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# Use of Electric Arc Furnace Black Slag (EAF) As A Coarse Aggregate in the Asphalt Mixture

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Black slag, being a by-product from steel and the waste from the production of cast iron and industrial steel, is proposed as a potential alternative for incorporation into the composition of asphalt mix in the consolidation of the components that form the wearing course layer. This initiative generates a positive environmental impact by providing an area of application for this type of metallurgical waste. This is supported by a series of laboratory tests, including the study of the basic petrography of the element and its response to various real physical and mechanical conditions, using the material (EAF black slag) from the steel producer DIACO located in Boyacá, Colombia. This will ensure that the results obtained are suitable for the conditions of Tunja, Boyacá, and allow their implementation in flexible pavements according to the Colombian standard INVIAS-22. This article is part of the dissemination of progress in the results of the doctoral thesis in Engineering and Materials Science currently underway, titled 'Evaluation of Asphalt Mixes Manufactured with Oxidizing Slags and Asphalts Modified with Recycled Rubber Granulate.

**Keywords:** Black slag, asphalt mix, flexible pavement, metallurgy.

## 1. Introduction

The growing increase in the construction of road infrastructure leads to the search for alternatives that allow to demonstrate the optimization of materials in favor of a better quality of the roads, as a result of this the approach of entering the paving sector with the alternative focused on the Coarse aggregate in the asphalt mixture that constitutes the rolling layer, when it is replaced with Black Slag from Electric Arc Furnace (EAF).

This substitution is supported by a series of laboratory tests established in accordance with the provisions of INVIAS 2022 in its section 200 (stone aggregates) and 700 (asphalt materials and mixtures) and the manual of the Ministry of Mines for stone materials in road structures, where it establishes the evaluation and analysis guidelines.

In the same way, a mixing design based on slag dosages is established as a scope, guaranteeing full compliance with the mechanical and physical requirements, and as a limiting counterpart of the investigation, the environmental component, considering the time requirements for carrying it out of no less than 20 years.

## 2. Methodological design

Based on the requirements that the execution of the investigation brings with it, so that the scope of the objectives and results presented guarantee their certainty, a structuring of the investigative methodology based on the objectives set and the nature of the data is essential. that will be presented in the course of its realization, taking into account that the development of the project will enter paths in which each of these will be applied and studied in detail in relation to the variables measured by means of laboratory tests. The way they will be related will be as follows:

Firstly, an experimental estimate focused on carrying out laboratory tests that verifies the parameters and aspects that intervene in the functionality of the black slag and the asphalt mixture, in order to create an experimental design of the asphalt mixture that allows a control of the their behavior and at the same time analyze them by means of the creation of significant analysis samples for each type of test, as a result, a descriptive evaluation is carried out that will allow to detail the behavior of the variables studied, using the information provided by the qualitative methodology, in order to consolidate a report of the behavior of these and their affectation within the research, according to this, the qualitative observation is carried out with principles based on the analysis separately from the variables, to later integrate the estimates made to consolidate a final result, contributing to interpreting the entire research in order to perform the correlation of data, based on the methodology focused on establishing the relationship between the project variables, in order to provide information that allows analyzing their behavior and thus create optimization strategies.

### 2.1. Sample Methodology

The stresses of use in the tread layer as a component of a tri-layer pavement have high quality criteria in terms of its coarse aggregate component. From this, the content of black slag (EAF) is set as an independent variable, by estimating that this factor will modify the results obtained in the analysis of the behavior of the mixture, the results always being variable when studying the dosages.

According to this, the physical properties (size, shape, color, texture, structure, degree of weathering, porosity) and mechanical properties (resistance, adherence, stability, flow, tension) that will present both the material such as the asphalt mixture component, evidenced in the characteristics such as:

Table 1. Research variables

| VARIABLES | CLASSIFICATION | CONTENT |
|---|---|---|
| Black slag (HEA) | Independent | Dosing of the black slag content within the design of the asphalt mix. |
| Basic petrography (macroscopy) | Dependent | - Size.<br>- Shape.<br>- Colour.<br>- Texture.<br>- Visual structure (homogeneous, banded, nodulous or brecciated)<br>- Degree of weathering.<br>- Porosity.<br>- Endurance.<br>- Identification of constituents. |
| Hardness | Dependent | Mechanical properties:<br>- Endurance.<br>- Percentage of fines. |
| Durability | Dependent | Mechanical properties:<br>- Solidness of the aggregate. |
| Particle geometry | Dependent | Physical properties:<br>- Fractured particles.<br>- Flattening.<br>- Elongation. |
| Asphalt mix | Dependent | Mechanical properties:<br>- Endurance.<br>- Adhesion.<br>- Stability.<br>- Flow.<br>- Tension |

Source: Authors

The correlation between the "proposed objectives" and the "trials and / or tests involved" in the execution of the project is presented below, in order to establish the way in which they contribute to giving resolution to the objectives established at the beginning of the investigation, highlighting its importance within it, and allowing feedback focused on consolidating the acquired knowledge and reinforcing it through the experience that brings the constant performance of laboratory tests and the inclusion of new material alternatives such as black slag (EAF)

Table 2. Expected direct results in relation to the objectives set

| OBJETIVES | TRIALS AND/OR TESTS INVOLVED | DIRECT RESULTS (RELATIONSHIP OBJECTIVES - TRIALS AND/OR TESTS INVOLVED) | CHARACTERISTICS OF NEW KNOWLEDGE |
|---|---|---|---|
| To establish the physico-mechanical behavior of black slags (HEA) as a substitute for the coarse aggregate within the asphalt mixture. | -Tray adhesion test.-Resistance to simple compression of bituminous mixtures.-Stability and flow of hot asphalt mixtures using the Marshall apparatus.-Indirect stress test to determine the resilient module of asphalt mixtures.-Resistance of hot asphalt mixtures using the Marshall apparatus on specimens of 152.4 millimeters (6 inches) in diameter.-Resistance to fatigue of hot asphalt mixtures by means of the bending test in two pu ntos on trapezoidal specimens | By means of these laboratory tests quantifiable and qualitative values of the properties contained by the mixture are obtained, considering in its composition the joint behavior of the black slag of electric arc furnace with asphalt cement; This allows to demonstrate clearly and under the standards of INVIAS-13, the quality of the design created to be implemented in flexible pavements. | When a different element is implemented for the constitution of the asphalt mixture, new knowledge is acquired focused on the behavior of the designed mixture as a whole, including the proper handling that requires inclusion within the tests, such as the affectations that it brings with it in the times that entail performing them. |
| Determining which of the two percentages of replacement of the coarse aggregate by black slag allows for better operation. | Asphalt mixture design by the Marshall method. | The realization of the design of the asphalt mixture by means of the Marshall method, allows to identify the behavior of the evaluated mixtures to establish which of them have the conditions of stability and flow, according to the relationship of voids and asphalt content present in it, being evidence through laboratory tests to choose the final design. | The inclusion of black slag within the asphalt mixture design provides high levels of experience in the field of innovative design, considering the realization of multiple laboratory tests and calculations that allow to identify the optimal mixture designs, leading to increase the understanding and correlation of the influential factors, allowing a greater capacity for analysis and reasoning in the area. |
| Identify the properties that condition the functionality of black slags in asphalt mixtures. | -Petrografía.<br>-Hardness.<br>-Durability.<br>-Geometry of particles.<br>-Resistance to polishing. | The evaluation of the physical, chemical and mechanical properties of black slag based on its petrography focused on studying and analyzing the conditions in which the deposit of the material is made, its characteristics and other aspects that generate alterations in them, starting from the point where the same type of studies practiced to conventional samples of aggregate for pathways are carried out , allowing to know the capacity of the same to meet the requirements of use to which it will be subjected. | The own studies of the granular material (black slag) allows to acquire knowledge focused on establishing the possible alterations that the material suffers against the various solicitations in asphalt mixtures, and to understand in an analytical way the conditioning that they must have to comply with the solicitations of use. |

Source: Authors

For the evaluation of the variables are considered significant samples of briquettes that will have as a purpose of manufacture, the determination of the asphalt mixture design to be implemented, considering the ranges established by the design fundamentals according to the Marshall method, where it establishes that the design must consider percentages of asphalt content within the briquettes to be tested in ranges ranging between 4.5% and 7.5 with intervals of 0.5% between them, in order to obtain a better behavior and certainty of the asphalt content conditions to establish the optimal design.

Similarly, it is established that the NSA Mixturein Caliente (MDC-19) provides greater ranges of thickness estimation, being admissible to adapt to an asphalt folder thickness of 6cm;all this, following the standards that determine parameters such as the granulometry that the sample must meet.

Additionally, environmental factors such as the temperature of the area are incorporated into the design, through the information provided by the IDEAM of the annual weighted average temperatures presented by the city of Tunja through the record collected from station No. 24035130 - UPTC with a historical record corresponding to the years present between 1964 and 2017, presenting a TMPA of 13.13 °C in this way, a type of asphalt cement is established as a material to make the hot mixture with a penetration of 80-100,being suitable for implementation based on the environmental and climatic conditions of the sector.

Consequently, it incorporates the information provided by INVIAS on the values corresponding to the volume of traffic with the highest incidence in mobility presented by station N°71 "Sector Tunja-Ventaquemada" presented between the years 2007 and 2017 estimating the percentages contained in the distribution of incidence in the typology of roads, resulting in a requirement of 3.8*107 equivalent axes of 8.2 ton in the design lane for 15 years, corresponding to a classification of Traffic Level2 (NT2) according to the ranges established by INVIAS, this provides greater coverage of the scope and benefits that the implementation of the design brings ,As a result it is obtained that to carry out the design of asphalt mixture by the Marshall method, a total of three (3) representative samples are required for each percentage of substitution of aggregate by black slag, which having three percentages, adding the seven intervals of measurement of the asphalt content, resulting in a total of twenty-eight (28) briquettes for each percentage of substitution, which leads to an overall total of 84 briquettes (Table 3).

Table 3. Number of briquettes for Marshall design realization

| **MARSHALL DESIGN** | |
|---|---|
| % REPLACEMENT | BRIQUETTES |
| 50 | 21 |
| 75 | 21 |
| 100 | 21 |
| ***TOTAL BRIQUETTES*** | ***63*** |

Source: Authors

Based on the results obtained through the Marshall design test, the guide dosage for the study and application of all laboratory tests proposed will be determined. According to this, taking into account the optimal design for each dosage typology, a total of 3 briquettes are taken for the realization of the tests concerning those specified in Table 4, resulting in a total of 93 briquettes to be tested in the evaluation section of the asphalt mixture.

Table 4. Number of briquettes for Marshall design realization

| **Designs** | | **BRIQUETTES REQUIRED PER TEST** | | | | | |
|---|---|---|---|---|---|---|---|
| No | (%) | MARSHALL DESIGN | STABILITY AND FLOW | DIRECT VOLTAGE TEST | RESISTANCE HOT ASPHALT MIXTURE | FATIGUE RESISTANCE | TOTAL BASED ON DOSAGE |
| 1 | 50 | 21 | 3 | 3 | 3 | 1 | 31 |
| 2 | 75 | 21 | 3 | 3 | 3 | 1 | 31 |
| 3 | 100 | 21 | 3 | 3 | 3 | 1 | 31 |
| | | | | | | ***TOTAL BRIQUETTES*** | ***93*** |

Source: Authors

## 2.2 Determination of laboratory tests

The approach and determination of all laboratory tests to be carried out, in accordance with the provisions of the National Institute of Roads (INVIAS) in its most recent update of the "Standards for Testing Materials for Roads" presented in 2022, contained by section 200 (stone aggregates) and section 700 and 800 (asphalt materials and mixtures and pavement prospecting), as well as the elaboration of the tests corresponding to basic petrography(macroscopy)with the provisions of the "Preliminary manual of petrography applied to the study of stone materials for roads" presented by the Ministry of Mines and Energy in collaboration with the Colombian Institute of Geology and Mining (INGEOMINAS).

These laboratory tests are focused on obtaining precise results to determine the conditions of behavior of the material and the asphalt mixture, for which reason, six (6) categories were established that cover various tests. Previously, the asphalt mixture design test is established by the Marshall method, which will empirically determine the final content of proportions within the sample that will constitute the final design to be studied; this design is conditioned to establish the optimal asphalt content within the mixture, raiding the aggregate dosage standards already raised previously, giving a total of 58 test briquettes.

The tests specified for the implementation of EAF black slag as a matter of analysis are "Basic petrography (macroscopy), hardness, durability, particle geometry and polish resistance" and the last category is called "Asphalt mixture tests", because it contains the tests that will determine the characteristics and properties of the designed asphalt mixture (Table 5).

Table 5. Established laboratory tests

| CATEGORY | NAME OF THE TRIAL | REFERENCE STANDARD |
|---|---|---|
| Petrografía | Preliminary investigation<br><br>Overview of land conditions:<br>-Identification<br>-Overview<br>-Zoning<br>-Description ofzones<br>-Identification of uniqueareas<br>Macroscopy:<br>-Shape and size of grains<br>-Color<br>-Texture<br>-Visual structure(homogeneous, banded, nodulous or brechoid)<br>-Degree ofweathering<br>-Porosity<br>-Identification ofconstituents<br>-Degree ofweathering<br>-Resistance | PRELIMINARY MANUAL OF PETROGRAPHY APPLIED TO THE STUDY OF STONE MATERIALS FOR ROADS |
| hardness | Resistance to degradation of thick aggregates of sizes less than 37.5mm (1 1/2") by means of the angels machine | INV E-218-13 |
| | Determination of the resistance of the coarse aggregate to abrasion degradation using the micro-deval apparatus | |
| | Determination of the value of 10% of fines | |
| durability | Strength of aggregates against the action of sodium sulfate or magnesium solutions | INV E-220-13 |
| Particle geometry | Granulometric analysis of coarse and fine aggregates | INV E-213-12 |
| | Percentage of fractured particles in a thick aggregate | INV E-227-13 |
| | Flattening and lengthening rates of aggregates for roads | |
| Polish resistance | Determination of the accelerated drive coefficient (CPA) of coarse aggregates | INV E-232-13 |
| Tests to asphalt mixture | Tray adhesion test | I.N.V.E - 740 |
| | Resistance to simple compression of bituminous mixtures | I.N.V.E - 747 |
| | Stability and flow of hot asphalt mixtures using the Marshall apparatus | I.N.V.E - 748 |
| | Indirect stress test to determine the resilient module of asphalt mixtures | I.N.V.E - 749 |
| | Resistance of hot asphalt mixtures using the Marshall apparatus on specimens of 152.4 | I.N.V.E - 800 |
| | Fatigue resistance of hot asphalt mixtures by two-point bending test on trapezoidal specimens | I.N.V.E - 808 |

Source: Authors

## 2.3 Determination of materials

According to the number of tests indicated in the previous paragraph, a calculation of materials required in each one is made (Table 6), being estimated according to the specifications presented by the I.N.V.E 2022 and the "Preliminary manual of petrography applied to the study of stone materials for roads" and including the elements required for its elaboration.

As a complement, the consolidated quantities of black slag of electric arc furnace, gravel and asphalt cement that make up the manufacture of briquettes that will be required for the realization of design tests and tests that will allow to demonstrate the capacity of the asphalt mixture is presented. For this second part, the tests focused on evaluating the conditions of the mixture design that presents the best behavior will be carried out (Table 4). The unit and total material content that will be required for the manufacture of the briquettes is then calculated, including the dosage variables and the quantity of briquettes (Table 6).

Table 6. Quantity of material required

| BRIQUETA NUMBER | REPLACEMENT PERCENTAGE (%) | | | NUMBER OF BRIQUETTES | BLACK SCUM (Kg) | | GRAVA (Kg) | | ASPHALT CEMENT (Lt) | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 50 | 75 | 100 | | C/U | TOTAL | C/U | TOTAL | C/U | TOTAL |
| 1 | X | | | 38 | 0,6 | 24,3 | 1,0 | 23,3 | | 8,36 |
| 2 | | X | | 38 | 1,0 | 36,5 | 0,6 | 23,3 | 0,2 | 8,36 |
| 3 | | | X | 38 | 1,3 | 48,6 | 0,0 | 0,0 | | 8,36 |
| | | ***TOTAL*** | | ***114*** | ***109,4*** | | ***46,7*** | | ***25,1*** | |

Source: Authors

## 3. Stages of development

3.1 Request for material

Due to the internal policies of the DIACO System, a request was submitted signed by the dean of PhD in materials engineering and science and the director of the project tocertify the veracity of the need to obtain the material for the realization of the tests that were established in it, this application contains the object of the research and the amount of material collected, as well as specifying that the results and analysis obtained will be sent to the company at the time of the final consolidated. In the digital application, it was made under the request of a total of two hundred and two kilograms (202 Kg) of black slag of electric arc furnace, a value that has contained an additional percentage of waste of five percent (5%), which will serve as a guarantee that there will be no lack of material.

3.2 Obtaining raw materials and inputs

The purchase of the most raw materials was made from local suppliers, in order to reduce the transport times of the materials and the costs involved. The amounts to be requested include an increase of five percent (5%), which will serve as a guarantee that there will be no lack of material.

3.3 Analysis and estimation of technical feasibility of its implementation

The tests specified above were carried out over four months (4), in order to have constancy and intensification in them, in such a way that at the same time the systematization of the same in digital formats was carried out in the course of its development, to guarantee the quality of the processes and the certainty of the information recorded.

This has allowed to evaluate from early moments the behavior of the variables studied during the practice of tests and laboratory tests. From there, the final result of the project is obtained, by determining the technical feasibility of implementing the asphalt mixture design with EAF black slag content as a substitute for the coarse aggregate, based on its ability to meet the actual requests.

## 4. Analysis and discussion

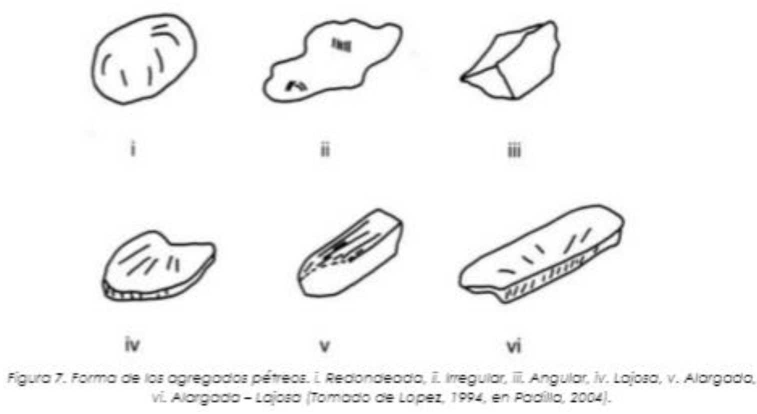
4.1 Basic petrography (macroscopy)

The petrographic evaluation was performed based on the parameters presented by the "Preliminary manual of petrography applied to the study of stone materials for roads", following a sequence of visual evaluation of a set of 58 units of grains of black slag EAF, to obtain a unified compendium of response of visual characterization.

Shape, angularity and size

The analysis of the shape of the black slag EAF as an aggregate of the asphalt mixture for a flexible pavement indicates a pattern of concord an irregular aspect, according to the comparison with the typology of form of stone aggregates presented by López, evidenced by the presence of modifications in its  context, accompanied by pore content.

Figure 1. Shape of stone aggregates




Source: Preliminary manual of petrography applied to the study of stone materials for roads, taken from López, 1994.

Being amorphous contributes to not allowing physical alteration or modification in its granulometry when subjected to compaction environments due to the levels of transit to which it would be exposed as a material of the rolling layer.

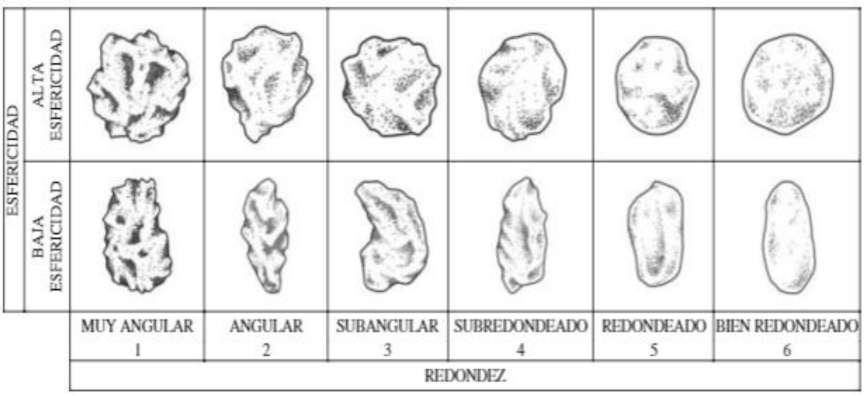
Additionally, presenting this typology of angularity and surface texture conditions the EAF black slag (Figure 2) as an element capable of resisting the solicitations of use throughout its useful life contributing to the increase of the internal friction existing between the slag and the other agglomerating components of the asphalt mixture.

Figure 2. Selection of EAF black slag particles for visual analysis

Source: Authors

Similarly, the evaluation made based on the table of the correlation table between sphericity and roundness taken from Powers (Figure 3), shows that the shape of the EAF slag corresponds to a high sphericity due to its rounded condition with angular incidence.

Figure 3. Roundness and sphericity of particles




Source: Preliminary manual of petrography applied to the study of stone materials for roads, taken from Powers, 1953.

The characterization of shape is accompanied by a physical configuration of size corresponding to coarse grain when the size exceeds 2mm, being equivalent with the type of rock corresponding to gravel (Figure 4).

Figure 4. EAF black slag sample

Source: Authors

Color

The visual observation allowed to classify the black slag within three parameters: matrix or base color, brightness or intensity of the color and the value or clarity of the same, according to the indicators presented in the preliminary manual of petrography applied to the study of stone materials for roads, obtaining the following results:

Table 7. Color classification of HEA black slag

| **matrix** | **brightness** | **value** |
|---|---|---|
| grey | Greyish - reddish | dark |

Source: Authors

The basic color presented by the EAF black slag is consistent even dark gray that extends throughout its interior and surface, accompanied by a grayish brightness with the presence of reddish tones at various points of the sample from the presence of iron in its composition (Figure 5).

Figure 5. Evidence of color in BLACK Slag EAF

Source: Authors

Texture

The valuation of the texture in a visual way allows to establish a correspondence to "vitreous texture" because the black slag EAF presents an amorphous form with content of crystalline grains of iron minerals and presence of empty spaces identified as pores  (Figure 5).

Structure

The distribution and spatial order of the components of the EAF black slag on a macroscopic scale presents a homogeneous structure in which a preferential distribution of them is not distinguished, giving a solid and unified context (Figure 5).

Porosity

The selected sample of EAF black slags for macroscopic evaluation presents a high porosity considering that the presence of pores contained in it is between 16 and 32% of the totality of its individual surface under analysis, characteristic of macropores to contain large sizes that allow the circulation of water without generating its retention, being a repetitive response along the particles visualized (Figure 6), evaluated based on the letter of estimation of the percentage of porosity of Compton.

Figure 6. Evidence of porosity in EAF black slags

Source: Authors

Resistance

The removal of sole particles present on the surface of the sample was performed to obtain a better visualization of the response obtained by the EAF black slag. As analysis samples, two categories were selected, the first with particles with very high pore content and the second with high pore content (standard range between 16%-32%); when analyzing the resistance from field indices presented by González Vallejo, it was evidenced that the material does not allow the generation of marks with elements such as the nail and the knife, in the same way, the sample with very high presence of pores presented disintegration of the material and fracture after applying a total of 3 blows with hammer; on the contrary, the sample with high pore content did not present particle detachment or fractures after being exposed to the same procedure (Table 8).

Table 8. Result of resistance analysis based on González de Vallejo field indices

| | description | eld identificati | ≈Pressures (Mpa) | Sample type | evidence |
|---|---|---|---|---|---|
| R4 | Hard rock | It takes more than one hammer blow to fracture it | 50 - 100 | Very high porosity |  |
| R6 | Extremely hard rock | When hitting with the hammer only shrapnel jumps | >250 | High porosity |  |

Source: Authors

This leads to establish that by increasing the porosity in the hea black slag, it tends to be more susceptible to damage before the application of external loads because in its surface structure there is no continuity to be able to transmit and support the loads in a uniform and homogeneous way.

## 5. Granulometric analysis of aggregates. I.N.V.E. – 213 – 22

This method is mainly used to determine the granulometry of materials proposed as aggregates or being used as such. The results are used to determine compliance with the specifications in relation to the distribution of particles and to provide the data necessary for the control of the production of aggregates and mixtures containing them. The data can also be used for the study of relationships regarding porosity and packaging between particles (INVIAS 2022).

The granulometric analysis for coarse aggregate was performed with a total of 5787.8g of black slag HEA,of this a higher content of the same retained in thesieve 1/2 " with 1635.6g and in the sieve 3/4 " with 1082.2g was observed; allowing to denote that the evaluated particles present predominant conditions of sizes corresponding to large dimensions, and in the same way a high content of residue (dust) corresponding to the processes of loading, transport and disposal of the material was found.

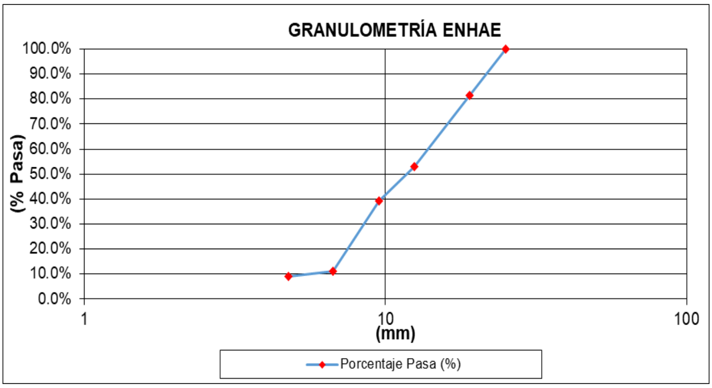
Table 9. Results granulometry of black slags (EAF)

| SIEVE OPENING | | Retained Mass (g) | Percentage Retained (%) | Cumulative Retained Percentage (%) | Percenta Passes ( |
|---|---|---|---|---|---|
| (Denom. Standard) | (mm) | | | | |
| 1" | 25 | 520,1 | 9,0% | 0,0% | 100,0% |
| 3/4" | 19,00 | 1082,2 | 18,7% | 18,7% | 81,3% |
| 1/2" | 12,50 | 1635,6 | 28,3% | 47,0% | 53,0% |
| 3/8" | 9,50 | 800,4 | 13,8% | 60,8% | 39,2% |
| 1/4" | 6,68 | 1629,6 | 28,2% | 88,9% | 11,1% |
| No. 4 | 4,76 | 119,9 | 2,1% | 91,0% | 9,0% |
| bottom | - | 0,0 | 0,0% | 0,0% | 100,0% |
| ***TOTAL RETAINED:*** | | ***5787,8*** | | | |

Source: Authors

This is an indication that the EAF from the steel company DIACO presents optimal sizes to form an asphalt mixture with a focus on implementing a thick aggregate with dimensions required by INVIAS to compose the diameters of the thick aggregate that makes up the asphalt mixture.

Figure 7. Granulometric curve of black slags EAF




Source: Authors

5.1 Rates of lengthening and flattening of aggregates for roads. I.N.V.E. – 230 – 22

The sample selected for the performance of the test of lengthening and flattening was received completely isolated from external contamination by means of a storage carried out by the respective delivery in transparent plastic bags of laboratory, fully sealed.

Table 10. Material information

| | |
|---|---|
| SAMPLE DESCRIPTION | Black electric arc furnace slags |
| PLACE OF ORIGIN | DIACO Tuta production plant |
| MODE OF TRANSPORT | Transparent plastic bags |

Source: Authors

The importance of this study lies in "the shape of the particles of the aggregates is important in the construction of roads, because the defective particles usually generate inconveniences. Flat, elongated particles tend to produce unworkable concrete mixtures, which can affect their long-term durability. In granular layers and asphalt mixtures, these particles are prone to breakage, disintegration during the compaction process, modifying the granulometry of the aggregate and adversely affecting its behavior" (INVIAS 2022).

The sample corresponding to EAF had an initial weight of 5458.3g to perform the flattening and eltening test, with which it was passed one by one of the fragments that integrate it by the measuring instruments of each parameter (wingingandflattening); in the first of these (elonging) the classification corresponding to each fraction of passes and retains of the material was verified based on the longest measurement present by it; in the second (flattening) it was taken into account to classify the sample based on its narrowest surface, taking into account its ability to pass without the need to exert force on it.

Table 11. Results of lengthening and flattening

| Fractions | | INITIAL MASS (g) | MASS OF FLAT PARTICLES (g) | % FLATTENING | MASS OF LONG PARTICLES | % LENGTHIN |
|---|---|---|---|---|---|---|
| % PASSES | % RETAINED | | | | | |
| 2½" | 2" | 0 | 0 | 0 | 0 | 0 |
| 2" | 1½" | 0 | 0 | 0,0 | 0 | 0,0 |
| 1½" | 1" | 520,1 | 842,6 | 162,0 | 308,9 | 59,4 |
| 1" | 3/4" | 1082,8 | 1487,3 | 137,4 | 1263,9 | 116,7 |
| 3/4" | 1/2" | 1635,6 | 1215,2 | 74,3 | 1413,4 | 86,4 |
| 1/2" | 3/8" | 801 | 460,1 | 57,4 | 801 | 100,0 |
| 3/8" | 1/4" | 1418,8 | 7,9 | 0,6 | 161,8 | 11,4 |
| IN TOTAL | | 5458,3 | 4013,1 | 431,7 | 3949,0 | 373,9 |
| *GLOBAL FLATTENING INDEX* | | | | | *74* | |
| *GLOBAL LENGTHING INDEX* | | | | | *72* | |

Source: Authors

The laboratory test showed that the highest percentage retained of material based on the flattening of the same, was located in the fractions of 1 "-3/4" with 1478.3g and in 3/4"-1/2" with a total of 1215.2g, generating an overall flattening index of 74%; Similarly, it is established that in the fractions corresponding to the same flattening, the largest amount of material is concentrated in the fractions of 3/4"-1/2" with 1413.4g and 1"-3/4" 1263.9g respectively, generating an overall elration index of 72%.

This allows to establish that the material has conditions of eltenation and flattening predominant, but when evaluating the relationship of the two parameters together allows to denote the presence of particles of large and proportional dimensions, due to the small difference between the values obtained from them evidencing a difference between them of 2% , guaranteeing that when implemented as an aggregate in the asphalt mixture it will comply with the conditions of workability, durability without presenting breakage or disintegration.

5.2 Resistance to degradation of aggregates of sizes less than 37.5mm (1 1/2") by means of the los angeles machine. I.N.V.E. – 218 – 13

A total of 5003.4g EAF black slag was implemented, including as material retained in the 3/4", 1/2", 3/8" and 1/4" sieves. After entering the material to the machine of the angels, a total of 12 steel spheres with a weight of 5000g each were entered, which rotated at 500 revolutions, which is equivalent to 17 minutes. After leaving the material and being classified by means of the sieve N°12, a total weight of 4107.7g is evidenced, this led to determine a wear percentage of 17.9%.

Table 12. Contained material for machine rehearsal of angels

| SIEVE RETAINED | Weight (g) | Total sample (g) | Final sample (g) |
|---|---|---|---|
| 3/4" | 1249,7 | 5003,4 | 4107,7 |
| 1/2" | 1253,2 | | |
| 3/8" | 1250 | | |
| 1/4" | 1250,6 | | |

Source: Authors

When evaluated together with the ranges established by standard to be a thick aggregate suitable to be implemented as a component of the rolling layer it is established that it is within the ranges by not exceeding the required percentage of 25% and being below with a difference of 7.1% (table 13). From this it is concluded that the black slags being a sub-product of steel presents a high hardness, which contributes to resist the effects of impact, abrasion and therefore grinding, additionally, it takes into account the state of the art research carried out by the engineer Héctor Sánchez (Sánchez et al. 2014), who presents in his conclusions an analysis concerning that this type of slag presents degradation compared to mechanical solicitations.

Table 13. Results of wear in angels machine

| CHOSEN GRANULOMETRY | A | B | C | D | compliance | | |
|---|---|---|---|---|---|---|---|
| LOAD MASS (g) | 5000 ± 25 | 4584 ± 25 | 3330 ± 25 | 2500 ± 25 | Rolling layer (25% Max) | Intermediate layer (35% Max) | Bas laye (35% Max |
| NUMBER OF SPHERES | 12 | 11 | 8 | 6 | | | |
| INITIAL WEIGHT (g) | 5.003,50 g | - | - | - | | | |
| FINAL WEIGHT (g) | 4.107,70 g | - | - | - | Meets | N/A | N/A |
| WEAR (%) | 17,90 % | - | - | - | | | |

Source: Authors

5.3 Percentage of fractured particles in a thick aggregate. I.N.V.E. – 227 - 13.

The test was performed with a total sample of 1560.2g contained its particles between the sieves retained in 3/4" and 3/8", in each retained fraction the amount of material with fractured faces, non-fractured faces and boundary material was evaluated; from there it was determined that 100% of the evaluated particles have fracturing conditions.

Table 14. Results of fractured faces

| Fraction | | SAMPLE WEIGHT (g) | WEIGHT FRACTURED PARTICLES (g) | WEIGHT BOUNDARY PARTICLES (g) | WEIGHT NON-FRACTURED PARTICLES (g) | FRACTURED FACES (%) |
|---|---|---|---|---|---|---|
| Come in | Retains | | | | | |
| 1 1/2" | 1" | 0 | 0 | 0 | 0 | 0 |
| 1" | 3/4" | 696,60 g | 696,60 g | 0,00 g | 0,00 g | 100 % |
| 3/4" | 1/2" | 708,60 g | 708,60 g | 0,00 g | 0,00 g | 100 % |
| 1/2" | 3/8" | 155,00 g | 155,00 g | 0,00 g | 0,00 g | 100 % |
| Total: | | 1560,2 | 1560,2 | 0,0 | 0,0 | |
| *TOTAL FRACTURED FACES* | | | | | *100 %* | |

Source: Authors

This high percentage of fracturing allows it tobe known that the EAF black slags are very irregular materials which increases the resistance to cutting by contributing decisively in the greater friction between the elements that make up the asphalt mixture, giving stability and texture to the final composition of the rolling layer by allowing an optimal coupling which leads to obtain better adhesion and consolidation.

## 6. Conclusions

The research conducted on the incorporation of Electric Arc Furnace (EAF) black slag as a coarse aggregate in asphalt mixtures for flexible pavements has yielded promising results. The experimental findings indicate that EAF black slag can be effectively utilized as a substitute for conventional aggregates, offering comparable, and in some cases superior, performance characteristics in terms of stability, durability, and resistance to deformation.

The laboratory tests, including the Marshall Stability, Indirect Tensile Strength, and Fatigue Resistance tests, demonstrated that the mixtures incorporating EAF black slag met and exceeded the standards set by the Colombian norm INVIAS-22. This suggests that the material is not only viable but also advantageous in terms of enhancing the mechanical properties of asphalt mixtures under various environmental conditions.

Additionally, the use of EAF black slag contributes to environmental sustainability by providing a beneficial use for a by-product that would otherwise require disposal. This aligns with global trends toward the circular economy and sustainable construction practices.

Further research is recommended to explore the long-term performance of these mixtures under real traffic conditions and to assess the potential for scaling up the use of EAF black slag in road construction across different regions with varying climatic conditions. The findings of this study contribute to the growing body of knowledge supporting the innovative use of industrial by-products in infrastructure development, paving the way for more sustainable and cost-effective construction solutions.

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