PRACE ORYGINALNE
ORIGINAL PAPERS

Scientific Review – Engineering and Environmental Sciences (2019), 28 (4), 503–515
Sci. Rev. Eng. Env. Sci. (2019), 28 (4)
Przegląd Naukowy – Inżynieria i Kształtowanie Środowiska (2019), 28 (4), 503–515
Prz. Nauk. Inż. Kszt. Środ. (2019), 28 (4)
http://iks.pn.sggw.pl

DOI 10.22630/PNIKS.2019.28.4.46

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Performance characteristics and mechanical resistance of a hot mix asphalt using gilsonite and blast furnace slag

Key words: blast furnace slag, BFS, gilsonite, hot mix asphalt

Introduction

Blast furnace slags (BFS) are materials obtained in the manufacturing of iron in blast furnaces. Most countries in the world consider these materials as waste products, given that their use in multiple engineering applications (e.g. as fertilizers, in road construction, in the production of ceramic materials, bricks and cement, among others) is less in comparison to its production. The amount of material that is unused tends to pollute the environment, since it is generally dumped and piled in landfills or stored in open air production plants. Because of this, several research efforts are being carried out in the world with the purpose of evaluating use sources for this material.

Blast furnace slags possesses physical-chemical properties that are interesting for replacing natural aggregates in asphalt mixes. Some of these are: (a) present cementing properties and chemical composition properties similar to Portland cement (Das, Prakash, Reddy & Misra, 2007); (b) particles present a coarse and porous superficial texture, as well as good compatibility with asphalt, which could result in good adhesion with asphalt (Rondón, Ruge, Patiño, Vacca, Reyes & Muniz de Farias, 2018; Rondón, Ruge & Muniz de Farias, 2019). Constituting part of the aggregate in asphalt mixes with it would be helpful not only for seeking another use source, but at the same time additionally, reducing negative environmental impacts associated to the exploitation and production of natural aggregates in quarries. Several studies have been undertaken in order to evaluate the use of BFS as substitute for aggregates in asphalt mixes. Based on consulted literature, there is a main disadvantage evidenced, namely, that these materials need to be covered with greater quantities of asphalt, due to their high level of absorption and superficial porosity (FHWA, 2008). Likewise, it is evidenced, that most studies dose the substitution of aggregates in mass (Rondón et al., 2019). This practice increases asphalt consumption, given that there is a greater quantity of BFS particles employed (increasing the volume of aggregate for covering with asphalt) because of BFS's lower specific gravity (*Sg*) in comparison to natural origin aggregates (Rondón et al., 2019). Another widely reported disadvantage is its low wear and abrasion resistance in the Los Angeles Machine.

On the other hand, Colombia is a tropical country where high temperatures prevail in most of its regions. Additionally, in a large part of the country, rainfall is abundant and regular throughout the year. This causes asphalt mixes to be mainly exposed to two widely studied damage mechanisms in asphalt pavements: rutting and moisture damage. In order to avoid rutting, in general, there is an attempt to increase stiffness in the mix, as well as improving its elastic response and/or improving properties associated to cohesion. For the case of moisture damage resistance, there is generally an attempt to improve properties associated to adhesion between the aggregate and asphalt. Both properties, cohesion and adhesion may be improved in mixes through the use of modified asphalt technologies, which have been widely studied and used throughout the world. One way of increasing rutting resistance is modifying asphalt through the use of gilsonites (G). These materials of natural origin help to increase stiffness in asphalts given that they present softening points superior to 90°C and are known as asphalt hardening materials (Ameri, Mansourian, Ashani & Yadollahi, 2011) because of their high quantity of asphaltenes (Li et al., 2015). Likewise, they are materials that increase asphalt viscosity, its performance grade (PG) and reduce its thermal susceptibility in high service temperatures (Ke, Dongwei & Qing-quan, 2008; Feng, Zha & Hao, 2010; Ameri et al., 2011; Ameri, Mirzaiyan & Amini, 2018; Ren et al., 2018; Mirzaiyan, Ameri, Amini, Sabouri & Norouzi, 2019). In Colombia, there is a large amount of natural G asphalt reservoirs. Some studies have evidenced an increase in stiffness under monotonic and cyclic load, and rutting resistance of G-modified asphalt may be reviewed in Ameri et al. (2011), Esfeh, Ghanavati and GhaleGolabi (2011), Kök, Yilmaz, Turgut and Kuloğlu (2012), Yilmaz, Kök and Kuloğlu (2013) and Rondón, Noguera and Urazán (2016). On the other hand, studies that report increase to aging resistance, moisture damage and fatigue resistance may be consulted in Feng et al. (2010) and Jahanian, Shafabakhsh and Divandari (2017).

This study evaluated resistance under monotonic load, cyclic load and moisture damage resistance in a hot mix asphalt (HMA) when part of the coarse fraction of the natural aggregate (NA) is substituted with BFS and used an G-modified asphalt (wet modification process). In reviewed literature, only one study reported by Rondón et al. (2018) evaluated the behaviour of HMA when employing BFS and G. In said study, there was a limited experimental phase carried out (only Marshall, indirect tensile strenght and Cantabro tests were performed) and dosage as well as substitution of aggregates was carried out in mass. In a different manner to the study reported by Rondón et al. (2018), this study carried out dosage in volume (mainly in order to reduce asphalt consumption), and also conducted additional tests such as resilient modulus, permanent deformation and fatigue resistance. Additionally, the chemical and mineral composition of BFS was established. Likewise, a control HMA with a particle size distribution that displays the maximum particle size was used with the purpose of better utilizing BFS, given that this material generally presents large sized particles. The same optimum asphalt content (*OAC*) was used in all mixes. This contributes in the reduction of HMA mix production costs, given that less BFS would be required for fracturing. Additionally, the possibility of using said material without the addition of large asphalt contents was evaluated. ANOVA variance analysis was additionally conducted on the obtained results, attaining a reliability level of 95%. This had the purpose of evaluating if said results were statistically different or not. In said analysis, if $F > F_{0.05}$ means that changes in evaluated parameters are significant in relation to the control mix.

Materials and methods

Material characterization

Natural aggregate and blast furnace slags characterization is presented in Table 1. The NA complies with the minimum quality requirements demanded by Instituto Nacional de Vías (INVIAS, 2013) standard for the manufacturing of HMAs. Such as it has been reported in other studies, BFS presents a lower *Sg* and greater absorption in comparison to NA and does not comply with the Los Angeles Machine abrasion resistance value (35% maximum) and Micro-Deval

TABLE 1. Natural aggregate (NA) and blast furnace slags (BFS) characterization

Test	Method	NA	BFS
Sg/absorption (3/4”)	AASHTO T 84-00 AASHTO T 85-91	2.51/1.66%	2.11/3.89%
Sg/absorption (1/2”)		2.49/1.70%	2.27/3.67%
Sg/absorption (3/8”)		2.50/1.61%	2.34/3.37%
Sg of sands and fines/adsorption		2.50/1.50%	–
Abrasion in Los Angeles Machine	AASHTO T 96-02	23.7%	45.1%
Micro-Deval	AASHTO T327-05	22.8%	30.1%
10% of fines (dry resistance)	DNER-ME 096-98	125 kN	120 kN
Fractured particles: 1 face	ASTM D 5821-01	89%	95%
Flattening index	NLT 354-91	7.5%	3.2%
Elongation index		8.5%	6.1%

(25% maximum). However, it presents a good fracture resistance in the 10% of fines test, as well as particles with a good geometry.

X-ray diffractometry (XRD) and X-ray fluorescence (XRF) tests were conducted, as well as observation in an scanning electron microscopy (SEM) were carried out on BFS and NA particles. Chemical and mineralogical composition are presented in Tables 2 and 3. The main difference in both samples is the greater quantity of CaO in BFS and the presence of some clay minerals in the NA. Blast furnace slags is mainly comprised of silica, calcium oxide (CaO) and aluminum oxide – Al_2O_3 (92.76%), while the NA sample is mainly comprised of silica and Al_2O_3 (86.86%). SiO_2 and Al_2O_3 oxides are pozzolanic compounds that may develop self-hardening properties (Misra, Biswas & Upadhyaya, 2005). This pozzolanic property may increase moisture damage resistance in HMAs (Nassar, Mohammed, Thom & Parryk, 2016). Additionally, these two oxides may help to increase adherence and internal cohesion within the HMA (Modarres & Rahmanzadeh, 2014). According to Modarres and Rahmanzadeh (2014), CaO oxide is alkaline, which could contribute to increase adhesion between the asphalt and aggregate and improve moisture damage resistance and stripping resistance. Scanning electron microscopy observations (Fig. 1) were performed in a JEOL JSM 6700F equipment with an acceleration voltage of 20 kV in high vacuum at a working distance of approximately of 15 mm. High amounts of large pores can be distinguished clearly on the surface of BFS. The BFS particles have higher porosity (50–63%) and pore diameter (27.5–82.6 μm) than particles of NA (porosity of 0.6–20.8% and pore diameter of 6–36.4 μm), which explains the lower specific gravity, higher absorption and higher fracture probability under mechanical load of the BFS compared to NA.

Asphalt AC 60-70 (PG 58-22) characterization is presented in Table 4. This asphalt complies with minimum quality requirements demanded by INVIAS standard (2013), and was chosen given that it is the most used one in Colombia for HMA production. Gilsonite presents a specific gravity of 1.3, penetration

TABLE 2. Chemical composition of blast furnace slags (BFS) and natural aggregate (NA) in the XRF test

Component	CaO	SiO_2	Al_2O_3	MgO	Na_2O	Fe_2O_3	TiO_2	K_2O	P_2O_5
BFS [%]	30.8	52.0	9.9	0.8	0.7	1.5	1.0	0.9	0.06
NA [%]	1.1	79.0	7.9	2.3	1.8	3.7	0.4	1.2	0.11

TABLE 3. Mineral percentages of blast furnace slags (BFS) and natural aggregate (NA) samples in the XRD test

Sample	Mineral [%, in mass]				
BFS	quartz (58.9)	cristobalite (18.1)	boehmite (12.8)	calcite (4.8)	natrolite (5.3)
NA	quartz (61)	albite (25.1)	illita (5.3)	chlorite (8.7)	–

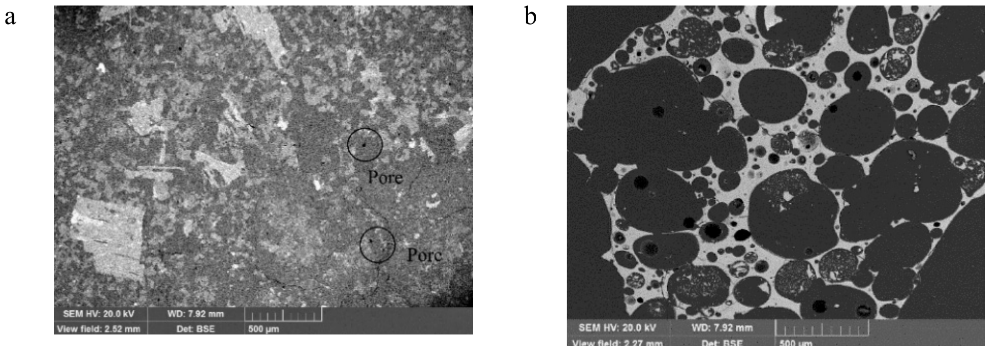

FIGURE 1. Scanning electron microscopy observations

TABLE 4. Asphalt AC 60-70 and asphalt modified (G/AC = 10%)

Test	Method	Unit	AC 60-70	G/AC = 10%
Neat asphalt				
Penetration (25°C, 100 g, 5 s)	ASTM D5	0.1 mm	61.5	43.0
Penetration index	NLT 181/88	–	–0.9	–0.78
Softening point	ASTM D3695	°C	48.9	53.2
Specific gravity	AASHTO T 228	–	1.012	1.11
Ductility (25°C, 5 cm·min^{-1})	ASTM D113	cm	> 105	> 105
Flashpoint	ASTM D92	°C	288	299
Tests on the residue after the RTFOT				
Mass loss	ASTM D2872	%	0.34	0.30
Penetration of the residue after loss by heating, in % of the original penetration	ASTM D5	%	78	82

(25°C, 100 g, 5 s, ASTM D5) of 0 and a softening point of 92°C (ASTM D3695). Additionally, the totality of particles was passed through sieve No 40 in a particle-size distribution test. Based on previous studies (e.g. Rondón et al., 2016), a ratio of 10% G/AC in mass was chosen in order to modify via wet process the AC 60-70. When using this G/AC ratio, the main result is producing a high rutting resistance in high temperature climates. Contents of G/AC superior to 10% were not chosen given that asphalt tends to significantly increase its viscosity and stiffness, considerably hindering mixing and compaction in mixes. Temperature and time of asphalt mix with G were 160°C and 20 min, respectively. Asphalt modified properties are presented in Table 4. Viscosity curve of AC 60-70 (with and without modification) is showed in Figure 2. Compared with Table 4, G increases asphalt stiffness (reduces penetration, increases softening point and viscosity), as well as flashpoint and a slight increase in aging resistance.

Performance grade of conventional asphalt and asphalt modified at high

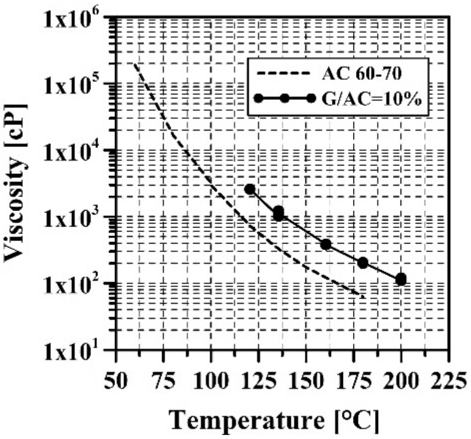

FIGURE 2. Viscosity curve

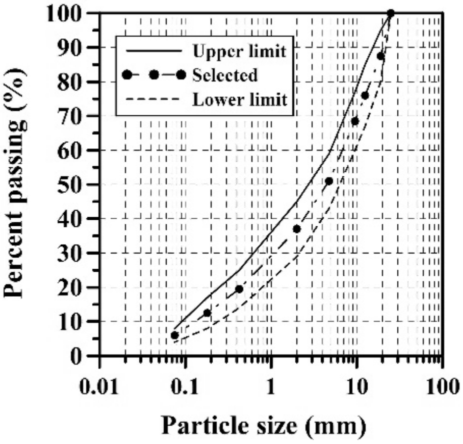

FIGURE 3. Particle size distribution curve (HMA-25)

and intermediate service temperatures was obtained by using a dynamic shear rheometer – DSR (AASHTO T 315-05). Shear complex modulus (*G**) and phase angle (δ) were the obtained parameters. Performance grade in high temperatures for AC 60-70 was 58°C and for G/AC = = 10% modified asphalt 70°C. This higher PG of the modified asphalt could result in greater permanent deformation resistance in high-temperature climates. Performance grade in intermediate service temperatures was 22°C for both asphalts, meaning that at intermediate service temperatures there is no variation when G is added in a proportion of G/AC = 10%.

Marshall tests

Hot mix asphalt type HMA-25 (see particle size distribution in Fig. 3) was used as control asphalt mixture (according to INVIAS standard, 2013).

Control HMA-25 was designed based on Marshall test (AASHTO T 245). Samples were compacted using 75 blows per face. Five samples were manufactured and tested for each percentage of asphalt in mass of 4.5, 5.0, 5.5 and 6.0%. Mixing and compaction temperatures were 150°C (asphalt viscosity of 170 cP) and 140°C (asphalt viscosity of 280 cP), respectively. Optimum asphalt content was 5%, based on the requirements established by INVIAS (2013) for HMA-25 mixtures. Marshall tests were performed on samples made with the *OAC* but using the asphalt modified with G/AC = = 10%. This HMA-25 was called HMA-25-G. Five samples were manufactured to perform the Marshall tests. For the HMA-25-G mixture, ASTM D6925 recommends approximate mixing temperatures of the asphalt modified with the aggregate of 190°C for G/AC = 10% (Fig. 2). This mixing temperature was not used because for modified asphalts, the determination of this temperature is not reliable when following the criteria recommended by ASTM D6925 mainly because the behaviour 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 asphalt when oxidizing and aging it. Therefore, a temperature of 160°C was selected as the mixing temperature of the asphalt modified with the aggregate. The process previously described was also carried out for mixes in which the volume of NA particles retained in sieves ¾" and ½" (24% of aggregate mass) were substituted with BFS. This replacement percentage was chosen based on a previous study carried out by (Ruiz, Rondón & Chaves, 2019), in which the larger substitution quantities generate adherence problems and the need of increasing *OAC*. Mixes with BFS manufactured with AC 60-70 were named HMA-25-BFS, and those manufactured with G-modified AC 60-70 were named HMA-25-G-BFS. Additionally, the approximate replacement in volume was calculated, considering the specific gravity of the aggregates retained in each sieve (NA and BFS). The required NA mass in each sieve was multiplied by the ratio of specific gravities between BFS and NA in order to obtain the new BFS mass that would replace NA in volume. Volumetric composition (air voids in volume – *Va*, voids in mineral aggregate – *VMA*, and voids filled with asphalt – *VFA*) as well as resistance under monotonic load (stability – *S*, flow – *F*, and *S*/*F* ratio) values were measured.

Indirect tensile strength (ITS) tests

For the case of ITS tests, six Marshall-type samples with air void percentages of 7 ±1% were manufactured for each HMA, following AASHTO T283 standard and using *OAC*. Three samples were tested with preconditioning (dry condition – ITS_D) and other three previously "conditioned" samples (vacuum saturated or wet – ITS_W). Moisture damage resistance was evaluated by means of $TSR = ITS_W/ITS_D$ ratio [%]. This test was performed on control HMA-25, and HMA-25-G, HMA-25-BFS, HMA-25-G-BFS asphalt mixes.

Resilient modulus, permanent deformation and fatigue resistance tests

Resilient modulus tests (BS EN 12697-26) were performed on control HMA-25 and HMA-25-G, HMA-25-BFS, HMA-25-G-BFS mixes under temperatures of 10, 20 and 30°C, and three loading frequencies (2.5, 5.0 and 10.0 Hz). Permanent deformation tests (BS EN 12697-25) under repeated square-wave load with a stress of 100 kPa, test temperature of 40°C and 3,600 load cycles (*N*) were performed on the Marshall HMA-25 and HMA-25-G, HMA-25-BFS, HMA-25-G-BFS specimens used in resilient modulus tests. Indirect tensile fatigue tests (ITFT), according to BS EN 12697-24 controlled stress procedure tests, were conducted on HMA-25 and HMA-25-G, HMA-25-BFS, HMA-25-G-BFS samples. Each fatigue test was performed using nine samples (three replicates for each of the three constant stress levels applied of 200, 300 and 400 kPa), temperature of 20°C and repetitive applications of compressive controlled-load in a haversine waveform with load time of 0.1 s and rest time of 0.4 s. Fatigue resistance was determined as the total number of load applications that caused the complete fracture of the specimen (N_f).

Results and analysis

Marshall test and ITS test

Marshall test and ITS test results are presented in Figure 4 and Table 5, respectively. We observe that by substituting NA particles (material retained in sieves ¾” and ½”) with BFS (HMA-25--BFS), resistance under monotonic load (evaluated through *S*/*F* ratio) drops. We also observe that *ITS* and moisture damage resistance drop, but these drops are not statistically significant ($F < F_{0.05}$). Reductions in evaluated resistances are mainly because of a lack of coating with asphalt for BFS particles as a product of using the same control mix *OAC*. Likewise, BFS particles present a lower abrasion and fracture resistance. Additionally, we observe that when substituting in volume, the contents of *Va* do not increase significantly when compared to other studies in which said substitution was carried out in mass (e.g. Rondón et al., 2018; Rondón et al., 2019).

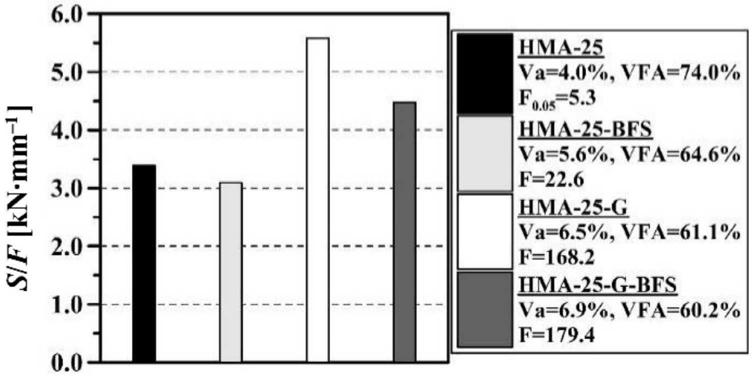

FIGURE 4. Stability (*S*) nad flow (*F*) ratio results

TABLE 5. Indirect tensile strength test results

Mixture	*Va* [%]	ITS_D [kPa]	*F* for ITS_D	ITS_W [kPa]	*F* for ITS_W	*TSR* [%]
HMA-25	6.8	1 234.9	$F_{0.05} = 7.7$	1 055.9	$F_{0.05} = 7.7$	85.5
HMA-25-BFS	6.7	1 269.6	5.6	1 005.1	4.8	79.2
HMA-25-G	7.1	1 333.1	78.4	1 156.5	20.8	86.8
HMA-25-G-BFS	6.8	1 278.7	8.1	1 044.6	0.3	81.7

When using G-modified asphalt, mixes undergo an increase in measured parameters (*S*/*F*, ITS_D, ITS_W, *TSR*) with relation to the control mix. In other words, G helps to increase resistance under monotonic load, *ITS* and moisture damage. The aforementioned occurs, despite the fact that mixes presented an increase in *Va* as a product of loss in manageability and compatibility of samples when the asphalt’s viscosity increases. These increases in resistance were statistically significant, except for the ITS_W parameter for HMA-25-G-BFS ($F < F_{0.05}$) mix. The increase in *S*/*F* ratio is mainly due to the increase of stiffness in modified asphalt, such as was demonstrated in its physical-rheological characterization.

Resilient modulus, permanent deformation and fatigue resistance tests

Resilient modulus, permanent deformation and fatigue test results are presented in Figures 5, 6 and 7, respectively. These results are coherent with those reported on Marshall test and ITS test. We observe a drop in resilient modulus (2.3–17%) and permanent deformation resistance of the mix that substituted in volume NA particles with BFS (HMA-25-BFS). However, said drops are not statistically significant in evaluated temperatures, given that *F*-factors were lower in relation to $F_{0.05}$. ANOVA analysis for permanent deformation test was calculated at N = 3,600 (final load cycle). On the contrary, when using G-modified asphalt, both resilient modulus as well as permanent deformation resistance increased in relation to control mix, and said increases were statistically significant. For example, for the case of HMA-25-G mix, increase in modulus was between 45.2 and 76.1% when testing temperature was 30°C, while for HMA-25-BFS-G mix, it was between 33.6 and 51.9%. Likewise, the drop in deformation in comparison to control mix in N = 3,600 was 45% and 20.6% for the case of HMA-25-G and HMA-25-BFS-G mixes, respectively. We observe a drop in fatigue resistance when replacing NA with BFS in volume. Similarly than in ITS, this drop may be because *OAC* in control mix is not enough to cover the optimum demand of aggregate as a product of the higher absorption and superfi-

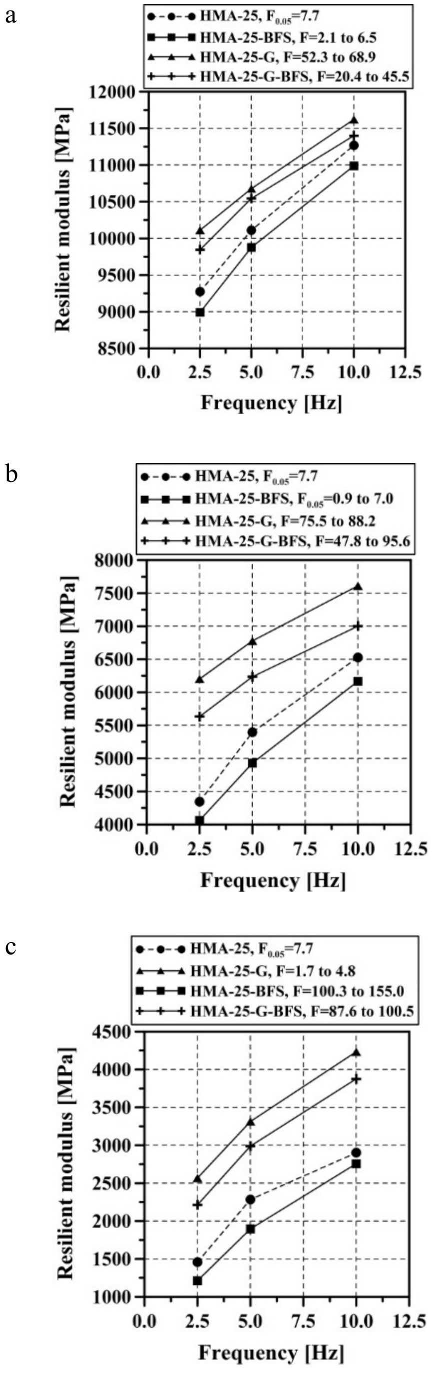

FIGURE 5. Resilient modulus: a – 10°C; b – 20°C; c – 30°C

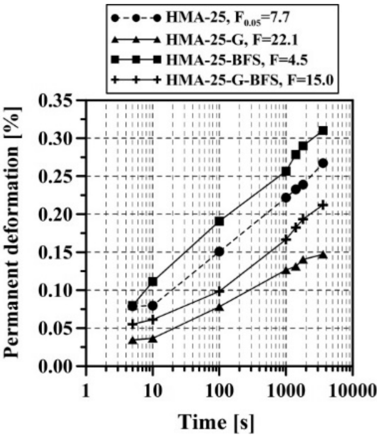

FIGURE 6. Permanent deformation

cial porosity of BFS, impacting in a loss of adherence. However, we observe an increase in fatigue resistance when using G-modified asphalt. This slight increase in fatigue resistance can be related to the mixture's response to this type of loading (controlled-stress). When mix stiffness increases with this type of loading, usually the same happens with its useful life load fatigue resistance. In contrast, when controlled deformation loading is imposed, usually greater fatigue life occurs when the mixture is less stiff (Di Benedetto, de la Roche, Baaj, Pronk & Lundstrom, 2004; Muniz de Farias, Quiňonez & Rondón, 2019). It is important to highlight that none of the changes presented in Figure 7 in relation to control mix were statistically significant ($F < F_{0.05}$).

Conclusions

Below, the obtained conclusions will be presented, which may only be considered for the HMA mix type, G and substitution percentage utilized.

When replacing NA in volume with BFS, resistances under monotonic load (*S*/*F*, ITS_D, ITS_W), cyclic (resilient modulus, permanent deformation and fatigue) as well as moisture damage resistance (*TSR*) drop. However, the *S*/*F* ratio drop alone, was statistically significant. These reductions may be attributed to using the same *OAC* content than control HMA-25 mixes in HMA-25-BFS mixes. In this regard, the high porosity and absorption that BFS particles present, generated an increase in air void content in the mix and a lower degree of coating with asphalt, which was not enough to promote

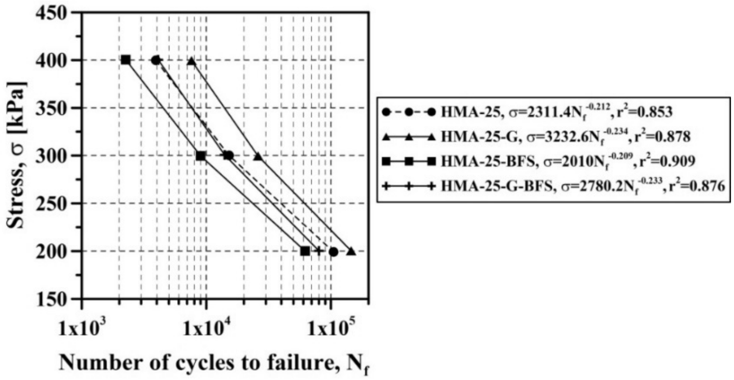

FIGURE 7. Fatigue test results

better characteristics of cohesion and adhesion.

When G is used in a G/AC = 10% ratio, it demonstrated to be a material that significantly increases asphalt stiffness (reduces penetration and increases softening point, viscosity G^* and PG at high service temperatures). Said increase in stiffness caused a significant increase in S/F ratio, resilient modulus and permanent deformation resistance of mixes that used NA in 100% (HMA-25--G) and in those where NA was replaced with BFS (HMA-25-BFS-G). The above despite the fact that air voids increased in relation to control mix, and the same *OAC* content from control mix was used. We also observe an increase in moisture damage resistance when using G as an asphalt modifier. The HMA with G undergone an increase in fatigue life, however said increases were not statistically significant in relation to control mix. The HMA that replaces NA with BFS and uses G-modified asphalt helps to increase rutting resistance in high temperature climates and may be recommended in the forming of thick asphalt layers. In low temperature climates and thin asphalt layers, it is possible to undergo premature cracking (brittle behaviour).

Acknowledgements

The authors thank the U. Distrital Francisco José de Caldas and U. Militar Nueva Granada.

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Summary

Performance characteristics and mechanical resistance of a hot mix asphalt using gilsonite and blast furnace slag. Replacing natural aggregates (NA) for blast furnace slag (BFS) is seen as a technique that is beneficial for the environment. Additionally, in high temperature climates, rigidizing the asphalt by employing gilsonites (G) could be an alternative in order to increase rutting resistance. This study substituted in volume, part of the coarse fraction of NA for BFS in a hot mix asphalt (HMA) that employed asphalt modified with G in wet process. Physical properties of BFS are presented, as well as its chemical and mineral compositions. Additionally, physical properties of asphalt modified are shown. In regards to HMAs, their resistance under monotonic load (Marshall test and indirect tensile strength test), cyclic (resilient modulus, permanent deformation and fatigue) and moisture damage (tensile strength ratio – TSR) was evaluated. All HMAs were manufactured employing the same asphalt content from the control mix. An ANOVA variance analysis was conducted. Based on ANOVA, when the NA volume is substituted with BFS, Marshall stability/ /flow relation significantly drops. However, when such substitution is carried out using G-modified asphalt, resistance under monotonic load, stiffness under cyclic load, resistance to permanent deformation and moisture damage notably increase. Fatigue resistance also increases but such increase is not statistically significant.

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