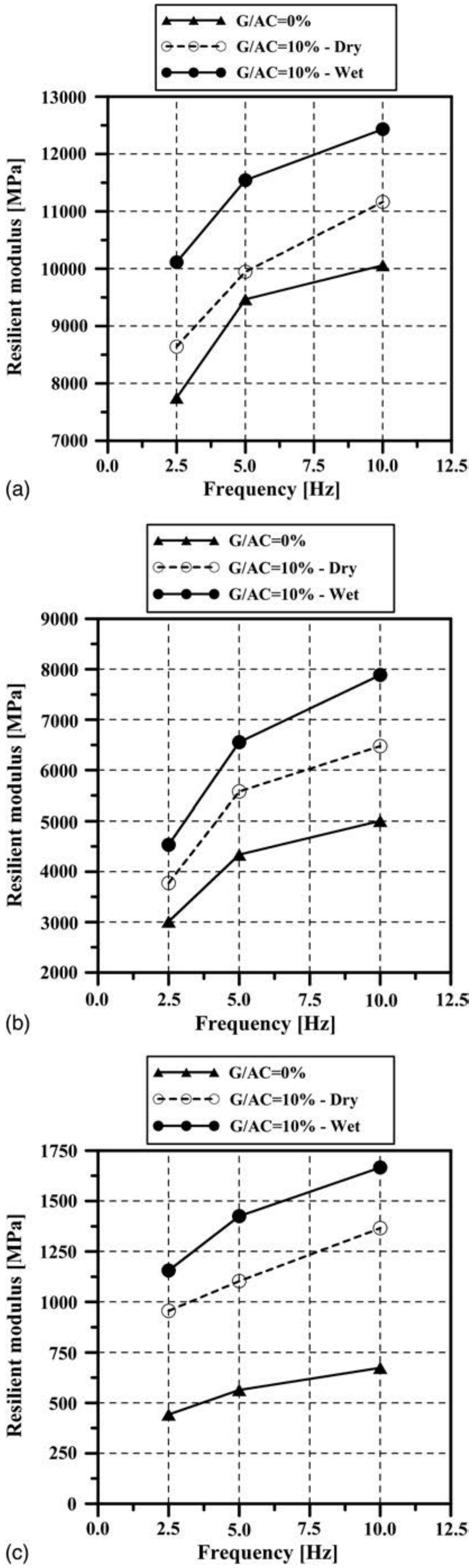

Fig. 7. Evolution of resilient modulus for (a) 10°C, (b) 20°C, and (c) 40°C

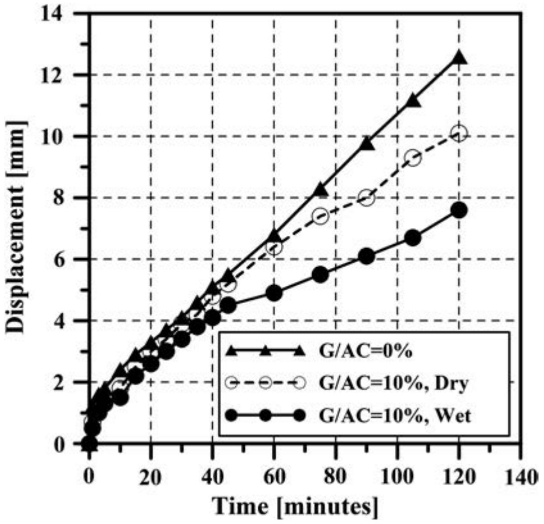

Fig. 8. Results of permanent deformation test

is generated, as evidenced by the increase in viscosity (Fig. 2), decrease in penetration, and increase in the softening point. Table 6 presents the results of the rheology test performed on the asphalt modified with G/AC = 10% and using a DSR. A comparison with the results in Table 4 (unmodified asphalt, G/AC = 0%) reveals that the modified asphalt exhibits a higher performance grade than AC 60–70 at high service temperatures, i.e., from 58 to 70°C. This higher performance grade results in a greater resistance against permanent deformation in high-temperature climates. In addition, it is observed that the performance grade at intermediate service temperatures does not vary when Gilsonite is added in a proportion of G/AC = 10%. At a low temperature of service, the PG of the modified asphalt binder with Gilsonite (G/AC = 10%) is −12°C (Table 7). In comparison with results in Table 5 (unmodified asphalt, G/AC = 0%), the modified asphalt binder is less resistant to low-temperature fatigue cracking.

In the indirect tensile tests for the unmodified MDC-19 mixture (G/AC = 0%), the resistances of the samples in the unconditioned state (US) and moisture-conditioned state (MS) were reported to be 1,075.3 and 926.4 kPa, respectively, with tensile shear ratios (TSRs) = MS/US = 86.2%. Table 8 presents the results of the indirect tensile tests performed on the modified asphalts (G/AC = 5, 10, and 15%). An increased strength is observed under monotonic loading during the indirect tensile tests performed on the modified mixtures compared with the reference mixtures (unmodified). However, the TSR parameter is similar for the two types of mixtures, suggesting that the Gilsonite does not affect resistance against moisture damage.

Dynamic Characterization

Figs. 7 and 8 present the results of the resilient modulus tests and permanent deformation tests, respectively, performed on the unmodified (G/AC = 0%) and modified MDC-19 mixture using wet and dry processes. A significant increase in the stiffness under dynamic loading is observed when the mixture is modified with Gilsonite. Average stiffness increases of 9, 28, and 105% were observed for test temperatures of 10, 20, and 40°C, respectively, when the mixture modification was performed using the dry process. When the modification was performed using the wet process, the resulting increases were 25, 53, and 154% for test temperatures of 10, 20, and 40°C, respectively. This increase in stiffness is consistent with the greater resistance against permanent deformation exhibited by the Gilsonite-modified mixtures (Fig. 8).

Conclusions

The present study measured the mechanical strength under monotonic and dynamic loading experienced by an asphalt concrete mixture modified with Gilsonite-type natural asphalt using wet and dry processes. The following conclusions can be drawn:

- A significant increase in the mechanical strength and stiffness under monotonic and dynamic loading was observed when the mixture was modified with Gilsonite at ratios of G/AC = 5 and 10%. This increase is primarily because of the increase in the stiffness developed by the asphalt when coming into contact with the Gilsonite. The Gilsonite generated an increase in the viscosity, softening point, and performance grade of the modified binder at high service temperatures and a significant reduction in the penetration grading. In addition, increases in the resistance and stiffness were observed for the modified mixture, despite the increase in its voids content.
- An increased mechanical strength and stiffness were obtained when the mixture was modified by the wet process, with G/AC = 10%.
- The increase in stiffness reported in the modified asphalt mixtures using wet and dry processes indicates that the Gilsonite can be used as a mixture additive/modifier to improve the resistance of the mixture against phenomena, such as rutting at high service temperatures in tropical climates. However, at low temperatures, the mixture could experience embrittlement, thus decreasing its resistance against phenomena, such as low-temperature fatigue cracking because of loading, especially in thin asphalt layers. Similarly, the modification by the wet process route is an economically viable alternative because this form of modification reduces fabrication costs in asphalt plants.
- Regarding the TSR value, the modified mixtures developed similar magnitudes compared with the unmodified mixture, which suggests that the Gilsonite did not affect the resistance against moisture damage.

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