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Behavior of a Hot Mix Asphalt using Blast Furnace Slag and Gilsonite

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Abstract

This paper shows the experimental results of testing a hot mix asphalt (HMA) when is replacing the coarse natural aggregate by a blast furnace slag (BFS), and its asphalt cement (AC 60-70) is modified by wet way with a natural asphalt type Gilsonite (G). Marshall and indirect tensile strength (ITS) tests were performed to evaluate the resistance under monotonic load. Cantabro Test was performed to evaluate the abrasion resistance. Moisture damage resistance was evaluated trough the tensile strength ratio (TSR). The results showed that when replacing the natural aggregate by BFS decreased the studied properties (resistance under monotonic load, and abrasion and moisture damage). However, these properties improve when using modified asphalt with Gilsonite. It is possible to obtain a HMA mixture with good mechanical properties when 21% (in mass) of the natural aggregate was substituted by BFS and AC was modified with G in a proportion of G/AC = 10% in mass.

Keywords: Blast furnace slag, Hot mix asphalt, Gilsonite, Modified asphalt.

INTRODUCTION

Blast Furnace Slag

Blast furnace slags (BFS) are obtained during the production of iron in blast furnaces. The main components of BFS are silica, calcium oxide, magnesium oxide, and aluminum oxide (Table 1). In Colombia, the iron production was estimated in 710,047 tons for 2013 [1] and increased to 901,736 tons during 2015 [2]. This allowed estimating an annual production of $2x10^5$ tons of BFS [3]. In developed countries this production was significantly higher [4]. On average, each ton of iron generated between 340-421 kg of BFS [5]. Using BFS decreased the exploitation of natural aggregates and the space occupied by waste in landfills [6]. Its greatest reuse was associated with the cement production industry [7, 8].

BFS's main interesting properties were the following: Aggregates with a rough surface texture and angularity, high porosity and absorption, good adhesion with the asphalt, similar chemical composition with the clinker and cement, pozzolanic compounds, and low specific gravity [3, 9-10]. The main disadvantages were the following: Greater consumption of asphalt, increase in costs, low abrasion resistance (Los Angeles Abrasion Test), and required longer drying time in asphalt mixture production plants [11-13].

Table 1. BFS chemical composition.

Component	[14]	[15]	[16]
CaO [%]	41.4	40.4	47.9
SiO_2 [%]	35.7	37.5	32.9
Al_2O_3 [%]	11.2	4.76	8.90
MgO [%]	6.89	3.65	5.70
Na_2O [%]	0.28	2.55	2.55
SO_3 [%]	2.43	-	-
Fe_2O_3 [%]	0.26	0.15	2.40
MnO [%]	0.60	-	-
TiO_2 [%]	0.63	-	0.50
K_2O [%]	0.64	0.62	0.40
P_2O_5 [%]	-	-	0.60

Gilsonite

Colombia has many natural asphalt deposits of Gilsonite (G). This material was successfully used to modify hot mix asphalts (HMA), and its best contribution was stiffening virgin asphalts and asphalt mixtures: increase the asphaltene content, softening point, viscosity and performance grade, and decreases the penetration [17-20]. When using Gilsonite, the resulting HMA improve mainly their resistance to rutting in hot climates, and increase the Marshall stability and resilient modulus [21-25]. Other mechanical characteristics that improved when G was added to asphalt mixes were resistance to fatigue and moisture damage [26-34].

Objective and scope

This paper shows an experimental program designed to evaluate the resistance under monotonic load to abrasion and moisture damage of an HMA-19 [35], in which the AC was modified with G and part of the natural coarse aggregate was replaced by BFS. The AC used is ‘AC 60-70’ (penetration test ASTM D-5 in 0.1 mm). The G was added to the asphalt at high temperature (wet way) and came from San Alberto mine (César, Colombia). The BFS used was of ACBFS type (Air-Cooled Blast Furnace Slag) produced by the company ‘Acerías Paz del Río’ (Nobsa, Colombia).

MATERIALS AND METHODS

Materials characterization

The natural granular aggregate, BFS, and AC 60-70 were characterized following the INVIAS standards [35-36]. The results of lab tests are presented in Tables 2, 3, and 4, respectively. Particle size distribution of HMA-19 is presented in Table 5. It was observed that the values met the requirements of INVIAS standard [35] to manufacture mixes of type HMA-19. Except for BFS's case, since they had a low resistance to wear by impact abrasion on 'Los Angeles' machine.

Table 2. Natural aggregate test results.

Test	Method	Recommended value	Result
Specific gravity/fine aggregate absorption	AASHTO T 84-00	-	2.64/1.7%
Specific gravity/gross aggregate absorption	AASHTO T 85-91	-	2.52/1.62%
Sand equivalent test	AASHTO T 176-02	50% minimum	77%
Fractured particles (1 side)	ASTM D 5821-01	85% minimum	89%
Soundness of aggregate using magnesium sulphate	AASHTO T 104-99	18.0% maximum	11%
Plasticity Index	ASTM D4318-00	Not plastic	Not plastic
10% of fines (dry resistance)	DNER-ME 096-98	100 kN minimum	133 kN
Micro-Deval	AASHTO T327-05	20% maximum	18.8%
Abrasion in Los Angeles machine	AASHTO T 96-02	25% maximum	23.7%

Table 3. Blast furnace slag test results.

Test	Method	BFS
Specific gravity/absorption (1/2” and 3/8”)	AASHTO T 84-00	2.28/4.2%
Specific gravity/absorption (1/2”, 3/8” and No. 4)	AASHTO T 85-91	2.16/4.5%
Abrasion in Los Angeles Machine, 500 revolutions	AASHTO T 96-02	49.6%
Micro-Deval	AASHTO T327-05	32.1%
10% of fines (dry resistance)	DNER-ME 096-98	119 kN
Fractured particles: 1 face	ASTM D 5821-01	95%
Impurities content	UNE 14613 : 2000	0%
Plasticity index	ASTM D 4318-00	No plastic
Flattening index	NLT 354-91	5.1%
Elongation index		9.2%
Iron unsoundness	T220 (RMS 12.495)	Free

Table 4. Test results performed on AC 60-70.

Test	Method	Unit	Recommended value	Result
Tests on the original asphalt				
Penetration (25°C, 100 g, 5 s)	ASTM D-5	0.1 mm	60-70	62.5
Penetration Index	NLT 181/88	-	-1.2/+0.6	-0.94
Viscosity (60°C)	ASTM D-4402	Poises	1500 minimum	1770
Softening point	ASTM D36-95	°C	48-54	49
Ductility (25°C, 5cm/min)	ASTM D-113	cm	100 minimum	>105
Flash and fire points	ASTM D-92	°C	230 minimum	289
Tests on the residue after RTFOT (Rolling Thin Film Oven Test)				
Mass loss	ASTM D-2872	%	0.8 maximum	0.63
Penetration (25°C, 100 g, 5 s)	ASTM D-5	%	50 minimum	77

Table 5. Particle size distribution of HMA-19.

Sieve	Sieve [mm]	Percent passing (%)	Percent retained (%)
3/4"	19.00	100.0	0.0
1/2"	12.50	87.5	12.5
3/8"	9.50	79.0	8.5
4	4.75	57.0	22.0
10	2.00	37.0	20.0
40	0.43	19.5	17.5
80	0.18	12.5	7.0
200	0.075	6.0	6.5
Bottom	-	-	6.0

A detailed description of the Gilsonite can be found in Rondón et al. [24]. This material had a specific gravity of 1.10 g/cm^3 and particles of brilliant black coloration that pass the No. 40 sieve in a particle size test (Figure 1). The AC 60-70 was modified with Gilsonite by wet process using a ratio in mass of G/AC = 10%. The mixing temperature of AC with G was 160 °C and the mixing time was 40 minutes. These conditions were chosen based on previous studies [24, 37], in which it is concluded that Gilsonite increases the asphalt stiffness, viscosity, softening point, and performance grade as well as a significant reduction in the penetration grading.

Figure 1. Gilsonite.

Asphalt control mix design

The control HMA-19 (without BFS and G) was designed based on Marshall Test. The HMA was designed from cylindrical Marshall-type samples, made as described in AASHTO T 245 standard. The air voids content of the compacted mixture were measured as indicated in the

AASHTO T 269-97 standard. The samples were compacted at 75 blows per face and the masses of them were 1200 g, distributing in according with values in percentages of the particle size distribution showed in Table 4. Five samples were manufactured and tested for each percentage of asphalt in mass of 4.5%, 5.0%, 5.5%, and 6.0%, in order to obtain the optimum asphalt content (OAC). Based on ASTM D6925 standard, the mixing and compaction temperatures were 150 °C (asphalt viscosity of 170 cP) and 140 °C (asphalt viscosity of 280 cP), respectively.

Marshall and Indirect Tensile Strength tests

Using the OAC, six Marshall-type samples were manufactured for the Indirect Tensile Strength test (ITS, AASHTO T 283 standard), following the same manufacturing process showed above. These samples were manufactured using natural aggregate (without BFS and G). Three samples were tested under dry condition (ITS-D) and other three in wet condition (ITS-W). The resistance to moisture damage was evaluated trough the ratio TSR = ITS-D/ITS-W (in percentage).

Then, Marshall and ITS tests were additionally performed on samples made with the OAC but replacing 21% (material retained in sieves ½" and 3/8", see Table 5) and 43% (material retained in sieves ½", 3/8", and No. 4, see Table 5) of the natural aggregate by BFS in mass. These samples with replacing of 21% and 43% were called BFS-21% and BFS-43%, respectively. Three BFS-21% and other three BFS-43% were manufactured to perform Marshall Test. For the case of ITS test were manufactured six for BFS-21% and other six for BFS-43% (three tested in dry condition and three in wet condition). The mixing and compaction temperatures were 150 °C and 140 °C, respectively. This experimental phase was repeated but using the modified asphalt with Gilsonite (G/CA=10%). In order to compare and taking into account the increase in viscosity caused by the Gilsonite, the mixing temperatures used were 150 °C (BFS-21%-G-150) and 160 °C (BFS-21%-G-160). A higher mixing temperature was not used to prevent premature aging of the asphalt. This last experimental phase was carried out substituting 21% of the natural aggregate for BFS (43% is not replaced, since the results were not satisfactory in previous phases).

Cantabro Test

Three Marshall-type samples of each HMA mixture (control, BFS-21%, BFS-21%-G-150, and BFS-21%-G-160) were tested following NLT 352/86 standard. Each sample was tested at 20 °C in an Angeles abrasion drum for 300, 500, and 1000 revolutions without the charge of steel spheres. The sample mass loss was expressed as a percentage relative to the initial mass and the final mass after the test.

RESULTS AND DISCUSION

Asphalt control mix design

The calculations obtained from the tests are showed in Table 6 and the OAC was 5%. This percentage was obtained taking in account the requirements established by [35] for HMA mixtures. Besides the OAC, with Marshall Tests is obtained the volumetric composition (air voids in volume-Va, voids in mineral aggregate-VMA, and voids filled with asphalt-VFA) and the resistance under monotonic load of the HMA (stability-*S*, flow-*F*, and *S/F* ratio).

Table 6. Marshall Test results of control HMA-19.

AC [%]	S (kN)	F (mm)	S/F (kN/mm)	Va (%)	VMA (%)	VFA (%)
4.5	11.19	4.01	2.79	6.2	16.3	61.7
5.0	11.79	3.68	3.20	4.4	15.6	72.2
5.5	11.60	3.78	3.07	3.5	15.9	78.0
6.0	10.94	4.22	2.60	2.7	16.3	83.4

Marshall and ITS tests

The results of Marshall and ITS tests are showed in Tables 7 and 8, respectively. By replacing 21% of the natural aggregate with BFS, the HMA showed similar resistance under monotonic load in relation to the control in Marshall Test. However, the ITS and moisture damage decrease markedly. In the case of 43% substitution, the HMA resistance in both tests was significantly lower compared to the control. These results can be explained by the following reasons: 1) BFS-21% and BFS-43% showed greater air void content in relation to control HMA due mainly to the higher absorption of BFS; 2) the rough texture of BFS could introduce additional difficulties in the coating process with the asphalt; 3) using the same OAC, the asphalt film thickness decreased because the surface area and number of particles increased (due to lower specific gravity of BFS compared with natural aggregate).

However, a notable increase in stiffness, resistance under monotonic loading, and ITS was observed when the modified asphalt with Gilsonite was used and the mixing temperature increased. Besides, TSR parameter were similar and therefore the resistance to moisture damage. The above, although the modified mixtures showed greater air voids content and the same OAC. Marshall Test results obtained can be due to the increase in stiffness of the asphalt when it was modified with Gilsonite. The increase of the mixing temperature (from 150 °C to 160 °C) improved the resistance under monotonic loading and the ITS due mainly to decreased of viscosity in the modified asphalt (facilitating the coating of aggregates and BFS and decreasing the Va).

Table 7. Marshall Test results.

Mixture	S [kN]	F [mm]	S/F [kN/mm]	Va [%]	VMA [%]	VFA [%]
Control	11.8	3.68	3.2	4.35	15.63	72.19
BFS-21%	11.7	3.60	3.3	6.28	16.55	62.08
BFS-43%	10.2	3.98	2.6	7.60	17.51	56.78
BFS-21%-G-150	13.8	3.77	3.7	7.77	17.86	56.52
BFS-21%-G-160	15.0	3.73	4.0	6.10	16.40	62.79

Table 8. ITS Test results.

Mixture	Va [%]	ITS-D [kPa]	ITS-W [kPa]	TSR [%]
Control	4.2	985.3	858.8	87.2
BFS-21%	6.1	967.9	771.2	79.7
BFS-43%	7.1	854.2	637.1	74.6
BFS-21%-G-150	7.4	1072.1	927.5	86.5
BFS-21%-G-160	6.0	1282.1	1107.8	86.4

Cantabro Test

The results of Cantabro Test are shown in Table 9. Comparing the BFS-21% asphalt mixture with the control HMA, the abrasion resistance in Cantabro Test decreased due mainly to: 1) BFS-21% showed higher Va content, and 2) BFS showed lower resistance to abrasion in Angeles machine compared with natural granular aggregate. However, this resistance improved when was used the modified asphalt with Gilsonite and even, it tended to be similar to the control HMA when the mixture was manufactured with BFS and the mixing temperature of 160 °C was used.

Table 9. Cantabro Test results.

Mixture	Va [%]	Mass loss (%) Revolutions		
		300	500	1000
Control	4.3	7.0	9.6	16.3
BFS-21%	5.9	9.1	12.2	20.9
BFS-21%-G-150	7.6	8.5	10.8	18.9
BFS-21%-G-160	6.2	7.2	9.8	15.9

CONCLUSIONS

This study measured the resistance under monotonic load (Marshall and ITS tests) and the resistance to abrasion (Cantabro test) and moisture damage (TSR) reached by a HMA mixture manufactured with BFS and modified by wet way with Gilsonite. Replacing the natural aggregate with BFS, all these properties in the HMA tended to worsen. However, when was used Gilsonite as a modifier of AC, it improved the resistance to abrasion and the resistance to monotonic loads and moisture damage. This improvement was obtained when the addition of Gilsonite was carried out by wet way in a proportion of 10% (in mass) in relation to that of the AC. The best performance was achieved when the HMA replaced 21% of the natural aggregate (material retained in sieves ½" and 3/8") with BFS, the modified asphalt with Gilsonite was used and the mixing temperature employed was 10 °C higher than the control HMA (BFS-21%-G-160). Compared with the control HMA, this mixture (BFS-21%-G-160) reached similar resistance to abrasion and higher resistance under monotonic loading and to moisture damage.

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