Civil Engineering Infrastructures Journal, 52(1): 155 – 166, June 2019
Print ISSN: 2322-2093; Online ISSN: 2423-6691
DOI: 10.22059/ceij.2019.259125.1486

Electric Arc Furnace Slag and Blast Furnace Dust, Use for the Manufacture of Asphalt Concrete for Roads

Ochoa, R.[1*] and López, A.[2]

[1] Ph.D. Candidate, Faculty of Engineering, Universidad Pedagógica y Tecnológica de Colombia, Tunja, Colombia.
[2] Associate Professor, Faculty of Engineering, Universidad Pedagógica y Tecnológica de Colombia, Tunja, Colombia.

Received: 29 May 2018; Revised: 20 Jan. 2019; Accepted: 22 Jan. 2019

ABSTRACT: This paper analyzes how feasible it is to use electric arc furnace slag as coarse aggregate, and blast furnace dust as fine aggregate in the manufacture of hot asphalt concrete for roads. Three mixtures were designed using the Ramcodes methodology, the M1 mixture of control with conventional materials, the M2 mixture replacing 50% and the M3 mixture replacing 100% of the conventional aggregates, which were submitted to tests to evaluate the susceptibility to moisture damage and plastic deformation, as well as others to determine the resilient modulus and the fatigue laws for each type of mixture. The mixtures with EAF and BFD presented better mechanical characteristics than the mixture with natural aggregates, met the acceptance requirements and the results of the performance tests are within the required requirements.

Keywords: Asphalt Concrete, Blast Furnace Dust, Electric Arc Furnace Slag, Ramcodes.

INTRODUCTION

During the steelmaking process, different wastes are produced, including slag. The best known are blast furnace slag (BF) (Askarinejad, 2017), blast oxygen furnace slag (BOF) and electric arc furnace (EAF) (Parish et al., 2014). Another residue produced during the manufacture of steel is blast furnace dust (BFD) (Kambole et al., 2017). EAF slag is produced during the steelmaking process from scrap in the electric furnace in semi-integrated steel mills (Loaiza and Colorado, 2018). BFD powder is produced during the process of transforming iron ore into pig iron in the blast furnace in integrated steel mills.

Investigations around the world have concluded that it is feasible to use slag in the manufacture of asphalt mixtures (Pasetto et al., 2017; Masoudi et al., 2017). The purpose of this study was to ratify and implement the use of BFD powder as fine aggregate.

In Colombia, the only integrated steel mill is *Acerías Paz del Río S.A.*, located in the Department of Boyacá, where the production of BFD powder is 7,200 tons per year. The EAF slag, used in the present study, was supplied by the steelmaker Gerdau-Diaco, also located in the Department of Boyacá, that produces approximately 60000 tons per year. Due to the little use of this waste, the environment is put at risk. Therefore, it is necessary to look for an alternative use to slag

* Corresponding author E-mail: alfonso.lopez@uptc.edu.co

produced in the department of Boyacá.

In addition, the increase in construction and maintenance of roads increases the use of non-renewable natural aggregates, such as limestone and sand. The exploitation of these materials causes another negative impact on the environment.

The objective of this work was to evaluate the feasibility of partially or totally replacing the natural aggregates with EAF slag and BFD powder, as coarse aggregate and fine aggregate respectively, complying with technical and environmental requirements. The total substitution with EAF is considered taking into account that in Colombia this material is waste, since it has no use and is causing pollution, the acquisition cost is low and from the economic point of view this substitution will be viable. To use this waste, it was necessary to know its physical and chemical characteristics. Therefore, the investigation included three stages.

First, the EAF slag, the BFD powder and the natural aggregates were characterized with X-ray fluorescence (XRF) and in the scanning electron microscope (SEM), obtaining the chemical elements present and microtopography. Additionally, they were characterized physically and mechanically in accordance with ASTM standards taking into account the tests for stone aggregates to be used in asphalt mixes.

Secondly, three types of mixtures were designed and manufactured with the Ramcodes methodology (Skaf et al., 2017), the control mixture identified as M1 that had natural aggregates (limestone as coarse aggregate and sand as fine aggregate), the mixture identified as M2 that substituted the limestone with EAF and sand with BFD in a 50%, and the M3 mixture that replaced both limestone and sand with EAF and BFD in its entirety. Void verification tests and stability and flow analysis were performed to verify compliance with specifications (Sánchez et al., 2002).

Finally, performance tests of the asphalt mixtures were carried out, such as susceptibility to humidity, resistance to permanent deformation, determination of the resilient modulus, and fatigue laws. The results were analyzed and used to determine the feasibility of using this waste in the manufacture of asphalt concrete for use in road construction.

MATERIALS AND METHODOLOGY

Materials

The materials used in this investigation were: limestone and sand as conventional natural aggregates, EAF slag and BDF dust (Figure 1) as alternative aggregates. Its properties of origin, consensus and routine are shown in Table 1. The asphalt cement used was AC 60-70, from IncoAsfaltos S.A.S., in Colombia. Its verification results are shown in Table 2, which are within the limits of the specification. The asphalt mixture chosen for the development of the investigation was a maximum size of 19 mm (MDC-19) for a traffic level NT3 (ESAL's (8.2 ton) > 5.0×10^6).

The gradation of all the mixtures studied was the same and chosen according to the specifications INVIAS (INVIAS, 2013) for hot dense mixtures type 19 (MDC-19), as shown in Figure 2.

METHODOLOGY

Chemical Characterization of Aggregates

To determine the chemical composition of the aggregates used, X-ray fluorescence was used, quantitatively evaluating the elements of EAF and BFD to compare them with those of limestone and sand. Scanning Electron Microscopy (SEM) was used to determine the morphology and obtain the digital topographic images of the EAF and BFD samples.

The design and determination of the optimum content of asphalt cement (AC) was carried out following the Ramcodes methodology. It is a methodology developed by the engineer Freddy J. Sánchez-Leal since 1998 which has been successfully applied in the design and quality control of compacted soils for structural fillings and roads, as well as for the design and production control of asphalt mixtures. In the particular case of asphalt mixtures, RAMCODES has two very powerful analysis tools, such as the gradation chart (Sánchez-Leal, 2007) and the void polygon (Sánchez-Leal et al., 2011).


(a)

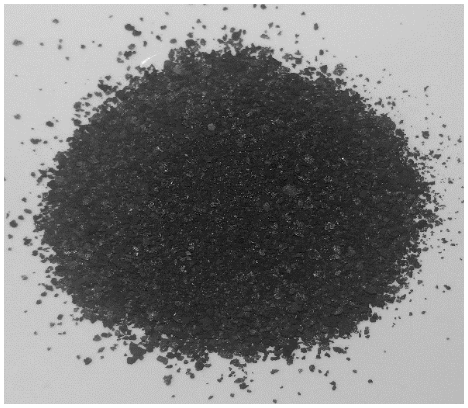

(b)

Fig. 1. a) EAF, b) BFD

Table 1. Origin, consensus and routine properties of the aggregates used (EAF, limestone, BFD, sand)

Properties	Coarse EAF	Aggregate limestone	Fine BFD	Aggregate sand	Specification	Standard
Loss Angeles abrasion (%)	20	20	N/A	N/A	<25	ASTM C 131
Degradation (micro-deval) (%)	20	20	N/A	N/A	<20	ASTM D 6928
Losses solidity test (%)	1.72	3.20	-	3.21	<18	ASTM C 88
Fractured faces (%)	99.5	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 2919
Gsb	3.470	2.593	2.363	2.722	-	ASTM C 127/128
Gsss	3.508	2.605	2.496	2.743	-	
Gsa	3.606	2.625	2.727	2.779	-	
Absorption (%)	1.09	0.47	5.6	0.59	-	

Gsb: bulk specific gravity, Gsss: saturated and superficially dry gravity, Gsa: apparent specific gravity

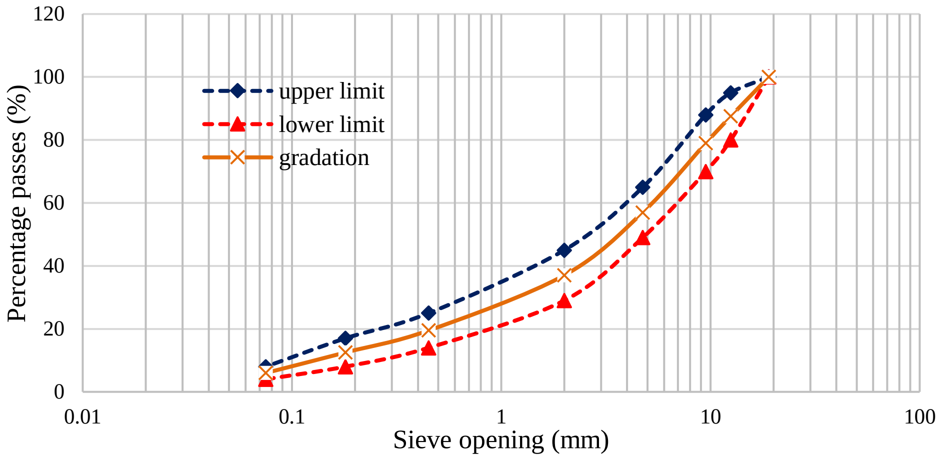


Fig. 2. Granulometry of the mixtures

Table 2. Basic properties of asphalt cement

Properties	Measured values	Specification	Standard
Penetration at 25 °C (0.1 mm)	67.2	60 - 70	ASTM D 5-97
Ductility, 5 cm/min, 25 °C (cm)	120	> 100	ASTM D 113
Softening point (°C)	49	> 48	ASTM D 36
Flashpoint (°C)	248	> 230	ASTM D 92
Viscosity at 60 °C (P)	158	> 150	ASTM D 2171

The gradation chart is an analytical environment in which one or more granulometries of asphalt mixtures can be represented simultaneously. Mechanical or hydraulic responses or production costs can be associated to these, allowing the optimization of the use of the raw material in the production of asphalt mix. On the other hand, the void polygon is a completely automated graphic construction that allows an optimum content of asphalt cement based on the specifications of voids and on the specific gravities of aggregates and asphalt cement, verifiable only with the elaboration and testing of three briquettes.

The empty polygon produces the same result with three briquettes, just as the Marshall method (Ochoa Díaz, 2012; Ochoa and Grimaldo, 2018), with the polygon, four and five different combinations of aggregates could be evaluated with the same time and resources with which a single combination would be evaluated using the aforementioned methods. This has great advantages for scientific research.

Performance Tests for Asphalt Mixtures

Susceptibility to Humidity

Moisture damage in asphalt mixtures can be defined as the progressive loss of strength and durability caused by the presence of water at the interface asphalt-aggregate cement or within asphalt cement (Lytton et al., 2005; Tan and Guo, 2013). The test was carried out using the indirect tensile test on specimens of 100 mm in diameter and 62.5 mm in height, which evaluates the change in tensile strength resulting from the effects of saturation and accelerated conditioning to water on asphalt mixtures compacted in laboratory. The test was carried out following the procedure of the ASTM D4867 standard; six test pieces were prepared for each type of mixture, three to be tested in dry and three to be tested after partial saturation. The wet group samples were taken to a water bath for 24 hours at a temperature of 60 °C; after said time, the two groups of test pieces were submerged in a water bath at 25 °C for one hour. Indirect tensile strength was determined using Eq. (1) (Taherkhani and Afroozi, 2017).

$$R_T = \frac{2000P}{\pi h D} \qquad (1)$$

where R_T: is tensile strength (kPa), P: is Maximum applied load (N); h: is thickness of the specimen (mm) and D: is diameter of the specimen (mm).

The tensile strength ratio (RRT) was calculated as the ratio of the average resistance to the tension of the water conditioned subgroup (RTH) and the average resistance to the tension of the subgroup maintained in dry (RTS), as expressed in Eq. (2).

$$RRT = \left[\frac{R_{TH}}{R_{TS}}\right] * 100 \qquad (2)$$

Susceptibility to Plastic Deformation

Plastic deformation is one of the main faults in asphalt mixtures and is the result of the combined effect of load repetitions and high temperatures (Tarefder et al., 2011; Zhu et al., 2016). The plastic deformation resistance test was performed to evaluate the resistance to permanent deformation

(Taherkhani and Arshadi, 2018). The test was carried out in accordance with the European standard EN-12697-22, using the "Wheel Tracking Test" equipment. The test was carried out at a constant temperature of 60 °C, passing a metal wheel of 20 cm in diameter, equipped with a tread of solid rubber 5 cm wide and 2 cm thick, which exerts a contact pressure on the surface of the test piece of 900 KN/m^2.

The total deformations were measured in minutes 1, 3 and 5 starting from the beginning of the test, then every 5 minutes until completing 45 minutes, and then measuring every 15 minutes until the end of the test after 120 minutes. From the deformations corresponding to the different times, the mean deformation speed corresponding to the time intervals was calculated with the previous results by means of Eq. (3).

$$V_{t2}/V_{t1} = \frac{d_{t2} - d_{t1}}{t_2 - t_1} \quad (3)$$

where V_{t2}/V_{t1}: is average speed of deformation, in the time interval between t_1 and t_2 (µm/min), d_{t1} and d_{t2} are deformations at t_1 and t_2 respectively (µm), t_1 and t_2: are times in the established time (min).

Resilient Module

The resilient module test was performed on the NAT (Nottingham Asphalt Tester) equipment at a frequency of 10 Hz and at three different temperatures (5, 25 and 40 °C). This test was determined using the procedure described in ASTM D7369-11. The test consisted of the application of 10 initial charging pulses of conditioning, and subsequently 5 load impulses were applied to the briquette for the determination of the module along the first diametral plane. Once this first calculation of the module was made, the briquette was rotated 90° and the described procedure was repeated.

The team offered the calculated module for each of these, made with Eq. (4).

$$S_m = \frac{F * (\mu + 0.27)}{z * h} \quad (4)$$

where S_m: is measured resilient module (MPa), F: is maximum value of vertical load applied (N), z : is amplitude of the horizontal deformation obtained during the load cycle (mm), h: is measured thickness of the briquette (mm) and μ: is Poisson coefficient (0.35).

Finally, the measured module is adjusted to a load surface factor of 0.6 with Eq. (5)

$$S'_m = S_m * [1 - 0.322 * (log(S_m) - 1.82) * (0.6 - k)] \quad (5)$$

where S'_m: is resilient module, (MPa), k: is load surface factor measured and S_m: is measured resilient module (MPa).

Fatigue Resistance

The purpose of this test was to determine the number of cycles (of a certain load) necessary to reach the failure of a briquette and was carried out with the BS-EN 12697-24 Annex E. It was carried out at a temperature of 20 °C, at a frequency of 2.5 Hz and under controlled deformation using the NAT (Nottingham Asphalt Tester).

Eight briquettes were manufactured with the optimum asphalt percentage obtained and its corresponding granulometric composition. The elaborated briquettes were divided into four groups, which were subjected to the test with different loads: 250 kPa, 300 kPa, 320 kPa and 350 kPa correspondingly. The life of each briquette subjected to this test was determined until its break from the number of loading applications that cause briquette breakage. The stress in the center of the briquette was calculated with Eq. (6) and the maximum tensile strain was calculated with Eq. (7).

$$\sigma_0 = \frac{2P}{\pi t \varphi} \quad (6)$$

$$\varepsilon_0 = \left(\frac{2\Delta H}{\phi}\right) \times \left[\frac{1+3\mu}{4+\pi*\mu-\pi}\right] \quad (7)$$

where σ_0: is tensile stress in the center of the test piece (MPa), P: is maximum load (N), t: is thickness of the test piece (mm), φ: is diameter of the test piece (mm), ε_0: is deformation by traction in the center of the test piece (με), ΔH: is horizontal deformation (mm) and μ: is Poisson coefficient.

To obtain the fatigue laws for predicting the fatigue life, we used Wholer's Eq. (8) (Pasandín and Pérez, 2017):

$$\varepsilon_o = k(N_f)^{-n} \quad (8)$$

where N_f: is the number of load cycles to fatigue failure, k and n: are material constants and ε_0: is the horizontal strain of initial tension in the center of the sample in με.

RESULTS AND DISCUSSION

Chemical Characterization and Morphology of the Aggregates

The weight percentage of each of the components present in the limestone and the EAF are different. The predominant components in the limestone are CaO and SiO_2 while in the EAF are CaO and Fe_2O_3. In the BFD, the predominant component is Fe_2O_3 with 77.5%, while in the sand it is SiO_2 with 88.7%. The EAF has a CaO / SiO_2 ratio of 2.6, lower than limestone which is 3.8. The BFD has a CaO / SiO_2 ratio of 0.9 and in the sand the ratio is 0.005, as shown in Table 3. Said relationship considers the level of alkalinity of the aggregate and high ratios lead to stronger affinity with the asphalt (Xie et al., 2012). The results of the chemical characterization tests indicate that these residues can be used as aggregates and do not present a risk to the environment.

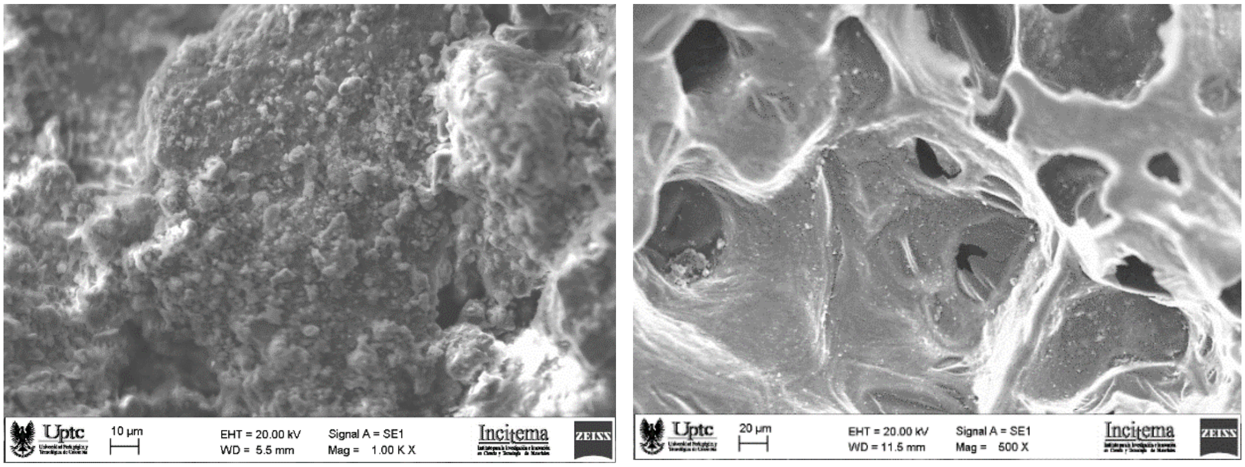
The microscopic morphology of the EAF is shown in Figure 3a at a scale of 1.000X. It presents a rough texture and very irregular angularity, which facilitates the adherence with the asphalt. The microscopic morphology of the BFD is shown in Figure 3b at a scale of 500X. It shows many micropores, which facilitate the entry of asphalt.

Preliminary Design of the Mixtures

Once the compliance with the requirements of the aggregates and the asphalt cement has been verified, the optimum content of asphalt with the Ramcodes methodology is determined. An analysis of voids is performed: air voids (Va), voids in the mineral aggregate (VMA) and voids filled with asphalt (VFA), which relate the behavior of the compacted mixtures. The voids are a function of the percentage of asphalt (Pb) and the specific bulk gravity of the mixture (Gmb). It is represented in maps with isolines for the values allowed in the specifications, shown in Table 4. The intersection of these lines produces a graphical construction in the Pb-Gmb space, which gives place to the void polygon. The centroid of said polygon establishes the optimal binder content and the specific bulk gravity (density). The empty polygon for the mixture M2 is shown as an example in Figure 4.

Table 3. Chemical components of BOF slag, limestone, AH powder and sand

Component (% in weigh)	MgO	Al_2O_3	SiO_2	P_2O_5	CaO	MnO	Fe_2O_3	Others
EAF	3.70	6.10	11.00	-	28.60	5.99	42.10	2.51
Limestone	3.80	9.30	16.60	-	63.40	0.17	3.04	3.63
BFD	1.00	3.60	5.50	0.20	4.95	3.32	77.50	0.90
Sand	1.60	7.30	88.70	-	0.46	-	0.99	1.00



(a) (b)

Fig. 3. Microscopic morphology: a) EAF, b) BFD

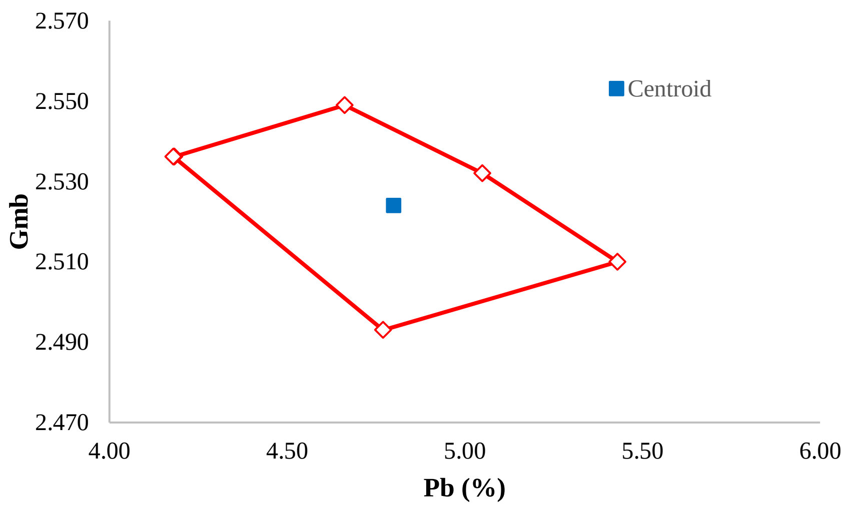


Fig. 4. Void polygon for M2 mixture

This way, an optimum percentage of asphalt of 5.1% and a density of 2.376 gr/cm^3 was obtained for the M1 mixture; 4.9% of asphalt and 2.54 gr/cm^3 of density for the M2 mixture and 5.5% of asphalt and 2.73 gr/cm^3 of density for the M3 mixture. Once the optimum percentage of asphalt was determined, three test pieces were prepared for each mixture and the compliance with the requirements regarding voids, stability and flow established in the specifications was verified. The results are shown in Table 4.

The stability improves in the mixtures manufactured with EAF and BDF, since the behavior of the M2 mixture is better. Similarly, the flow is greater for the mixtures made with EAF and BFD, due to the greater percentage in cement content asphalt due to the porosity of the BFD.

Performance Tests

Susceptibility to Humidity

Table 5 shows the results of the RRT test, performed with the test pieces prepared for each type of mixture. The average RTT values of the different mixtures decrease as the content of EAF and BFD increases, but they meet the minimum requirement of 80%.

Table 4. Results verification of mixture parameters

Parameter	M1	M2	M3	Request
Va (%)	4.70	4.69	4.68	4.0-6.0
VMA (%)	16.00	15.99	15.98	> 15
VFA, %	70.62	70.64	70.72	65-75
Stability (N)	11967	16158	13578	> 9000
Flow (in)	3.35	3.50	3.54	2-3.5

Table 5. RRT trial results

Condition	Id	P_{ult} (N)	RT (KPa)	RT_{ave} (KPa)	RTT_{ave} (%)
M1					
Wet	M1-1	9340	948.1		
	M1-2	10520	1075.2	968.5	
	M1-3	8620	882.4		89
Dry	M1-4	10450	1066.8		
	M1-5	9920	1101.1	1086.2	
	M1-6	10740	1090.7		
M2					
Wet	M2-1	7830	920.5		
	M2-2	7580	868.6	882.8	
	M2-3	7450	859.4		82
Dry	M2-4	8450	1028.1		
	M2-5	9320	1087.5	1076.3	
	M2-6	9310	1113.3		
M3					
Wet	M3-1	5630	637.9		
	M3-2	5520	610.0	608.9	
	M3-3	4950	578.7		80
Dry	M3-4	6370	747.5	759.5	
	M3-5	6280	712.9		
	M3-6	7130	818.2		

Susceptibility to Plastic Deformation

Figure 5 shows the results of the test. Mixture M1 showed a maximum deformation of 3.3 mm, while mixtures M2 and M3 showed less maximum deformation of 2.3 and 1.9 mm respectively.

The EAF and the BFD seem to offer a high resistance to permanent deformation under transit, the EAF has a very angular shape and a rough texture. These characteristics could make the EAF a suitable aggregate in the use of asphalt mixtures for road courses.

Resilient Module

As is natural, as the temperature increases, the resilient module decreases. Figure 6 shows that the highest values were determined in the M1 mixture, with a notable difference at 5 ºC. The lowest resilient module values are those of mixture M3 which contains 100% non-conventional aggregates.

Fatigue Laws

The fatigue life is defined as the number of load cycles up to where the failure occurs (N_f) and represents the capacity of the mixture to withstand the cyclic loads of traffic (Li et al., 2013). Figure 7 shows the tensile strain versus the number of cycles for the mixtures tested. This figure also includes the equations of the fatigue law and the correlation coefficient (R^2). These coefficients are above 0.9, which indicates a good statistical relationship between the results obtained to determine each fatigue law.

Figure 7 shows that the mixtures M2 and M3 present similar slopes in their fatigue life laws, while the M1 mix presents a greater slope. This is why for lower initial deformations the mixture M1 has a lower fatigue life and for higher initial deformations the mixture M1 has a longer life to fatigue.

The initial deformation from which this change in behavior occurs between the mixture M1 and M2 is 305.9 µm and between the mixtures M1 and M3 is 374.5 µm.

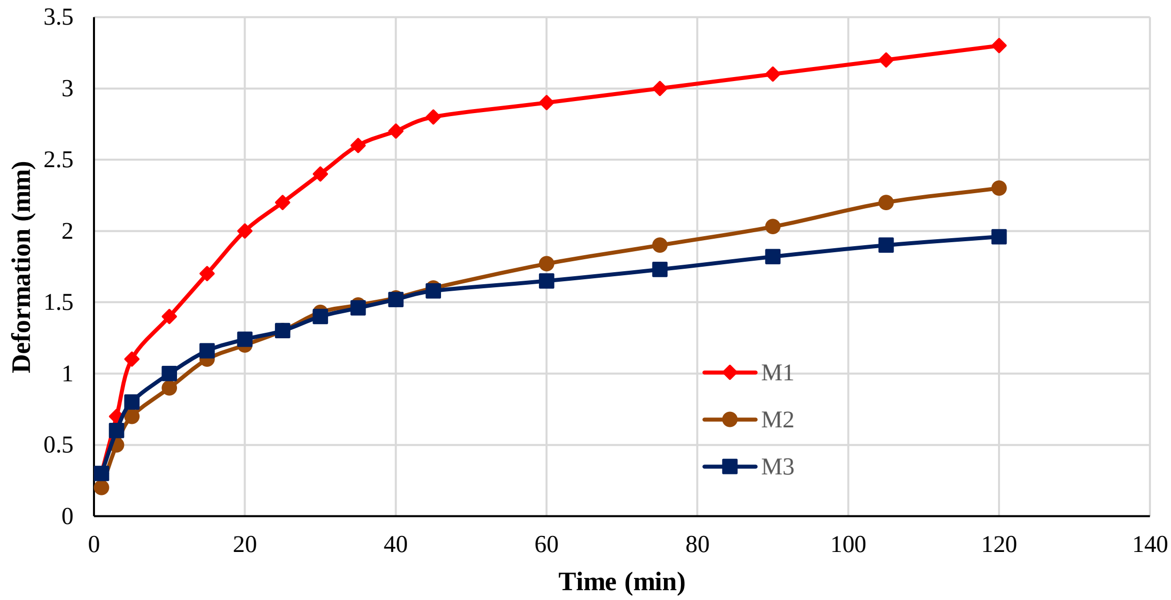


Fig. 5. Evolution of plastic deformation

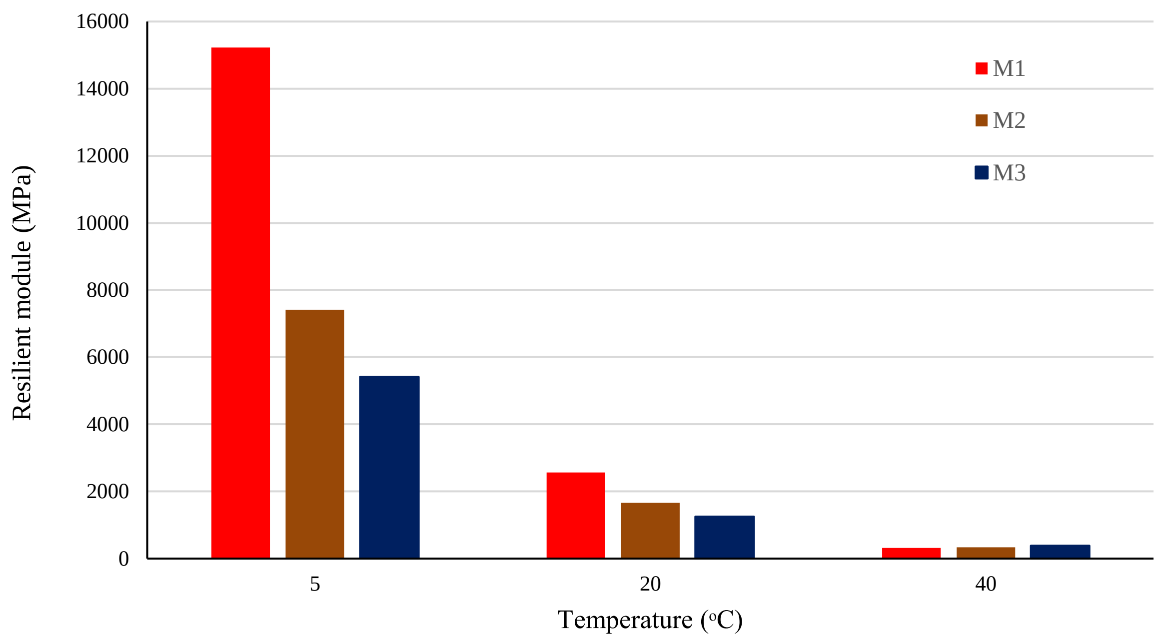


Fig. 6. Resilient module variation

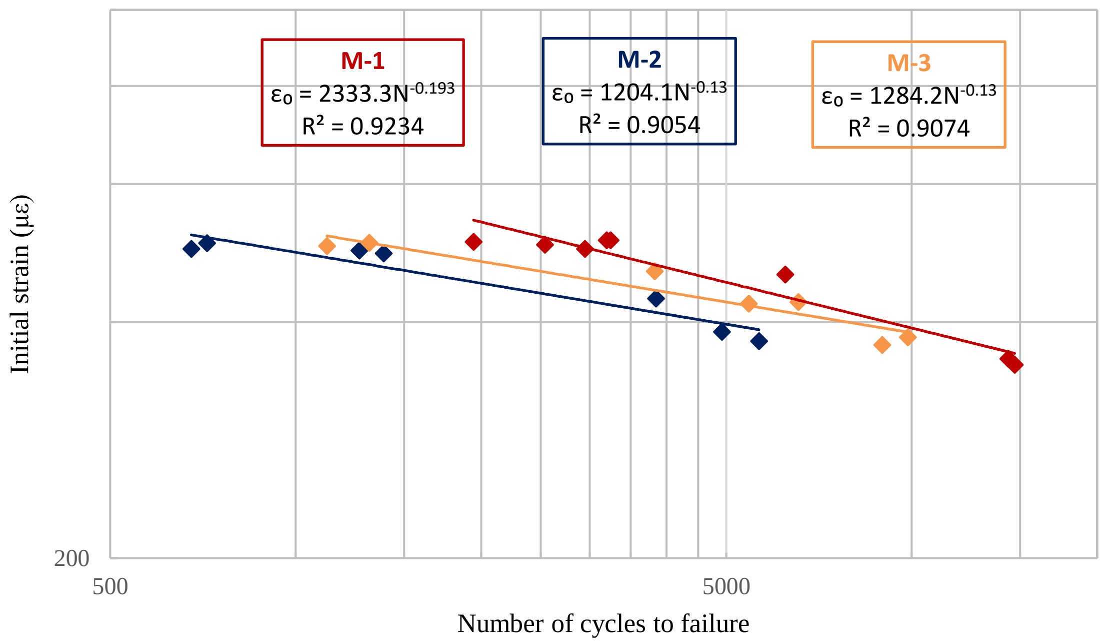


Fig. 7. Fatigue laws for mixtures

CONCLUSIONS

This research promotes the use of EAF and BFD as aggregates in asphalt mixes for pavements as an alternative to help with their negative impact on the environment. This is due to the exploitation of non-renewable materials and the accumulation of waste without control. For this purpose, the performance of the asphalt concrete samples was evaluated, partially and totally replacing the traditional aggregates with EAF and BDF. Based on the results of the tests carried out, the following conclusions are presented.

The mixture prepared with partial substitution of the conventional aggregates shows an asphalt cement similar to conventional mixtures, more stability and a small flow increment.

The mixture prepared with total conventional aggregates substitution exposed a higher content of asphalt cement, more stability and more flow value. EAF and BFD porosity could explain the increment in the content of asphalt cement.

Mixes prepared with EAF and BFD also behave more in plastic deformation resistance, humidity susceptibility between the required parameters and clearly more resistance to fatigue. The resilient module under low temperature presents greater variability than the traditional mixture, while as the temperature increases the differences are smaller.

The results obtained in this research contribute to a better understanding of the implications of the manufacture of asphalt mixtures with unconventional materials or waste and suggest that the incorporation of these is a feasible alternative for the construction of roads.

The contribution to the environment of this type of projects focuses on reducing both the use of non-renewable natural resources and the accumulation of waste, improving the environmental conditions of the areas surrounding the steel companies.

AKNOWLEDGEMENTS

The author thanks Acerías Paz del Río S.A. and Gerdau-Diaco for the support and supply of the materials, to the company IncoAsfaltos S.A.S. for the supply of asphalt cement, to the INCITEMA of the Pedagogical and Technological University of Colombia for the development of the chemical characterization tests of the materials, to Engineer Manuel Sierra, coordinator of the pavement laboratory of the same university. The Governorate of Boyacá is also thanked for the support through the call 733 of 2015.

REFERENCES

Askarinejad, A. (2017). "Using different methods of nanofabrication as a new way to activate supplementary cementitious materials, A review", *Civil Engineering Infrastructures Journal*, 50(1), 1-19.

INVIAS. (2013). *Especificaciones generales de construcción de carreteras*, Colombian technical standards, Bogotá, Colombia.

Kambole, C., Paige-Green, P., Kupolati, W.K., Ndambuki, J.M. and Adeboje, A.O. (2017). "Basic oxygen furnace slag for road pavements: A review of material characteristics and performance for effective utilisation in southern Africa", *Construction and Building Materials*, 148, 618-631.

Li, N., Molenaar, A.A.A., Van De Ven, M.F.C. and Wu, S. (2013). "Characterization of fatigue performance of asphalt mixture using a new fatigue analysis approach", *Construction and Building Materials*, 45, 45-52.

Loaiza, A. and Colorado, H.A. (2018). "Marshall stability and flow tests for asphalt concrete containing electric arc furnace dust waste with high ZnO contents from the steel making process", *Construction and Building Materials*, 166, 769-778.

Lytton, R.L., Masad, E.A., Zollinger, C., Bulut, R. and Little, D. (2005). "Measurements of surface energy and its relationship to moisture damage", (FHWA/TX-05/0-4524-2), Retrieved from https://static.tti.tamu.edu/tti.tamu.edu/documents/0-4524-2.pdf

Masoudi, S., Abtahi, S.M. and Goli, A. (2017). "Evaluation of electric arc furnace steel slag coarse aggregate in warm mix asphalt subjected to long-term aging", *Construction and Building Materials*, 135, 260-266.

Ochoa Díaz, R. (2012). "Diseño de mezclas bituminosas para pavimentos con alquitrán, usando las metodologías Marshall y Ramcodes 1", *Respuestas*, 17(2), 63-70.

Ochoa, R. and Grimaldo, G. (2018). "Validation of the polyvoids in the design of bituminous mixtures with coal tar as a binder", *Revista Ingeniería de Construcción*, 33, 137-146. Retrieved from http://www.ricuc.cl/index.php/ric/article/view/827/pdf

Parish, C.M., White, R.M., Lebeau, J.M. and Miller, M.K. (2014). "Response of nanostructured ferritic alloys to high-dose heavy ion irradiation", *Journal of Nuclear Materials*. 445(1-3), 251-260.

Pasandín, A.R. and Pérez, I. (2017). "Fatigue performance of bituminous mixtures made with recycled concrete aggregates and waste tire rubber", *Construction and Building Materials*, 157, 26-33.

Pasetto, M., Baliello, A., Giacomello, G. and Pasquini, E. (2017). "Sustainable solutions for road pavements: A multi-scale characterization of warm mix asphalts containing steel slags", *Journal of Cleaner Production*, 166, 835-843.

Sánchez-Leal, F.J. (2007). "Gradation chart for asphalt mixes : Development", *Journal of Materials in Civil Engineering in Civil Engineering*, 19(2), 185-197.

Sánchez-Leal, F.J., Anguas, P.G., Larreal, M. and Valdés, D.B.L. (2011). "Polyvoids : Analytical tool for superpave HMA design", *Journal of Materials in Civil Engineering*, 23(8), 1129-1137.

Sánchez, F., Garnica, P., Gómez, J. and Pérez, N. (2002). *Ramcodes: Metodología racional para el análisis de densificación de geomateriales compactados*, Sanfandila, Querétaro, Retrieved from https://imt.mx/archivos/Publicaciones/PublicacionTecnica/pt200.pdf

Skaf, M., Manso, J.M., Aragón, Á., Fuente-Alonso, J.A. and Ortega-López, V. (2017). "EAF slag in asphalt mixes: A brief review of its possible re-use", *Resources, Conservation and Recycling*, 120, 176-185.

Taherkhani, H. and Afroozi, S. (2017). "Investigating the performance characteristics of asphaltic concrete containing nano-silica", *Civil Engineering Infrastructures Journal*, 50(1), 75-93.

Taherkhani, H. and Arshadi, M.R. (2018). "Investigating the creep properties of PET-modified asphalt concrete", *Civil Engineering Infrastructures Journal*, 51(2), 277-292.

Tan, Y. and Guo, M. (2013). "Using surface free energy method to study the cohesion and adhesion of asphalt mastic", *Construction and Building Materials*, 47, 254-260.

Tarefder, R.A., Zaman, M. and Hobson, K. (2011). "A laboratory and Statistical Evaluation of Factor Affecting Rutting", *International Journal of Pavement Engineering*, 4, 59-68.

Xie, J., Wu, S., Lin, J., Cai, J., Chen, Z. and Wei, W. (2012). "Recycling of basic oxygen furnace slag in asphalt mixture: Material characterization and moisture damage investigation", *Construction and Building Materials*, 36, 467-474.

Zhu, T., Ma, T., Huang, X. and Wang, S. (2016). "Evaluating the rutting resistance of asphalt mixtures using a simplified triaxial repeated load test", *Construction and Building Materials*, 116, 72-78.