

# Behavior of the Dynamic Modulus and Fatigue in Asphalt Mixtures with Blast Oxygen Furnace Slag and Blast Furnace Dust

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## Abstract

Slag from a Blast Oxygen Furnace (BOF) is produced during the transformation of cast iron, coming from the blast furnace, into steel during the integrated steelmaking process, just as blast furnace dust (BFD) is produced during the transformation of the iron mineral into cast iron. These residues have generated environmental problems due to the accumulation and inadequate disposal thereof. Consequently, this study aims to analyze the use and behavior of the dynamic modulus and the fatigue in asphalt mixtures with partial (50 %) and total (100 %) substitution of the coarse aggregate for BOF slag and the fine aggregate for BFD. The results are compared with the behavior of a mixture elaborated with conventional aggregates. To achieve this objective, the chemical and physical properties of BOF and BFD were determined along with the optimum asphalt cement content, determined using the Ramcodes methodology. Tests were carried out to evaluate the physical characteristics, the dynamic modulus, and the fatigue of each type of mixture. The results of this study demonstrate adequate fatigue behavior and a slight reduction in dynamic modulus in mixtures with BOF and BFD. This allows us to deduce that the use of these residues is feasible and thereby to contribute to sustainable development and the protection of the environment.

## Keywords

blast furnace dust, blast oxygen furnace, dynamic modulus, fatigue, asphalt mixture

## 1 Introduction

During the steel manufacturing process, different residues are produced, among which are slags [1–3]. The most well-known are blast furnace slag (BFS), blast oxygen furnace slag (BOF) and electric arc furnace slag (EAF) [4]. Another residue that is produced during the manufacture of steel is blast furnace dust (BFD) [5].

BOF slag is produced in integrated steelmaking plants during the transformation process of the cast iron, coming from the blast furnace, to steel. The cast iron reacts with lime, silicates, aluminum oxides, magnesium oxides and ferrites depending on the quality of the steel that is produced [6]. BFD is produced during the transformation process of the iron mineral to cast iron in which this material, coke and limestone are melted at a temperature of

approximately 1500°C. During this process, gasses and fine particulate material are generated and recovered in the collectors [7].

Investigations have been carried out around the world, the majority of which have concluded that it is feasible to use slag as aggregate in the construction of roadways [8]. In Colombia studies have also been undertaken, but the use of BFD as a fine aggregate to replace natural aggregate (sand) has not been investigated.

In Colombia, the only integrated steelworks is Acerías Paz del Río S.A., located in the state of Boyacá, where approximately 7200 tonnes of BFD and 72000 tonnes of BOF slag are produced each year [9]. Due to the lack of utilization of these residues and their inadequate disposal,

an environmental problem arises. Taking this into account, the necessity to find an alternative use for these steelmaking residues emerges. Furthermore, the construction and maintenance of roadways increases the use of non-renewable materials such as limestone and sand, causing further negative impact to the environment through mining.

The aim of this study is to evaluate the feasibility of partially or completely replacing natural aggregates with BOF slag as coarse aggregate and BFD as fine aggregate in asphalt concretes, complying with the technical and environmental requirements.

In accordance with this, the investigation includes three stages. First, in order to understand the physical and chemical characteristics of the materials used, BOF slag, BFD and natural aggregates were characterized by X-ray fluorescence (XRF), in the scanning electron microscope (SEM) and by X-ray diffraction (XRD), establishing the chemical elements present and the microtopography. The physical and mechanical characterization was carried out following the ASTM [10–11] and INVIAS [12] standards, taking into account the tests for stony aggregates used in asphalt mixtures. Secondly, three types of mixture were designed and fabricated using the Ramcodes methodology [13]: one control mixture, prepared with natural aggregates (gravel and sand), and two mixtures in which the natural aggregates were partially and totally replaced by the residues utilized in this investigation. Void verification tests and stability and flow analyses were carried out to ensure compliance with the specifications [14]. Subsequently, tests were undertaken to determine the dynamic modulus and the fatigue laws. Finally, the results were analyzed and used to determine the viability of use for these residues in the manufacture of asphalt concrete for use in the construction of roadways.

## 2 Materials and methods

In this section, experimental studies are conducted to investigate the behavior of dynamic moduli and fatigue of asphalt concretes with BOF and BFD. The details of the materials used in the preparation of the mixtures and the details of the tests carried out as explained below.

### 2.1 Materials

Blast oxygen furnace slag in Fig. 1(a), and blast furnace dust in Fig. 1(b), were obtained from the *Acerías Paz del Río S.A.* steelworks; the limestone was selected as the coarse aggregate and sand as the fine aggregate for the reference mixture, these materials supplied by the Roca quarry in the municipality of *Monquirá* in the state of Boyacá.

The physical properties of these materials are shown in Table 1. The asphalt cement (bitumen) used was of an 80/100 penetration, coming from *IncoAsfaltos S.A.S.*, in Colombia. The results of the characterization tests were within the specification limits and are shown in Table 2. The asphalt mixture chosen for this investigation was an MDC-19, in accordance with the INV E-450-13 specifications, for an NT3 ( $ESALs > 5.0 \times 10^6$ ) level of transit [15].

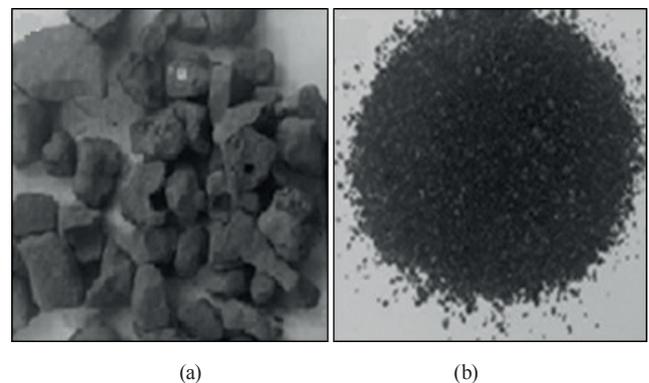


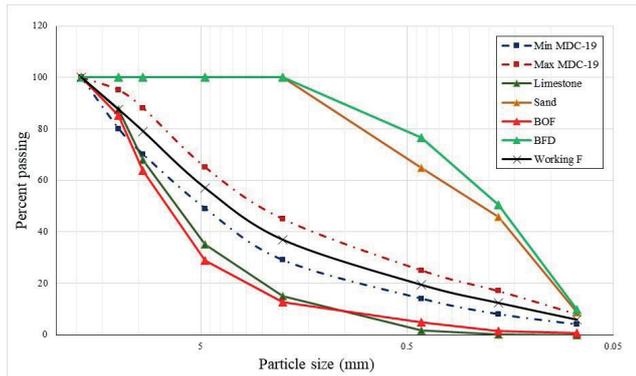
Fig. 1 Visual characterization of materials (a) BOF; (b) BFD

Table 1 Properties of the aggregates used (BOF, limestone, BFD, sand)

Properties	Coarse aggregate		Fine aggregate		Specification	Standard
	BOF	Limestone	BFD	Sand		
Abrasion in the Los Angeles machine (%)	19.8	19.5	N/A	N/A	<25	ASTM C 131
Abrasion in the Micro-Deval apparatus (%)	20	19.8	N/A	N/A	<20	ASTM D 6928
Soundness aggregates (%)	1.72	3.20	-	3.21	<18	ASTM C 88
Fractured particles (%)	91.4	94	N/A	N/A	>85	ASTM D 5821
Plasticity index (%)	N/A	N/A	NP	NP	NP	ASTM D 4318
Sand equivalent (%)	N/A	N/A	93.8	68.5	>50	ASTM D 2419
Gsb	2.468	2.593	2.363	2.722	-	ASTM C 127/128
Gss	2.564	2.605	2.496	2.743	-	
Gsa	2.729	2.625	2.727	2.779	-	
Absorption (%)	3.8	0.47	5.6	0.59	-	

**Table 2** Basic properties of asphalt cement

Properties	Measured values	Specification	Standard
Penetration (0.1 mm)	81.35	80-100	ASTM D 5-97
Ductility (cm)	120	>100	ASTM D 113
Softening point (°C)	50.5	>48	ASTM D 36
Flashpoint (°C)	245	>230	ASTM D 92
Viscosity at 60°C (P)	2336	>1000	ASTM D 2171

**Fig. 2** Particle size distribution of natural aggregates, BOF and BFD

The granulometric band of the MDC-19 mixture and the granulometry of the materials used are shown in Fig. 2.

## 2.2 Methods

### 2.2.1 Chemical characterization of the materials

Morphology and chemical composition of the aggregates. The gravel, slag, sand, and BFD particles were subjected to microscopic examination to characterize their shape and surface texture. The examination was carried out using a Leo 410 scanning electron microscope (SEM) with a vacuum chamber of 9.85E-5 Torr, current in the filament of 1.2 nA and voltage in the anode of 15 kV.

The evaluation of the chemical composition was performed using X-ray fluorescence analysis, employing a Rigaku Primus II sequential spectrometer with a rhodium tube and a 30-micron beryllium window.

With the goal of obtaining the phases present in the BOF slag and the BFD, an X-ray diffraction analysis was completed. This was carried out using Emyream equipment from the Panalytical brand, equipped with a copper tube, using the Bragg – Brentano configuration and with a solid state, high velocity detector, denominated PIXEL 3d 2 × 2, for the acquisition of data. This was set at an acceleration voltage of 45 kV, a current intensity of 40 mA and with a scanning angle ( $2\theta$ ) from 6.0996° to 81.98096°. This test is based on the relation that exists between the intensities of the diffraction peaks of a defined mineralogical phase (grouping of chemical elements).

### 2.2.2 Mixture design

The gradation chosen had a maximum nominal size of 19 mm and was designed following the Ramcodes method of design. In the specific case of asphalt mixtures, Ramcodes has a very powerful analysis tool; the polygon of voids [16]. The polygon of voids is a completely automated graphical construction which allows the optimum asphalt cement content to be obtained based on the void specifications and on the specific gravities of the aggregates and asphalt cement. Following this, verification is performed through the elaboration and testing of just three briquettes, in place of the 12 or 15 needed for the traditional procedures of the Superpave or Marshall methods, respectively. It has been found that the results obtained using this methodology are very similar to those obtained with the Marshall methodology [17].

In designing the mixtures, three types were initially considered. The first using conventional materials (limestone as the coarse aggregate and sand as the fine aggregate), identified as mix M1, the control mixture; the second substituting 50 % of the coarse aggregate with BOF slag and the same proportion of fine aggregate with BFD, identified as mix M2; the third completely replacing the coarse and fine aggregate for BOF slag and BFD respectively, labelled as mix M3.

### 2.2.3 Dynamic modulus

The latest trends in pavement structure design, for instance MEPDG, are fundamentally based on the dynamic modulus considering that this is a parameter that represents the behavior of the material under the load induced by vehicles [18]. The dynamic modulus can be determined and estimated by using laboratory tests or through mathematical models, the most well-known of which being that known as the Witczak dynamic model predictive equation, designed using the MEPDG guide framework [19]. Some laboratory test methodologies, which allow for the dynamic modulus to be determined, are regulated in international regulations such as EN 12697-26 [20], AASHTO T342 [21], ASTM D3496 [22] and ASTM D3494 [23].

To determine the dynamic modulus of the asphalt mixtures in this study, three cylinders of each type of mixture were elaborated and tested through the procedure contained in the prNE-12697-26 regulation at Annex C [24] in the Nottingham Asphalt Tester (NAT) equipment. The test cylinders were created with the working formula and compacted with the gyratory compactor in all cases. With this test, the dynamic modulus was determined for a Marshall-type test cylinder by way of the indirect tensile strength

principle. This principle states that, upon the application of the compressing force through the diameter of a cylindrical sample, tension is produced on the orthogonal diameter to which load is applied. In registering the vertical force applied and the horizontal deformation produced, the dynamic modulus is obtained.

Considering that the test is non-destructive, the samples were tested at 5°C, 25°C and 40°C and at a frequency of 10 Hz. Ten conditioning impulses were applied to allow the equipment to be adjusted and thereafter the load impulses were applied over the length of the first diametrical plane. This was then rotated by 90° and the procedure was repeated.

The dynamic modulus depends on the temperature of the test. Based on the values of the tests carried out and applying the minimum least squares regression technique, it fits into a mathematical formula of the type given in Eq. (1), said equation representing the behavior of the dynamic modulus for each mixture.

$$E = A * e^{B * T}, \quad (1)$$

where  $E$  is the dynamic modulus at temperature,  $T$  is the temperature of the mixture,  $A$  and  $B$  are regression constants.

### 2.2.4 Fatigue

Fatigue in asphalt concretes is a phenomenon associated with the loss of mechanical resistance under the effects of cyclical load below the breaking value. In flexible paving it is one of the principal deterioration mechanisms, which leads to an increase in deflections and a reduction in the support capacity of the layer of asphalt mixture [25–26].

Fatigue in asphalt mixtures occurs due to an increase in the number of cracks, themselves beginning as air cavities that are compressed during the compacting process and as defects in the asphalt concrete. The growth of these cracks may occur as adhesive and cohesive flaws within the mixture. Adhesive flaws occur in the thin layers of asphalt cement that cover the aggregates and they develop in the interface between the aggregate and the asphalt cement. Cohesive flaws occur within the asphalt cement in the thickest layers [27].

The goal of this test is to determine the number of cycles (of a determined load) necessary to arrive at the failure of a briquette. It was carried out under the standards set out in BS-EN 12697-24 Annex E [28], at a temperature of 20°C, a frequency of 2.4 Hz and under controlled stress conditions with the NAT (Nottingham Asphalt Tester) equipment. Fatigue tests can be performed under controlled

stress or under controlled strain, but results are usually expressed in terms of initial strain or tensile stress [29–30].

Eight test cylinders were elaborated for each type of mixture with the respective optimum asphalt obtained and its corresponding granulometric composition. The cylinders were divided into four groups, each group of two cylinders being subjected to test with distinct loads; in the range of 250 kPa to 350 kPa, respectively. The time until failure for each briquette tested was determined by the number of applications of load that caused the sample to break [31]. The stress in the center of the briquette was calculated with Eq. (2) and the maximum tensile strain was calculated from the Eq. (3).

$$\sigma_0 = \frac{2P}{\pi t \varphi}, \quad (2)$$

$$\varepsilon_0 = \left( \frac{2\Delta H}{\varphi} \right) \times \left[ \frac{1 + 3\mu}{4 + \pi * \mu - \pi} \right], \quad (3)$$

where  $\sigma_0$  is the tensile stress at the center of the specimen (MPa),  $P$  is the maximum load (N),  $t$  is the thickness of the specimen (mm),  $\varphi$  is the diameter of the specimen (mm),  $\varepsilon_0$  is the tensile strain at the center of the specimen ( $\mu\varepsilon$ ),  $\Delta H$  is the horizontal strain (mm), and  $\mu$  is the Poisson's ratio.

To obtain the fatigue laws for the prediction of the fatigue life, Eq. (4), by Wöhler [30–32], was used.

$$\sigma_0 = k \left( N_f \right)^{-n}, \quad (4)$$

where  $N_f$  is the number of load cycles until fatigue failure,  $k$  and  $n$  are constants of the material and  $\sigma_0$  is the tensile stress at the center of the sample.

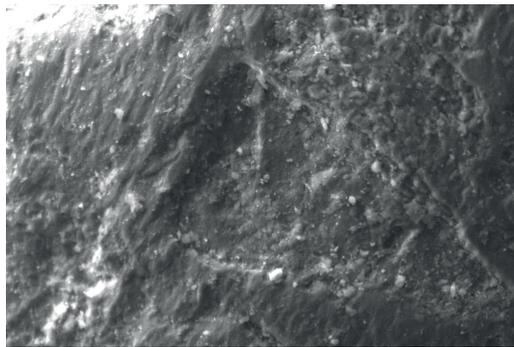
## 3 Results and discussion

### 3.1 Chemical characterization of the materials

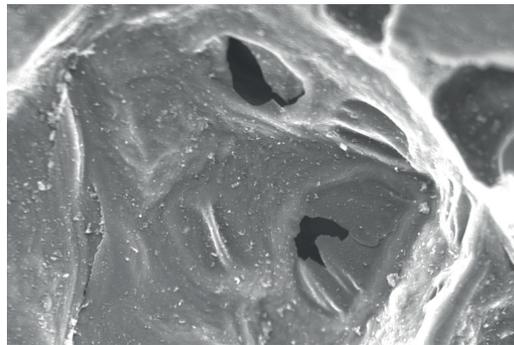
#### 3.1.1 Microscopic morphology

Fig. 3 presents SEM micrographs of the materials used as fine aggregates, showing the shape and texture of the surface of the particles of sand and BFD. Fig. 3(a) contains the SEM micrograph of the sand, indicating a rough surface texture with angled edges. Fig. 3(b) is the SEM micrograph of the BFD, which shows a coarse and porous surface texture with sub-angular rounded edges that have a strong bonding characteristic with the asphalt cement.

Fig. 4(a) shows the SEM micrograph of the gravel, indicating a rough surface texture with angular and sub-round shaped edges. Fig. 4(b) presents SEM micrograph of the BOF slag which has a rough texture including less angled

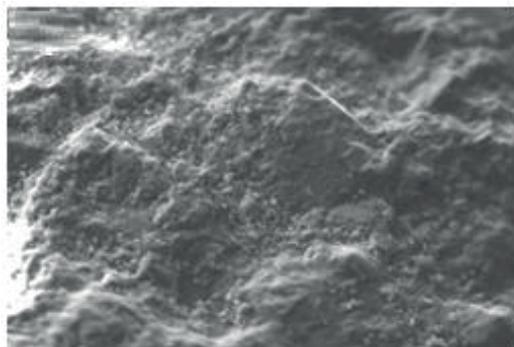


(a)

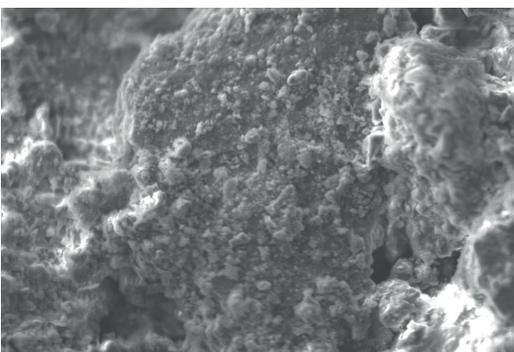


(b)

**Fig. 3** SEM micrographs of the fine aggregates at 1.00 KX (a) sand; (b) BFD



(a)



(b)

**Fig. 4** SEM micrographs of the coarse aggregates at 1.00 KX; (a) gravel; (b) BOF

and more rounded edges with superficial pores and being rougher than the natural aggregate. These characteristics of BOF slag can be associated with a strong bond and excellent interfacial zone for asphalt cement.

### 3.1.2 Chemical composition

The chemical composition of the BOF slag, gravel, sand, and BFD that was detected by XRF is shown in Table 3. The main chemical constituents of the gravel are CaO, SiO<sub>2</sub> and Al<sub>2</sub>O<sub>3</sub>. BOF slag is produced when converting cast iron from the blast furnace into steel and the chemical composition depends on the quality and type of steel being manufactured.

The main components of BOF slag are CaO, Fe<sub>2</sub>O<sub>3</sub>, SiO<sub>2</sub> and Al<sub>2</sub>O<sub>3</sub>. When comparing the gravel and the slag, it can be seen that the main component of the gravel is CaO at more than 50 % due to its limestone origin. Although Fe<sub>2</sub>O<sub>3</sub> also appears as a component in the gravel, the percentage by weight is far inferior to that in the slag. CaO content can be associated with better adhesion between the aggregate and the asphalt cement [33]. BOF slag will demonstrate good adhesion with asphalt cement due to its level of CaO content.

The CaO/SiO<sub>2</sub> relation considers the alkalinity of the aggregate, higher relations leading to better adherence of the aggregate and the asphalt cement [34]. The BOF slag has a CaO/SiO<sub>2</sub> relation of 4.3, higher than that of the gravel at 3.8. As a consequence, BOF slag has greater affinity to the asphalt cement. In the same way, BFD has a CaO/SiO<sub>2</sub> relation of 0.9, while the sand showed a relation of 0.005. BFD therefore has a stronger affinity with the asphalt cement than the sand.

The application of the X-ray diffraction (XRD) technique allows for the quantification of the phases that make up BOF slag and BFD. In Fig. 5, the diffractograms of the materials are shown.

**Table 3** Chemical components of BOF slag, limestone, BFD, and sand

Component (% in weigh)	BOF	Limestone	BFD	Sand
MgO	2.70	3.80	1.00	1.60
Al <sub>2</sub> O <sub>3</sub>	4.90	9.30	3.60	7.30
SiO <sub>2</sub>	10.80	16.60	5.50	88.70
P <sub>2</sub> O <sub>5</sub>	2.10	-	0.20	-
CaO	46.80	63.40	4.95	0.46
MnO	2.00	0.17	3.32	-
Fe <sub>2</sub> O <sub>3</sub>	28.80	3.04	77.50	0.99
Others	1.73	3.63	0.90	1.00

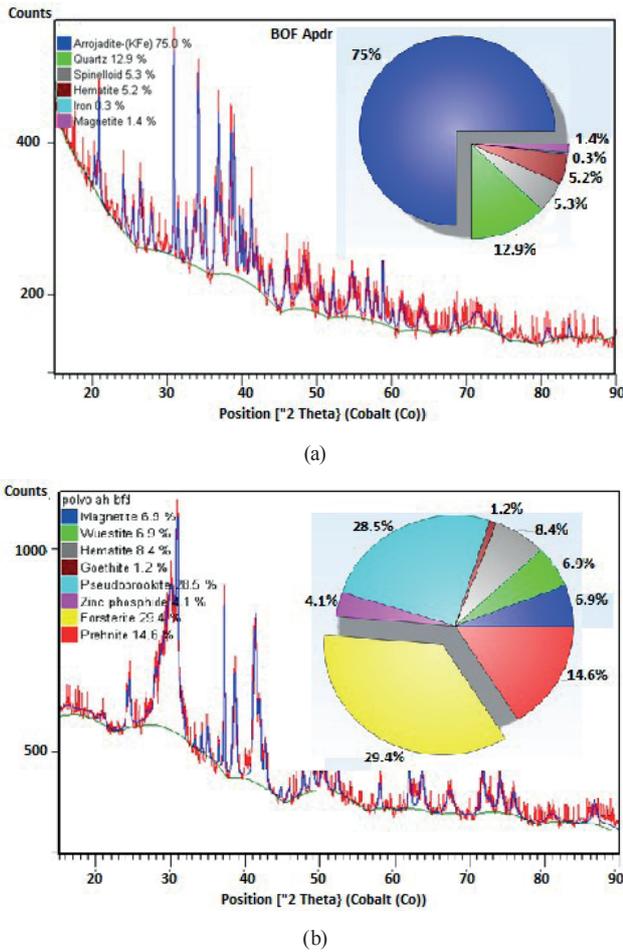


Fig. 5 Diffractograms for: a) BOF; b) BFD

The sample of BOF slag has three main phases: arrojadite (KFe), quartz (SiO<sub>2</sub>) and hematite (Fe<sub>2</sub>O<sub>3</sub>); there was also an observed peak of magnetite (Fe<sub>3</sub>O<sub>4</sub>). The sample of BFD had the following principal phases: forsterite (Mg<sub>2</sub>SiO<sub>4</sub>), prehnite (Ca<sub>2</sub>Al(Si<sub>3</sub>Al)O<sub>10</sub>(OH)<sub>2</sub>) and iron titanium oxide

(Fe<sub>2</sub>TiO<sub>5</sub>); there were also peak observed corresponding to magnetite (Fe<sub>3</sub>O<sub>4</sub>), hematite (Fe<sub>2</sub>O<sub>3</sub>) and wustite (FeO).

The identification of the phases found in the BOF slag utilized in this study accord with that reported in similar previous investigations and specifically in studies by Waligora et al. [35] and Mahieux et al. [36] who identified magnetite (Fe<sub>3</sub>O<sub>4</sub>) and quartz (SiO<sub>2</sub>). In these studies, calcite (CaCO<sub>3</sub>) and lime (CaO) were also identified, phases not identified in the sample of BOF slag utilized in this investigation. In the investigations carried out by Hu et al. [7] and Zhang et al. [37] phases of wustite (FeO), hematite (Fe<sub>2</sub>O<sub>3</sub>) and magnetite (Fe<sub>3</sub>O<sub>4</sub>) were found in the BFD just as in the simple analyzed in this study.

### 3.2 Design of the mixtures

The first step consisted of carrying out the granulometric dosage for each mixture. Next, the optimum binder content is determined using the Ramcodes methodology considering the characterization results of the aggregates and the binder. This methodology consists of realizing an analysis of the voids in the mixture, known as air voids (Va), voids in the mineral aggregate (VMA) and voids full of asphalt (VFA), each of which relates to the behavior of the compacted mixtures. Voids are a function of the percentage of asphalt cement (% Pb) and of the specific gravity bulk of the mixture (Gmb), which are represented in isoline maps for the values permitted in the specifications. The intersection of these lines produces a graphical construction in the % Pb-Gmb space, which gives rise to the void polygon. The centroid of said polygon establishes the optimum content of binder and the specific gravity bulk (density). In Fig. 6 the void polygons are shown for mixture M1.

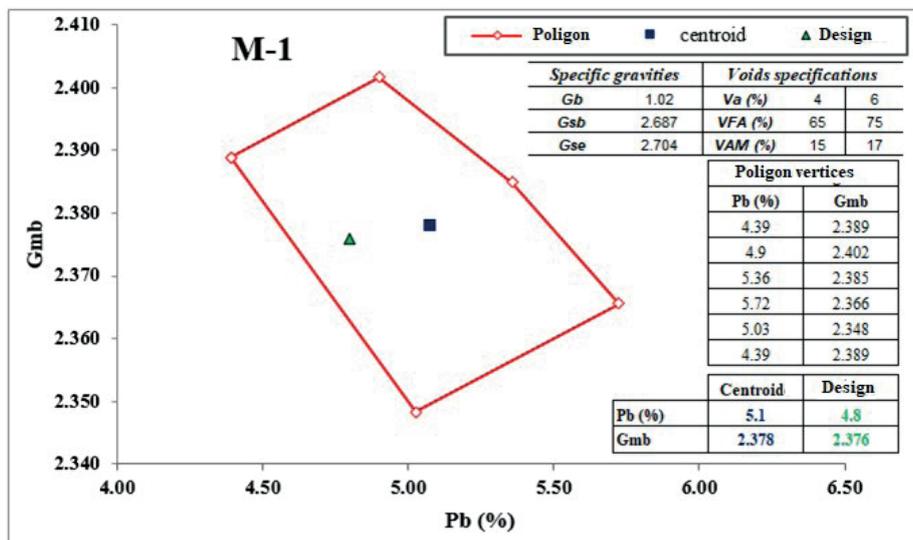


Fig. 6 Void polygon for M1 mixture

Following the steps of Ramcodes, three test cylinders were produced with the optimum asphalt content and aggregate combination. On these, stability and flow tests were carried out along with density and void analysis. The average of the results obtained in the tests shows the flow value (3.6 mm) to not comply with the requirement for the specified level of transit (2.0 to 3.5 mm). Considering the recommendation of Sánchez-Leal [38] and considering that the flow value was very close to the upper limit of the requirement, a further test was carried out on three new test cylinders, lowering the asphalt content to 4.8 % with the same combination of aggregates. With this percentage of asphalt, all requirements were satisfied. Table 4 shows the results of the preliminary design for all of the mixtures.

Mixture M2 and M3, elaborated with BOF slag and BFD, demonstrated an increase of 1.7 % and 2.1 % respectively in the asphalt content with respect to the asphalt content in the base mixture (M1), with the asphalt content in mixture M3 being the highest of all the mixtures analyzed. This increase can be attributed to the characteristics of porousness found in the BFD and, to a lesser extent, in BOF slag, which can be confirmed by the absorption percentages found for these materials, 5.65 % and 3.80 % respectively, each of which is higher than the absorption of the conventional materials (gravel and sand). Consequently, the greater the quantity of BOF slag and BFD used, the greater the content of asphalt, reason for which the mixture fabricated with 100 % slag BOF and BFD (M3) showed the greatest asphalt content.

### 3.3 Dynamic modulus

The modulus is an important property of asphalt concrete in any mechanistic design and analysis procedure for flexible pavements. The dynamic modulus is the property of the material required in the AASHTO empirical design method and is an important initial parameter in the mechanistic-empirical design guide. This parameter has been deemed a fundamental element in the design of pavements and, due to this, has been introduced as an element that rationally characterizes the force-deformation behavior of the material making up the structure [39].

Fig. 7 presents the modulus trend lines for each of the samples in this study. Modulus values are shown for a mixture temperature of 20°C considering the temperature at which the mixture will be operating in a region with a TMAP of 13°C. The dynamic modulus of the base mixture (M1) is 3351 MPa, this being the highest value of all mixtures. Mixtures M2 and M3 gave the lowest modulus values at 2480 MPa and 1350 MPa, respectively.

The lower modulus in the M3 mixture can be attributed to the mixture being elaborated with 100 % BOF slag as the coarse aggregate, this material demonstrating a weak behavior compared to gravel. In the same way, this mixture was fabricated with 100 % BFD as the fine aggregate and the optimum percentage of asphalt cement in the mixture increased.

Mixtures M2 and M3, which were fabricated with BFD and BOF slag as partial or complete aggregate replacements, show lower dynamic modules at 20°C than mixture M1.

**Table 4** Results of the initial design of the mixtures

Characteristic	Unit	Value			INVIAS Specification
		M-1	M-2	M-3	
Aggregate content (by weight)	%	95.2	93.5	93.1	-
Asphalt content (by weight)	%	4.8	6.5	6.9	-
Specific gravity bulk ( $G_{mb}$ )	g/cm <sup>3</sup>	2.376	2.371	2.340	-
Maximum Specific Gravity ( $G_{mm}$ )	g/cm <sup>3</sup>	2.510	2.500	2.470	-
Stability	N	11967	10561	11372	9000
Flow (mm)	mm	3.35	3.45	3.48	2.0–3.5
Ratio: Stability / flow	kN/mm	3.57	3.03	3.27	3.0–6.0
Voids with air ( $V_a$ )	%	5.15	5.19	5.10	4.0–6.0
Voids in mineral aggregates (VAM)	%	15.80	15.97	16.05	>15.0
Asphalt-filled voids (VFA)	%	67.42	67.51	68.23	65–75
Absorbed asphalt ( $P_{ba}$ )	%	0.24	1.99	2.28	-
Effective asphalt ( $P_{be}$ )	%	4.57	4.64	4.77	-
Ratio: filler / effective binder	-	1.10	1.10	1.00	0.8–1.2

However, considering the gradient of the trend lines, at higher temperatures, these mixtures have a higher modulus than the base mixture, as shown in Fig. 7. The aforementioned can be attributed to the temperatures at which BOF slag and BFD are produced, something which gives the materials thermal energy absorption capacity and can augment the effect of heat retention in the asphalt concrete [40].

### 3.4 Fatigue

Fatigue life is defined as the number of load cycles until failure ( $N_f$ ) and represents the capacity of the mixture to support the cyclical loads of transit [41]. Fig. 8 shows the tensile stress at a given number of cycles for the mixtures being studied. It also includes the fatigue law equations and

the correlation coefficient ( $R^2$ ), indicating the existence of a statistical correlation between the results obtained to determine each fatigue law, given that the  $R^2$  coefficients are higher than 0.84.

As can be seen in Fig. 8, mixtures M2 and M3 have similar gradients in their fatigue laws, which are less steep than in the fatigue law of mixture M1. For this reason, for low tensile stress levels, M2 and M3 mixes have better fatigue life than M1 mix. For higher tensile stress levels, M1 mix has a greater fatigue life [30, 42, 43].

Comparing mixtures M2 and M3, mixture M3 has a slightly higher slope in its fatigue law than mixture M2. Therefore, for low stress levels mixture M2 has a better fatigue life and for high efforts mixture M3 shows a better fatigue life.

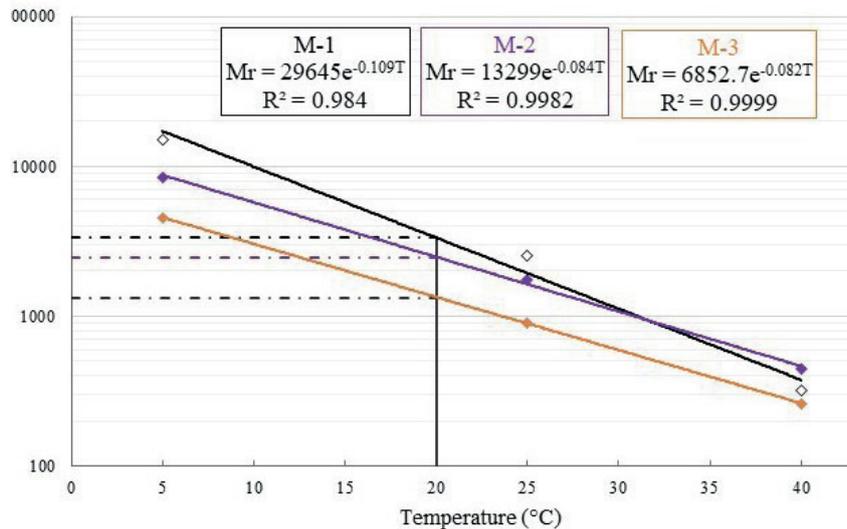


Fig. 7 Dynamic modulus master curves

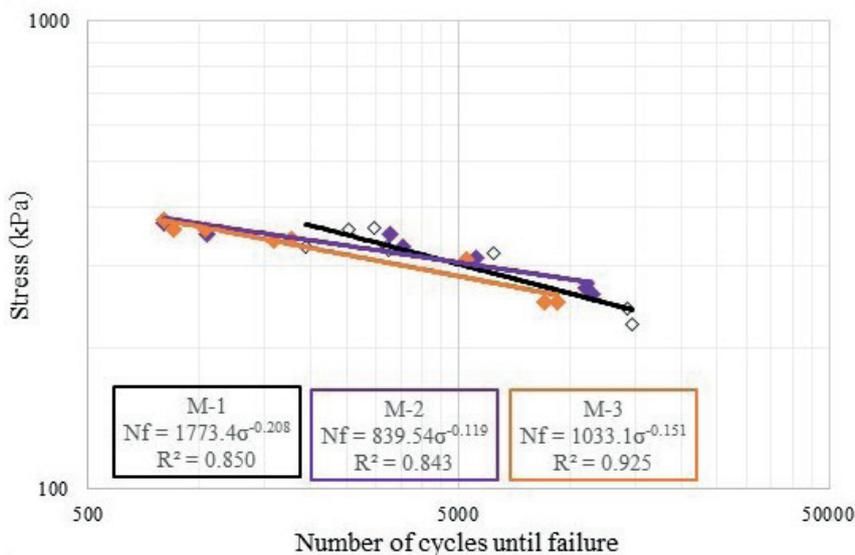


Fig. 8 Laws of fatigue for mixtures

Considering the characteristics of the fatigue test under controlled effort, the mixtures with greater stiffness such as M1 support a higher level of tensile stress for low load cycles, as the load cycles are increased these mixtures support lower levels of stress tensile. The opposite occurs with mixtures that have less stiffness, such as M2 and M3 mixtures, for low load cycles they support low levels of tensile stress and as load cycles are increased, they will support higher stress levels of voltage than the M1 mixture. The above coincides with what was found in the literature: if the stiffness of the mixture increases, the number of load cycles (fatigue life) also increases; but there comes a time when stiffness is detrimental to fatigue in asphalt mixes [44].

Fig. 9 shows the tensile stress for the mixtures and for three different load cycles (Nf) calculated from the extrapolation of the trend lines of the fatigue laws of each mixture. For  $5.0 \times 10^5$  load cycles, mixture M2 presented the greatest tensile stress ( $\sigma_o = 176$  kPa) which is 56 % higher than the tensile stress of the base mixture (M1) for the same amount of load cycles. Similarly, for  $5.0 \times 10^6$  load cycles, the tensile stress of mixture M2 greater with respect to mixture M1 for the same number of load cycles. Continuing the trend, for  $5.0 \times 10^7$  load cycles, mixture M2 presented the tensile stress three times greater than that of the mixture M1 and for the same number of load cycles. Mixture M3 presented lower tensile stresses than the mixture M2 but higher than the mixture M1.

Similarly, the fatigue life of the base mixture and the other mixtures at different levels of tensile stress is shown in Fig. 10. It can be observed that for a stress of  $\sigma_o = 200$  kPa, mixture M2 has a higher fatigue life than the base mixture (M1). As the stress increases, at high stress, it shows a lower fatigue life than the base mixture. The behavior of the M3 mixture is similar, that is, for low

tensile stress levels it presents better fatigue life than the M1 tensile mixture and for high stress levels the fatigue behavior of the M1 mixture is better.

Mixture M2 has a better fatigue life at low stress than the fatigue life of the base mixture. The M3 mixtures have a lower fatigue life than the base mixture. As a result, it can be reasoned that the partial replacement of natural aggregates for BOF slag and BFD in asphalt concretes improves the fatigue life of the mixtures, which can be attributed to the surface texture of the slag, the force of the union between the asphalt cement and the slag due to the high alkalinity of these materials, and to this mixture being prepared with a higher percentage of asphalt cement [45].

#### 4 Conclusions

The characterization tests of the aggregates showed optimal characteristics. For the BOF slag, the wear on the gravel the Los Angeles machine is below the maximum allowed at 5.5 %, while that of the BOF slag at 5.2 %. This indicates that they are hard and abrasion resistant aggregates. In the test of resistance of coarse aggregate to abrasion degradation, using the micro-deval apparatus, the results are very close to the requirement to be used as materials in asphalt mixtures, the value reported for gravel is below the maximum required in 0.2 % and the value for the BOF slag is the limit. In respect of the blast furnace dust (BFD), the test results also showed favorable characteristics compared with the natural aggregate (sand). Among the results, it can be observed that BFD is a non-plastic material and, in the equivalent test to sand, gave results 25.8 % better with respect to the natural aggregate. The other requirements established are within the ranges stipulated in the regulation. Additionally, the industrial origin of the BOF slag and BFD means that their composition is homogenous and free of impurities.

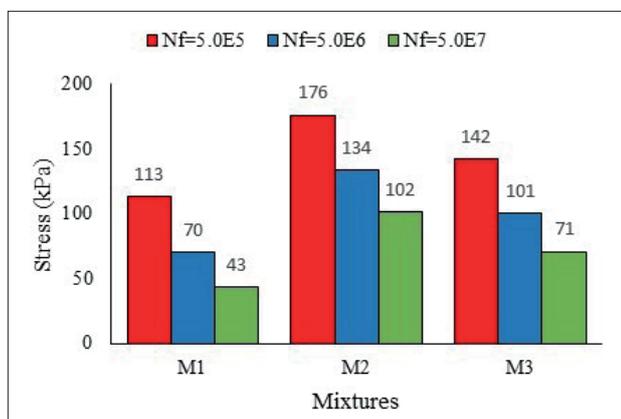


Fig. 9 Tensile stress for three different load levels

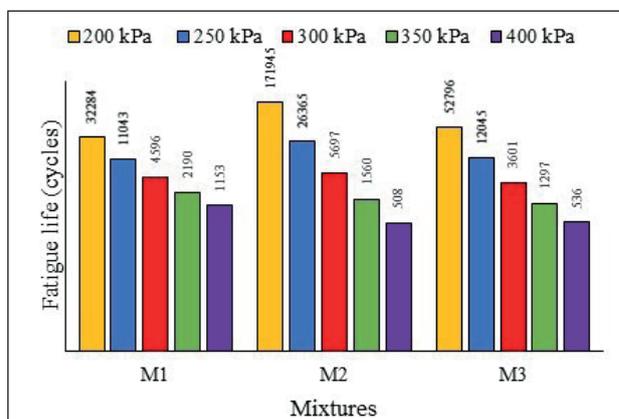


Fig. 10 Fatigue life at different stress

Steel manufacturing has a variety of environmental effects. The main impacts arise from the use of energy and the prime materials, and the generation of residues like slags, dusts and sludge which affect the environment as they have very little use, their accumulation evident in storage areas. Through the use of steelmaking residues like BOF slag and BFD in the fabrication of asphalt concretes for pavements, a positive impact would be produced as the accumulation of these materials would lessen.

The greater absorption by BOF slag and BFD when compared to natural aggregates demonstrates the necessity to increase the quantity of asphalt cement to guarantee coverage of the aggregates and ensure the appropriate behavior of the mixture. The optimum content of asphalt cement for mixture M2, in which partial substitution of the natural aggregates took place, increased by 1.7 % with respect to the base mixture (M1). The optimum content of asphalt cement for mixture M3, in which there was a total substitution of the natural aggregates, increased by 2.1 % with respect to the base mixture, and by 0.4 % with respect to mixture M2.

The fall in the stability values and the increase in the flow values may be due to the higher asphalt cement content. The stability value of mixture M2 decreased by 11 % and that of mixture M3 by 13 % with respect to the stability value of the base mixture. The stability value of mixture M3 fell 1.5 % with respect to mixture M2. Notwithstanding, the stability values for mixtures M2 and M3 were 17 % and 15 % higher than the minimum required value. The flow values, although showing an increase with respect to the base mixture, are within the range established by the regulation.

In terms of the dynamic modulus obtained for these mixtures, they are appreciably lower than the modulus obtained for the base mixture. The lowest modulus

obtained for the mixtures tested was that of mixture M3, having a value 60.3 % lower than that of the base mixture. This may be due to the increase in the optimum content of asphalt cement and the presence of BOF slag as the coarse aggregate considering its surface texture. In comparison, the modulus of mixture M2 is 26 % lower than that of the base mixture. This may be due to the combination of the natural and alternative aggregates, on which the impact of the increase in the optimum content of asphalt cement is not so prominent. In both cases, the decrease in the modulus value, at a temperature of 20 °C, affects the sizing of the pavement structure.

Conversely, mixture M2 has a better fatigue life with low stress than the base mixture. As the level of stress was increased, this mixture evidenced a lower fatigue life. Additionally, considering the number of load cycles, mixture M2 resists greater tensile stress. This may be due to the increase in the optimum asphalt cement content having in mind its elastic properties. Mixture M3 presented a lower fatigue life with low tension compared to the mixture M2, although at high tension, this mixture had a greater fatigue life than the mixture M2 but less than the fatigue life of the mixture M1.

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