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# Use of Blast Furnace Dust in the Production of Asphalt Concrete for Pavements, Performance and Environmental Contribution

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## Abstract

This study analyzed the possible use of a residue from the steel industry, blast furnace dust, as aggregate in asphalt mixtures for pavements, as a possible solution to the problems of generation and accumulation of industrial waste in the production of steel, as well as the exploitation of non-renewable materials for infrastructure construction. In the production of steel, solid residues such as slag and blast furnace dust are generated, which become industrial waste. Another found issue in pavement construction is the exploitation and use of stone materials are necessary. Two test states were selected to achieve the established objective where blast furnace dust totally (100%) or partially (50%) replaced the conventional fine aggregate in an asphalt mixture at the laboratory. The applied methodology consisted of four stages: establishing the properties of the materials, determining the composition of the blast furnace dust, designing each of the mixtures using the Ramcodes methodology, and finally performing performance tests such as dynamic modulus and fatigue laws. The results show an acceptable behavior of the blast furnace dust and allow to define that the use of this residue is technically feasible in manufacturing asphalt mixtures for pavements.

**Keywords:** blast furnace dust, asphalt mix, modulus, fatigue.

## Introduction

Blast Furnace Dust (BFD) is a residue from steelmaking in integrated steel mills. BFD is produced in the blast furnace during the smelting of ores (iron ore, limestone and coke) to produce pig iron. During this transformation, gases and particulate matter are generated that are recovered in the collectors.. (Hu et al., 2017).

In the only integrated steel company that exists in Colombia, Acerías Paz del Río S.A., approximately 7,200 tons of BFD are produced annually in most cases, due to its low use and storage in outdoor patios, this waste has negative environmental impacts. Due to the above, the BFD is proposed as an alternative material in the construction of pavements, which in turn allows to face the shortage of natural stone aggregates of quality specifications for the construction of roads.

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Currently, there is a growing interest in using industrial waste as a component in asphalt mixtures, as it has been shown that the addition of some of these wastes significantly improves the mechanical properties of the mixture (Pourtahmasb et al., 2015) (Delongui et al., 2018), resulting in greater pavement durability. The steel industry is one of the main producers of solid waste globally, which has raised concerns about its environmental impact. However, some of these wastes have been demonstrated to be a sustainable and cost-effective alternative for asphalt mixture production (Chen & Wei, 2016). In addition, by-products such as slags, blast furnace dust, and others, have also been investigated as possible additions in asphalt mixtures. The incorporation of these wastes into asphalt mixtures can improve their mechanical properties, resulting in greater pavement durability (Xie et al., 2017). Therefore, the use of waste from the steel industry in asphalt mixtures is an attractive option from an economic and environmental perspective. However, there is very little information in the literature on the use of blast furnace dust (BFD) in asphalt mixtures for pavements.

The purpose of this study is to analyze and evaluate the possibility of substituting the fine aggregate, in an asphalt mixture, by BFD, in two proportions: 50% and 100%, and to determine the behavior of the mixtures through the dynamic modulus and fatigue resistance. The experimental design consisted of manufacturing three types of mixtures using the void polygon concept of the Ramcodes methodology (Sánchez-Leal et al., 2011) to determine the adequate content of asphalt cement: a control mixture with natural aggregates (M-0), a mixture substituting 50% of the fine aggregate with BFD (M-50), and a mixture substituting 100% with BFD (M-100). The mixtures were tested on void, stability, and flow parameters to verify compliance with local specifications (INVIAS, 2013), and, finally, the dynamic modulus and fatigue resistance tests were carried out.

All the results were compared and analyzed to establish the possibility of using BFD as a material in the manufacture of asphalt mixtures.

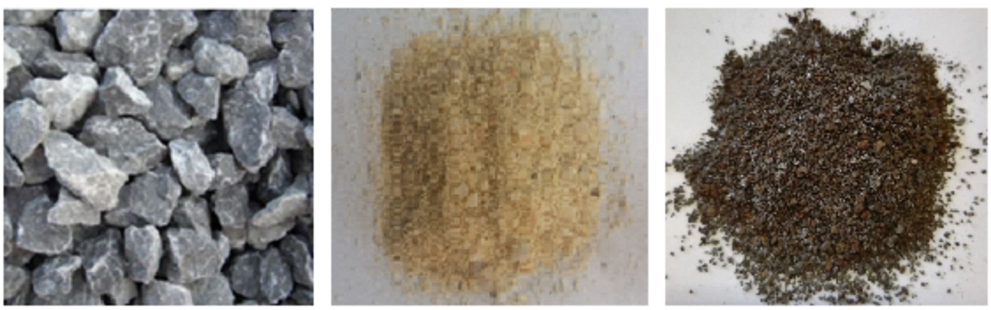
## Materials and methodology

This section exposes the conditions in which the analyzes and tests were carried out to investigate the behavior of asphalt mixtures with BFD as fine aggregate. As well as the origin and characteristics of the materials used.

### Materials

The materials used were natural stone aggregates, BFD, and 80/100 penetration asphalt cement. Fig. 1 shows the materials used, conventional stone aggregates and blast furnace dust, which were supplied by the La Roca quarry and Votorantin-Acerías Paz del Río S.A., respectively. The asphalt binder was supplied by the company Incoasfaltos S.A.S.

The type of asphalt mixture selected in the investigation was MDC-19 for an NT3 traffic level, following what is specified by Colombia's National Roads Institute (INVIAS).



(a) (b) (c)

Fig. 1

(a) Gravel-type coarse aggregate, (b) sand-type fine aggregate,
(c) BFD fine aggregate

## Methodology

The methodology comprises four organized and scheduled stages, each with its objectives and tasks to be carried out. Initially carry out the necessary tests to know the physical-mechanical properties of the BFD and natural aggregates. Test results were compared with the general road construction specifications in order to define material compliance or rejection for its use in asphalt concrete. The second stage consisted of carrying out the chemical characterization of the BFD: determination of the composition with the X-ray fluorescence equipment and the crystallographic structure in the X-ray diffractometer. The foregoing, to identify the predominant compounds of the BFD and establish the convenience of its use. risk-free use. In stage 3, the mixtures were designed in their material combinations and dosages using the Ramcodes methodology (Sánchez-Leal, 2009). Finally, in stage 4, the dynamic modulus and fatigue tests were carried out on each mixture with the working formula obtained. Results were analyzed and thus, the mixture with the best characteristics and behavior was determined.

### Dynamic module

To determine the dynamic modulus, the indirect stress test was used, with the procedure of standard NE-12697-26-Annex C (AENOR, 2012a). Three specimens were manufactured for each type of mixture and tested at 5°C, 25°C, and 40°C and a frequency of 10 Hz, Considering that the dynamic modulus is inversely proportional to the temperature, due to the viscoelastic behavior and the susceptibility of the asphalt cement to changes in temperature, when the temperature increases we will find lower modulus values. (Pourtahmasb et al., 2015).

With the results of the tests carried out and with the help of the least squares regression, a mathematical function of the type given (Eq.1) is adjusted.

$$E = A * e^{B*T} \tag{1}$$

$E$ is the modulus dynamic; $T$ is the temperature of the mixture; $A$ and $B$ are regression constants (AENOR, 2012b).

### Fatigue

The fatigue test was carried out by indirect traction according to standard BS-EN-12697-24 Annex E (AENOR, 2008) under controlled stress since it has a better correspondence with the working conditions of the mix in the field (Pasandín & Pérez, 2017). The specimens were tested at a frequency of 2.5 Hz and at a controlled temperature of 20 °C.

For the test, eight specimens were manufactured with the optimal binder content and for each type of mixture. each group of specimens are divided into four groups, two specimens were tested at different load levels. The selected loads were in the range of 250 kPa to 350 kPa. For each briquette subjected to this test, the life until breakage was determined from the number of load applications that cause breakage.

To find the fatigue laws in each type of mixture, Whöler's equation (Eq.2) was used.

$$\varepsilon_o = k\,(N_f)^{-n} \tag{2}$$

$\varepsilon_o$ is the horizontal strain of initial tension in με, $N_f$ is the number of load cycles until fatigue failure and $k$ and $n$ are constants of the material.

## Results and analysis

### Physical-mechanical characterization of the aggregates

**Table 1** shows the results of the characteristics of the material used as coarse aggregate and **Table 2** shows the characteristics of the fine aggregates. The results found are compared with the values required for a traffic level of NT-3 and for a hot mix asphalt. The foregoing, considering the general road construction specifications of the National Institute of Roads - INVIAS. As seen in **Table 1**, the material used as coarse aggregate meets the requirements established in the specifications.

Table 1

Coarse aggregate characterization results

| Properties | Gravel | Requirements | Standard test |
|---|---|---|---|
| L.A. Abrasion, (%) | 19.50 | <25 | ASTM C131 |
| Micro-Deval Abrasion (%) | 19.80 | <20 | ASTM D6928 |
| Mechanical strength, 10% fine (kN) | 122.80 | >110 | SABS Meth 842 |
| Soundness $Na_2SO_4$ (%) | 1.60 | <18 | ASTM C88 |
| Fractured particles (%) | 94.10 | >85 | ASTM D 5821 |
| Gsa | 2.76 | - | |
| Gss | 2.70 | - | |
| Gsb | 2.67 | - | |
| Absorption (%) | 1.20 | - | ASTM C127/128 |

Gsa: apparent specific gravity; Gss: saturated and superficially dry gravity; Gsb: bulk specific gravity

Table 2

Fine material characterization results

| Properties | Results | | Requirements | Standard test |
|---|---|---|---|---|
| | Sand | BFD | | |
| Plasticity index (%) | NP | NP | NP | ASTM D4318 |
| Sand equivalent (%) | 68.00 | 93.80 | >50 | ASTM D2414 |
| Angularity (%) | 46.80 | 53.00 | >45 | ASTM C1252 |
| Gsa | 2.78 | 2.73 | - | |
| Gss | 2.74 | 2.50 | - | |
| Gsb | 2.72 | 2.36 | - | |
| Absorption (%) | 0.76 | 5.65 | - | |

Gsa: apparent specific gravity; Gss: saturated and superficially dry gravity; Gsb: bulk specific gravity

Results in **Table 2** show that BFD has a low specific gravity, high absorption, high sand equivalent, and high angularity compared to sand. The lower specific gravity influences the greater amount of BFD material necessary in the material dosage to obtain work granulometry. Furthermore, its greater absorption is directly related to the greater amount of asphalt cement necessary in the asphalt concretes that use BFD as fine aggregate.

### Chemical characterization of the aggregates

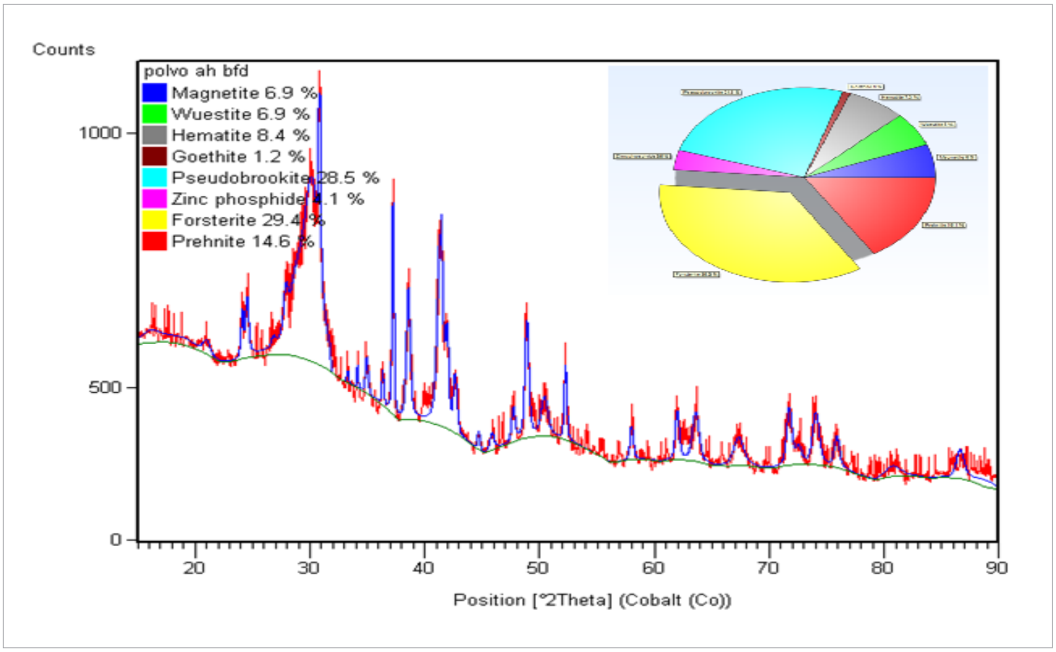
**Table 3** shows the results of the X-ray fluorescence (XRF) essay for each of the aggregates. The main chemical compounds of coarse aggregate are CaO, $SiO_2$, and $Al_2O_3$. The main chemical component of the sand is $SiO_2$ (88.69%), while this same compound in BFD is only 5.51%. The main chemical constituent of BFD is $Fe_2O_3$ (77.5%), while in sand, it's only 0.99%. Regarding the volumetric expansion of BFD, due to the low content of CaO and MgO, it can be asserted that this material has a low probability of having expansive characteristics.

The $CaO/SiO_2$ ratio estimates the alkalinity level of the materials, according to (Gao et al., 2017), alkalinity is classified into three degrees: low alkalinity (< 1.8), intermediate alkalinity (1.8 - 2.5), and high alkalinity (> 2.5). Intermediate or high alkalinities lead to a higher affinity between the asphalt cement and the aggregate (Xie et al., 2012). Gravel has a $CaO/SiO_2$ ratio of 3.8, BFD has a 0.9 ratio, and sand has a ratio equal to 0.005. Therefore, BFD has a better affinity with the asphalt binder than sand. Fig. 2 shows BFD's diffractogram. Iron hydroxides ($Fe(OH)_2$) were found, so it is interpreted that the material was wet and had a reaction. There are also forsterite-type magnesium silicates ($Mg_2SiO_4$) generated at high temperatures, and calcium and aluminum silicates such as prehnite ($Ca_2Al(Si_3Al)O_{10}(OH)_2$) and Goethite ($\alpha$-$Fe^{3+}O(OH)$), which is formed under oxidizing conditions as a product of the weathering of minerals containing iron, were also found.

Table 3
Chemical composition of aggregates in XRF

| Component (% in weight) | MgO | $Al_2O_3$ | $SiO_2$ | $P_2O_5$ | CaO | MnO | $Fe_2O_3$ | Otros |
|---|---|---|---|---|---|---|---|---|
| Gravel | 3.80 | 9.30 | 16.60 | - | 63.40 | 0.17 | 3.04 | 3.63 |
| Sand | 1.60 | 7.30 | 88.69 | - | 0.46 | - | 0.99 | 1.00 |
| BFD | 1.00 | 3.60 | 5.51 | 0.20 | 4.95 | 3.32 | 77.50 | 0.90 |

Fig. 2
Diffractogram for BFD




Considering that the major chemical component of BFD is $Fe_2O_3$, it can react with water and form a leachate that may be unfavorable to the environment. It can also have some reaction with CaO and MgO, although the content of these components is low. However, it is necessary to further analyze these chemical reactions and establish their potential impact on the environment.

### Mixture design

The mixtures were designed under the Ramcodes methodology premises, based on obtaining the optimum asphalt cement content with the void polygon. The void polygon is an analytical tool to determine the working formula for any hot-dense asphalt mixture based on the void specifications. The void parameters in an asphalt mix for both Marshall and Superpave are voids filled with asphalt (VFA), voids in mineral aggregate (VMA), and air voids (Va). These are analytically and graphically represented within a plane of density against asphalt content (Sánchez-Leal et al., 2011).

Table 4 compares the results of the base mix design (M-0) with the mix design with conventional coarse aggregate and with the incorporation of BFD as fine aggregate (M-50 and M-100). Table 4 shows the increases in asphalt cement content as the BFD proportion increases, which can be attributed to the BFD texture and porosity and ratified with the result of absorbed asphalt. The stability is higher than the minimum required in specifications but lower than the stability of the base mixture, which can be attributed to the shape and texture of the BFD rounded edges and the higher asphalt cement content in the mixtures. The volumetric properties and other characteristics are within the required range.

Table 4

Results of the characterization and design of the mixtures

| Characteristic | Unit | Value | | | Requirements |
|---|---|---|---|---|---|
| | | M-0 | M-50 | M-100 | |
| Aggregate content | % | 95.20 | 95.10 | 95.50 | - |
| Asphalt content | % | 4.80 | 5.90 | 6.20 | - |
| Bulk specific gravity ($G_{mb}$) | g/cm$^3$ | 2.38 | 2.35 | 2.31 | - |
| Maximum specific gravity ($G_{mm}$) | g/cm$^3$ | 2.51 | 2.46 | 2.48 | - |
| Stability | N | 11967 | 9925 | 9548 | 9000 |
| Flow | mm | 3.34 | 3.01 | 3.00 | 2.0 – 3.5 |
| Stability/flow | kN/mm | 3.56 | 3.31 | 3.16 | 3.0 - 6.0 |
| Air voids (Va) | % | 5.15 | 4.81 | 5.18 | 4.0 – 6.0 |
| VAM | % | 15.80 | 16.22 | 16.15 | >15.0 |
| VFA | % | 67.42 | 70.32 | 67.94 | 65 - 75 |
| Absorbed asphalt ($P_{ba}$) | % | 0.24 | 1.00 | 1.44 | - |
| Effective asphalt ($P_{be}$) | % | 4.57 | 4.96 | 4.85 | - |
| Filler/effective binder | - | 1.10 | 1.00 | 1.00 | 0.8 – 1.2 |

### Dynamic module

Fig. 3 shows the dynamic modulus trend lines for each of the mixtures tested. Mixes M-50 and M-100, which were manufactured with BFD in partial or total replacement of fine aggregate, show lower resilient moduli at 20°C than mix M-0, which did not use BFD. However, at high temperatures, the mixtures M-50 and M-100 present a dynamic modulus greater than the modulus of the control mixture M-0. This can be associated with the high production temperature of BFD, which makes this material capable of absorbing thermal energy and can increase the heat storage effect in asphalt concrete (Huang et al., 2012).

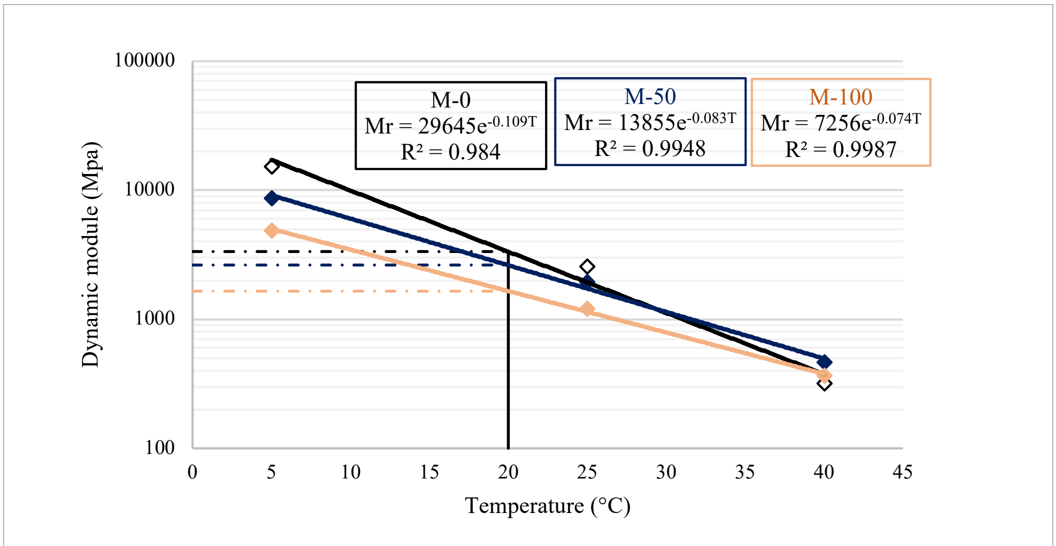


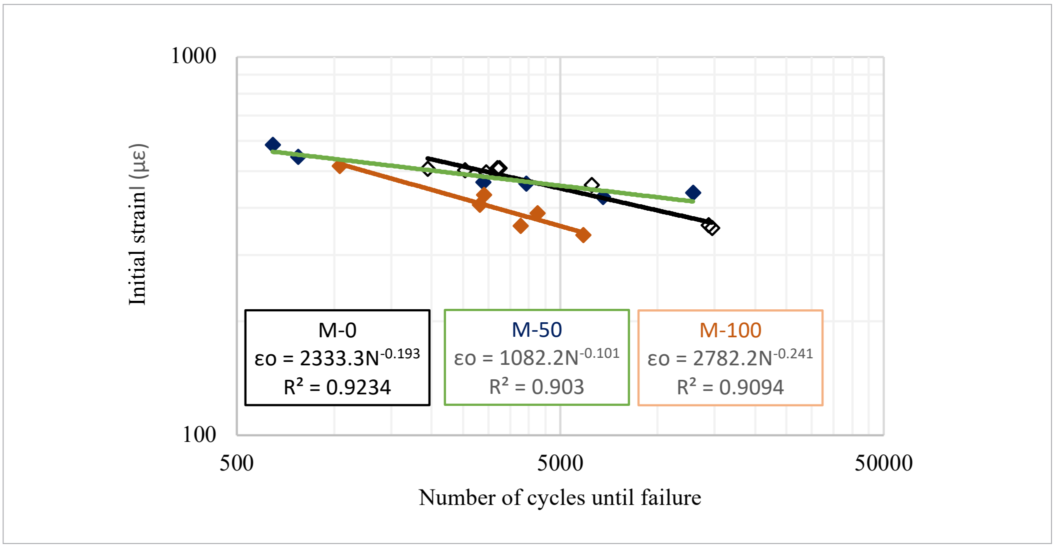

Fig. 3

Dynamic modulus master curves

**Fatigue**

Fatigue deterioration in asphalt mix layers is the most common deterioration. The test consists of determining the number of load repetitions until failure occurs (*Nf*) and is associated with the ability of the mixture to withstand cyclic traffic loads (Li et al., 2013). Fig. 4 shows the effort against the number of cycles for the mixtures under study. In the same way, the equations of the fatigue law and the correlation coefficient are shown ($R^2$), which indicates that there is a statistical correlation between the results obtained to determine each fatigue law, given that the $R^2$ coefficients are greater than 0.80. The fatigue law with the greatest slope is the M-0 mixture. The slope of the M-50 mixture fatigue law is slightly less inclined than that of the M-100 mixture. Consequently, the M-100 mixture has a better fatigue life for low stresses than the M-50 mixture.

Fig. 4
Laws of fatigue for mixtures




The inclusion of BFD in asphalt mixes can cause changes in the properties of the asphalt. The high alkalinity of BFD can affect the asphalt curing process, which can result in a reduction in the durability of the asphalt mix. However, the addition of BFD can also improve certain properties of asphalt mixes, such as resistance to deformation at high temperatures. Additionally, the inclusion of BFD in asphalt mixes can improve the adhesion properties of tires to the pavement and the durability of the pavement. BFD can increase the surface texture of the asphalt mix, which can lead to better contact between the tires and the pavement and improved skid resistance. BFD can also improve the resistance to rutting of asphalt mixes, which can result in increased pavement durability and lower maintenance costs.

## Conclusions

Due to BFD's porous surface texture, the optimal content of asphalt cement in mixtures M-50 and M-100 was greater than the optimal content of control mixture M-0. The M-50 mix, in which BFD partially replaced the fine natural aggregate, increased by only 1.1% compared to the optimal content of the base mix. Similarly, the M-100 mix, in which 100% BFD was used as fine aggregate, increased the optimum asphalt cement content by 1.5%. Previous results are supported by the surface texture and the greater BFD absorption compared to sand absorption. The increase in asphalt cement content will be reflected in the cost of the mix.

All the mixtures meet stability requirements, but BFD mixtures had lower values than the base mixture, although stability values for M-50 and M-100 mixtures are higher by 10.3% and 6.1. % with respect to the minimum required stability. The stability values for the M-50 mixture decreased by 17% and for the M-100 mixture by 20% compared to the base M-0 mixture. Similarly, the flow values in mixtures with BFD are lower than the flow value in the base mixture, however, still within the interval established in the requirement. Considering that the stability of a mixture depends on the friction between the particles, which is related to the texture, shape, size and cohesion of the asphalt cement, and because natural coarse aggregate was used, the decrease in stability can be attributed to the increase in the optimal content of asphalt binder.

The dynamic modules of BFD mixtures were lower than the modulus of the base mixture. In addition, the dynamic modulus of the mixture in which the fine natural aggregate was totally replaced by BFD (M-100) is lower than the mixture in which the natural aggregate (M-50) was partially replaced. The dynamic modulus decreased by 21.4% and 50.7% in the M-50 and M-100 mixtures, respectively, compared to the modulus of the base mixture. Similarly, the value of the dynamic modulus of the M-100 mix showed a decrease of 37.3% compared to the M-50 mix. The dynamic modulus values will affect the structural design of the pavement.

Finally, the M-50 mix presented better fatigue behavior at lower strains than the conventional mix. As we increase the level of deformation, that is, at high deformations, the M-50 mixture has a shorter life. Likewise, considering the number of load repetitions, the M-50 mixture will resist higher initial deformations. The M-100 mix has lower fatigue life at low strains compared to the M-50 mix and the base mix, while at high strains, the M-100 mix has better fatigue life than the M-50 mix and a little less than the base mix. Analyzing the M-100 mixture and considering the number of load cycles, it will resist lower initial deformations than the base mixture and less than the M-50 mixture.

Considering the results, using BFD as a fine aggregate in asphalt mixtures is technically feasible. Acceptable stability and adequate fatigue behavior are found with the incorporation of 50% BFD. Similarly, with 50% of BFD, a behavior of the dynamic module similar to that of the base mixture is obtained. Therefore, it can be established that the substitution of 50% of conventional aggregate BFD guarantees an adequate behavior of the asphalt mixture.

Technically, the use of BFD in the production of asphalt mixtures for pavements is feasible, but the most important contribution is that with the use of this residue, it contributes to environmental sustainability due to the fact that less exploitation and utilization of waste will be necessary natural materials. In addition, with the use of BFD, storage in yards and pollution caused in steel companies and in nearby towns are reduced.

Although it is evident that the analyzed properties did not show a significant improvement, it can be established that the use of BFD in asphalt mixtures is not detrimental to the behavior of the mixtures since they meet the requirements established in the standards and can contribute to the environmental impact generated by the exploitation of non-renewable stone materials and the reduction in the storage of low-utilization industrial waste. Therefore, it is possible to use BFD in asphalt mixtures, however, further research on the subject is necessary.

Based on the research findings, the authors recommend further investigation into the use of BFD in asphalt mixtures on topics such as determining the optimal amount of blast furnace dust to be added to asphalt mixtures to achieve desired properties and minimize potential negative effects, durability and long-term performance of pavements containing blast furnace dust, including factors such as resistance to moisture damage and rutting, effects of the use of blast furnace dust on different types of asphalt mixtures and under different environmental conditions. As well as the topic related to the reactions of the chemical components of BFD with water, since it is impossible to avoid water contact with the pavement structure.

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