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Use of blast furnace dust to improve the properties of granular material for pavements

Uso de polvo de alto horno para mejorar las propiedades de material granular para pavimentos

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Abstract

The granular base and sub-base materials used in the construction of road surface structures must comply with certain requirements. In some cases, the requirements are not complied with and it is necessary to search for alternatives to improve the properties of the materials and thereby enable the use of these materials in the construction of roadways. Blast furnace dust is a residue from the production of steel that is of little use and is causing a negative environmental impact due to its accumulation. This study was carried out to analyse the possibility of utilizing blast furnace dust to improve the properties of granular materials, as an alternative that mitigates the environmental problems caused by the disposal and accumulation of these residues, which affect the areas of influence of these companies. To achieve this goal, the chemical and physical properties of blast furnace dust were determined and a analysis was carried out on mixtures of granular base and sub-base materials with 0, 2, 4, 6, and 8 percent dust. The analysis took place of determined characteristics including optimum humidity, maximum dry density, resistance, plasticity, and expansion in the presence of water. The results indicate that with the incorporation of 6% of BFD the properties of the granular material are improved and it can be used as an optimal material in road construction.

Keywords: blast furnace dust; granular base; granular sub-base; resistance; plasticity; expansion; water stability.

Resumen

Los materiales tipo base y subbase granular utilizados en la construcción de estructuras de pavimento deben cumplir algunos requerimientos; en algunos casos, dichos requerimientos no se cumplen en su totalidad y es necesario buscar alternativas para mejorar las propiedades y así poder utilizar esos materiales en la construcción de carreteras. El polvo de alto horno es un residuo de la producción de acero, el cual tiene poco uso y está causando un impacto ambiental negativo debido a su acumulación. Este estudio se realizó con el objetivo de analizar la posibilidad de utilizar polvo de alto horno para mejorar las propiedades de los materiales granulares, como una alternativa para mitigar los problemas ambientales causados por la mala disposición y acumulación de estos residuos, que afectan las áreas de influencia de las empresas. Para alcanzar el objetivo, se determinaron las propiedades químicas y físicas del polvo de alto horno y se analizaron mezclas con material tipo base y subbase granular con 0, 2, 4, 6 y 8 %. Se determinaron y analizaron características como humedad óptima, densidad seca máxima, resistencia, plasticidad y expansión en

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presencia de agua. Los resultados indican que con la incorporación del 6 % de BFD se mejoran las propiedades del material granular y se puede utilizar como material en la construcción de carreteras.

Palabras clave: polvo de alto horno; base granular; subbase granular; resistencia; plasticidad; expansión; estabilidad hídrica.

1. Introduction

The structure that makes up a road surface is formed of a series of layers with different mechanical properties, starting with the rolling surface, followed by the granular layers, and finally the subgrade layer [1]. Each of these layers is comprised of materials and natural aggregates that must comply with construction specifications. In some cases, these aggregates do not comply with some of the specifications and it is necessary therefore to change the material or think about improving its properties through the process of stabilization. Currently, there are different stabilization techniques, among the most common are the use of cement, lime and asphalt products [2], [3]. In addition, recent research has used new materials such as slag, fly ash, and lime sludge [4], [5], [6].

Currently, during the execution of road infrastructure projects in Colombia, materials are constantly found which are not appropriate for said projects and so the need arises to explore new technologies. For this reason, this study proposes to determine the feasibility of the use of BFD as an alternative to stabilize and improve the properties of granular base and sub-base materials for road surfaces.

Blast Furnace Dust (BFD) is a residue of the process of transformation of the iron mineral into cast iron in integrated steelworks [7]. The integrated steel working process begins with the mining of prime materials: iron mineral, carbon, and lime [8]. These materials reach the blast furnace where they are melted and pig iron, granulated slag, and BFD are obtained [9]. BFD is a solid residue that does not have much use, containing mainly iron, carbon, and low quantities of silicon, aluminium, calcium, and magnesium [10]. The typical quantity of slag generated is between 200kg and 400kg with approximately 7kg to 45kg of dust per tonne of cast iron [11].

In Colombia, the only integrated steelworks *are Acerías Paz del Río S.A.*, located in the state of Boyacá, where the production of BFD is approximately 7,200 tonnes per year [12]. Due to the lack of use for this residue and the inadequate disposal of the same, an environmental problem is being created. Taking this into account, the necessity arises to search for an alternative use for BFD. Additionally, the construction and maintenance of roadways increases the use of natural, non-renewable aggregates, the mining of which also leads to a negative impact on the environment.

2. Materials and methodology

2.1. Materials

The material used in this study was granular base and subbase material and BFD as stabilizing material. The granular material was obtained from the *San Rafael* quarry in the municipality of Tunja. The characteristics of the granular materials were measured following the INVIAS-13 regulations [13] and the ASTM international regulations [14]. As can be seen in Table 1, and to analyze the effect of the addition of BFD, the material used did not meet some of the properties required in the specifications. The physical and mechanical characterization of the granular material was carried out considering the class A granular base and the class A granular subbase according to the general specifications for the construction of roadways [15].

Blast furnace dust is generated during the manufacture of cast iron. The iron mineral, coke, lime and sinter are melted at a temperature of approximately 1,500°C, during which process gasses and fine particulate material are generated and recovered in collectors [16], Figure 1.

This material was obtained from *Acerías Paz del Río S.A.*, Figure 2. Both companies are located in the state of Boyacá, Colombia. The BFD is of a fine granulometry with a maximum size of 2.0mm, and the physical characteristics were discovered through the respective tests where the results are shown in Table 2.

These results show that the BFD has a higher specific density than that of sand-type fine material. Furthermore, it has high absorption, high sand equivalent and high angularity in comparison to the fine particle fraction of granular material. The high absorption is directly related to the higher quantity of water needed to reach the maximum dry density.

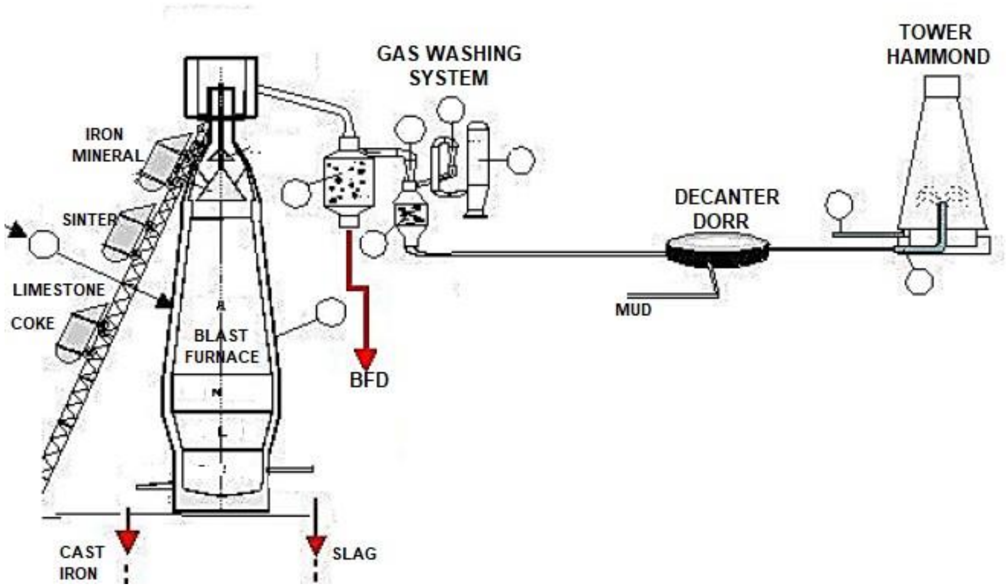

Figure 1. General process of the blast furnace at *Acerías Paz del Río S.A.* Source: [17].

Table 1. Results characterization of the material type base and granular subbase

Properties	**Standard [18],[13]**	**Granular base**			**Granular subbase**		
		Obtained value	**Specification Class A**	**Meets**	**Obtained value**	**Specification Class A**	**Meets**
Loss angel's abrasion, %	INV E-218 ASTM C 331	23.0	<35	Yes	23.0	<50	Yes
Degradation Micro-deval, %	INV E-238 ASTM D 6928	24.4	<25	Yes	24.4	<30	Yes
Resistance 10% fine, kN	INV E-224 SABS 842	93	>90	Yes	-	NA	-
Soundness test, %	INV E-220 ASTM C 88	8.2	<12	Yes	8.5	<12	Yes
Liquid limit, %	INV E-125 ASTM D 4318	11.0	-	-	27.0	<25	No
Plasticity index, %	INV E-126 ASTM D 4318	5.0	0	No	10.0	<6	No
Sand equivalent, %	INV E-133 ASTM D 2419	31.0	>30	Yes	28.1	>25	Yes
Methylene blue	INV E-235 EN 933-9	8.0	<10	Yes	-	NA	-
Clay lumps, %	INV E-211 ASTM C142	2.0	<2	Yes	1.5	<2	Yes
Elongation and flattening index, %	INV E-230 BS 812-105	25.0	<35	Yes	-	NA	-
Fractured faces, %	INV E-227 ASTM D 5821	100.0	100	Yes	-	NA	-
Fine fraction angularity, %	INV E-239 ASTM C 1252	49.7	>35	Yes	-	NA	-
CBR, %	INV E-148 ASTM D 1883	85	≥95	No	28	≥40	No

Figure 2. Blast furnace dust (BFD)

Table 2. BFD characterization results

Properties	Standard [18], [13]	BFD Obtained value
Plasticity index, %	INV E-126 ASTM D 4318	NP
Fine fraction angularity, %	INV E-239 ASTM C 1252	53
Sand equivalent, %	INV E-133 ASTM D 2419	86
Gsb	INV E-222 ASTM C 127/128	2.36
Gsss		2.50
Gsa		2.73
Absorption, %		5.7

BFD is a material that has been used very little as a material in road construction. In Colombia, some research has been carried out to analyse the feasibility of using this material in the manufacture of asphalt mixtures [19]. Materials such as slags, also residues from the iron and steel process, have been used to stabilize soils and granular materials [20].

2.2. Methodology

2.2.1. BFD Chemical characterization test

To discover the chemical composition, X-ray fluorescence was used to quantitatively determine the elements present in the BFD. A scanning electron microscope (SEM) was used to determine the morphology of the BFD. Digital topographical images of the sample were obtained.

2.2.2. Incorporation of the BFD to the granular materials

To achieve the objectives of this study, tests were carried out to investigate the behaviour of the granular material with the incorporation of BFD. The tests included the plasticity index, expansion, and California bearing ratio (CBR). These tests were undertaken with different percentages of BFD incorporated (0%, 2%, 4%, 6%, and 8%) in conditions of contained moisture and maximum dry density that were determined using the modified Proctor compaction test. The substitution of part of the fine particle fraction of the granular material for BFD was carried out in volume so as not to alter the granulometry of the material. Finally, the hydrolytic stability test was realized [21] with test cylinders elaborated of each material without the incorporation of BFD and others elaborated with the optimum BFD content. The optimum BFD content was determined as the percentage added to each granular material that offered the best characteristics.

The hydrolytic stability test is one visual inspection that aims to determine the behaviour of the test cylinder of material when in direct contact with water, achieved by submerging 2/3 of the test cylinder in water [22]. To carry out this test, test cylinders with a height of 17 centimetres and a diameter of 10 centimetres were elaborated with the granular material without the addition of BFD and others with the optimum BFD content. It could then be observed whether the addition of BFD improves the hydrolytic erosion of the materials. The cylinders were cured for 24 hours before being immersed and observed to measure the time elapsed before failing.

3. Results and discussion

3.1. Morphology and chemical composition of BFD

Particles of the BFD were subjected to a microscopic examination to characterize their shape and superficial texture. The examination was carried out with a scanning electron microscope (SEM) Leo 410, with a 9.85E-5 Torr vacuum chamber, 1.2nA of current in the filament, and a voltage of 15kV in the anode. The evaluation of the chemical composition was realized using X-ray fluorescence (XRF) analysis, using a Rigaku Primus II sequential spectrometer with a rhodium tube and a beryllium window of 30 microns.

Figure 3 shows the SEM micrograph of the BFD at a 500X scale, which shows a rough and porous superficial texture with sub-angular, rounded borders that have the characteristic of a strong link between particles of the same material and can account for better interaction between granular material particles. Taking the results of the physical characterization into account, the high absorption of the material can be attributed to the texture and porosity.

The chemical composition of the BFD detected by XRF is shown in Table 3. The principal chemical constituent is Fe_2O_3 at 45.3%. In terms of the volumetric expansion of BFD due to the low CaO and MgO content, it can be asserted that this material presents a low probability of having expansive characteristics. The CaO/SiO2 ratio considers the alkalinity of the material being classified in three levels: low alkalinity (<1.8), intermediate alkalinity (1.8-2.5), and high alkalinity (>2.5) [23]. The BFD has a CaO/SiO2 ratio of 0.5.

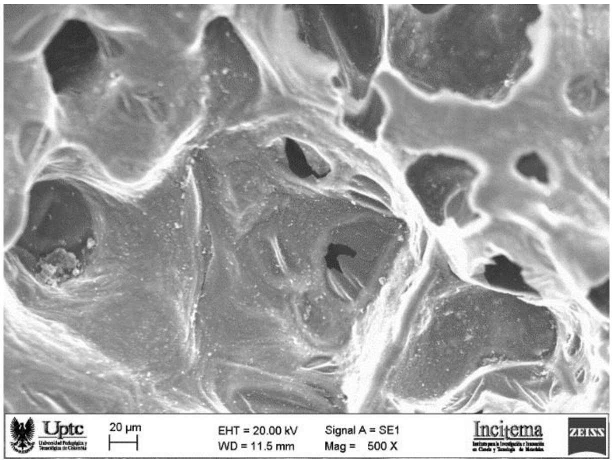

Figure 3. Microscopic morphology BFD

Table 3. Chemical components of BFD

Component	% in weigh
Fe_2O_3	55.30
SiO_2	10.45
CaO	4.95
Al_2O_3	3.60
MnO	3.32
MgO	1.00
P_2O_5	1.03
K_2O	1.33
Otros	19.02

3.2. Compaction test

The compaction tests were carried out in accordance with the INV E142-13 [24]/ASTM D1557 [25] regulations. The results for granular sub-base and base can be found in Table 4. As shown in the Table, the maximum dry densities increased with an increased percentage of BFD up to 6%. In the same way, the optimum humidity percentage increased with an increase in BFD. These results can be attributed to a higher specific gravity, to the porosity and absorption of the BFD.

Table 4. Compaction test results

BFD (%)	**Granular subbase**		**Granular base**	
	Optimal humidity (%)	Maximum density (g/cm^3)	Optimal humidity (%)	Maximum density (g/cm^3)
0	5.0	2.220	6.1	2.230
2	5.2	2.235	6.5	2.245
4	5.7	2.239	6.8	2.248
6	6.1	2.258	7.2	2.255
8	6.5	2.222	7.5	2.205

3.3. Plasticity

Figure 4 contains the results of the tests to determine the plasticity index of the fine particle fraction of each material. As shown, the plasticity index decreases with an increase in BFD. In the case of the granular sub-base, the plasticity index of the original material was 10% and, as the content of BFD was increased, this value decreased to 4%. Similarly, with the original granular base material, the plasticity index decreased from 5% until it became a non-plastic material. It is important to note that these results can be attributed to the addition of BFD, which is a non-plastic material.

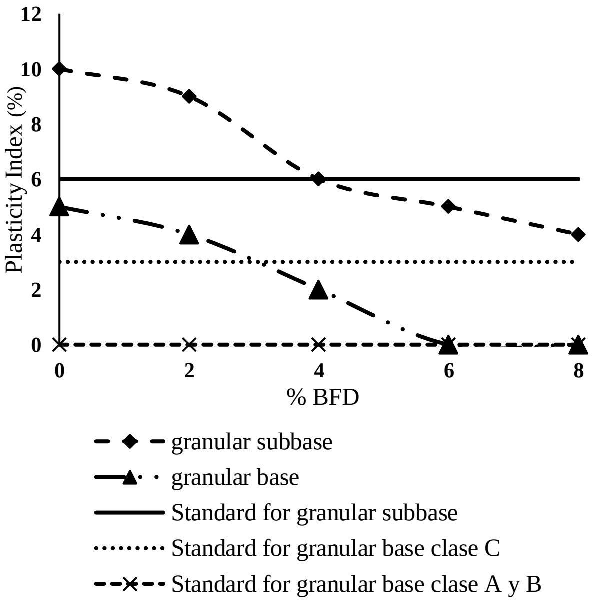

Figure 4. Behavior of the plasticity index.

The granular sub-base with the incorporation of 4% of BFD complies with the requirement by the article 320-13 of INVIAS while the granular base with the incorporation of 4% of BFD complies with the requirement following the article 330-13 of INVIAS for a class C granular sub-base and, with the incorporation of 6% of BFD, complies with the requirement for a class A and class B granular base.

3.4. Expansion test

Figure 5 shows the behaviour of the percentage of expansion of the granular base and sub-base materials with the incorporation of BFD. With an increase in the percentage of BFD, there was a reduction in the potential for expansion. This reduction being important as it signifies that if this material is exposed to water, it will not suffer considerable changes to its volume, one of the most important properties of the road surface.

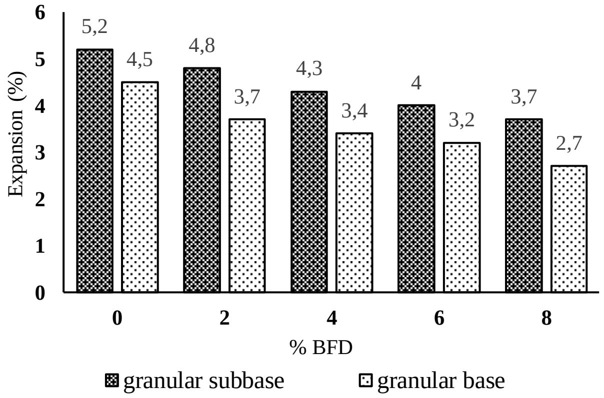

Figure 5. Behavior of the expansion percentage

3.5. CBR test

Figure 6 shows the CBR values of the granular sub-base samples with different levels of BFD incorporation. The CBR values for the incorporation of 0, 2, 4, 6 and 8% were 28, 32, 36, 42 and 38% respectively. The greatest resistance was obtained with the incorporation of 6% of BFD. The original sub-base material does not comply with the requirement in the article 320-13 of INVIAS as the minimum CBR is 30%. However, with the incorporation of 2 and 4% of BFD, the resistance value rose, and this could be used as a class B or C granular sub-base. The effect of the incorporation of 6% of BFD is important as this material could be used as a type-A granular sub-base.

In the same way, Figure 7 shows the CBR values obtained in the granular base samples with the incorporation of different percentages of BFD. The CBR values were 85, 91, 94, 96 and 92% for 0, 2, 4, 6 and 8% of BFD respectively. Although the original material complies with the requirement in the article 330-13 of INVIAS for a class B or C granular base, with the incorporation of BFD, there is an increase in the resistance of the material. Notwithstanding, with a 6% incorporation of BFD, the resistance increases and the material may be used as a type-A granular base.

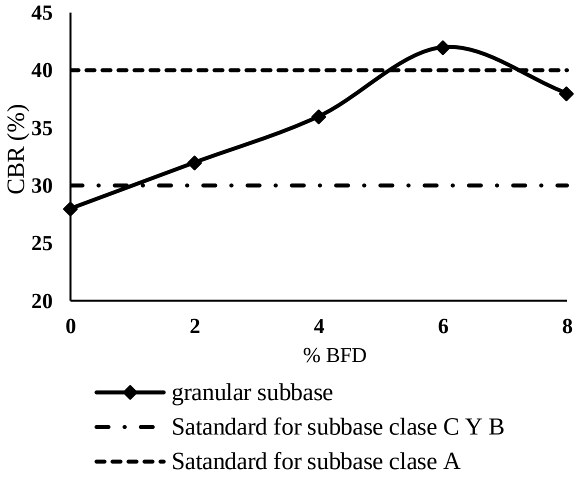

Figure 6. CBR behavior for granular subbase

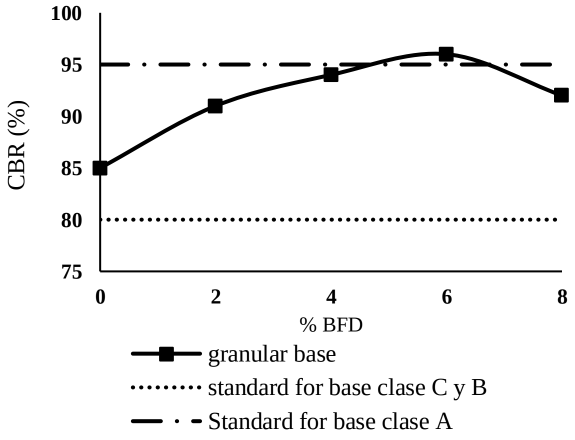

Figure 7. CBR behavior for granular base

3.6. Water stability

The established optimum percentage of BFD is 6% for both materials. This considering that with this percentage of BFD, the greatest dry density was found in the compaction test and similarly the greatest resistance (CBR). The test cylinders were compacted to the maximum dry density with a gyratory compactor and, after the curing time, they were placed in water immersion, Figure 8.

Following the immersion, a loss of material occurred in the cylinders without BFD. After 28 minutes, there was a loss of a greater quantity of the granular sub-base material and at 30 minutes of the granular base material, respectively. After 1 hour, the cylinders without BFD failed completely in both materials, as can be seen in Figure 9.

For the granular sub-base material, the cylinder with 6% of BFD failed after 2 hours and 22 minutes, and for the granular base material, the cylinder with 6% of BFD failed after 2 hours and 35 minutes.

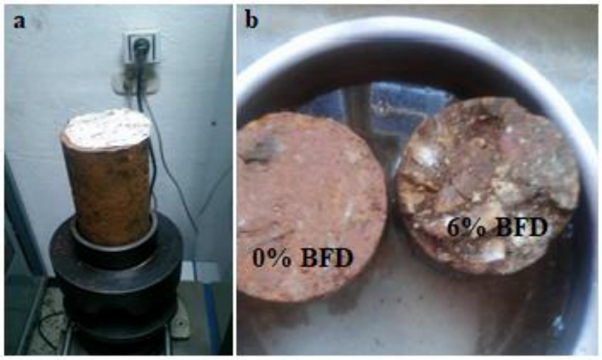

Figure 8. a) Test tube for water stability. b) Immersion specimens

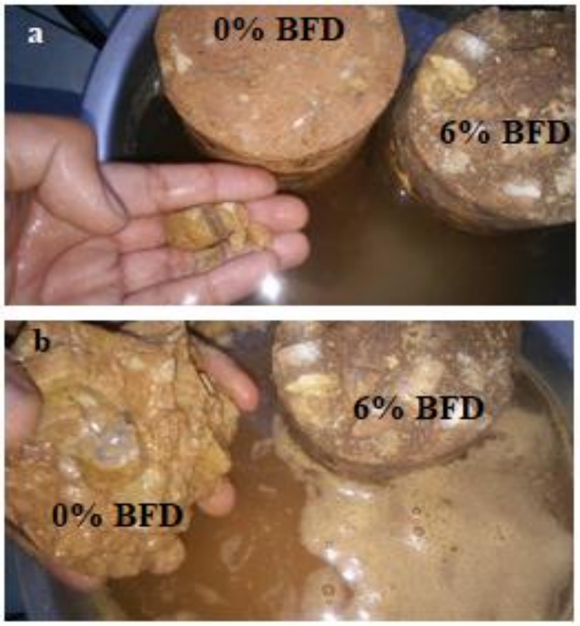

Figure 9. Granular base specimens. a) 30 minutes of immersion. b) 60 minutes of immersion

4. Conclusion

Once the characterization of the BFD was completed, it was defined that this material complies with the quality parameters to enable it to be used as part of the aggregate of granular base and sub-base as this is a non-plastic material with a high sand equivalent index. Furthermore, considering its granulometry, it can replace a part of the fine particle fraction of each material and do not alter the initial gradation thereby also not provoking distortions in the results.

Adding BFD to granular base and sub-base materials increases the dry density of the material as shown by the modified Proctor test carried out to establish the optimum compaction humidity. This increase in density can be attributed to the greater specific gravity of BFD when compared with the specific gravity of fine, sand-type material. There is also a slight increase in the optimum compaction humidity as the percentage of BFD incorporated increases due to the porosity of the material and the greater absorption reported in this test.

Due to the nature of BFD being a non-plastic material, adding it to a material that shows some form of plasticity and does not comply with the established requirements ending in a reduction in this parameter. This is beneficial as, by reducing the plasticity of the material, the expansive potential drops considerably, as evidenced by the results of the test carried out on the test cylinders during the immersion for the CBR test.

Of the mixtures created for the CBR test, a determination was made of the optimum percentage of BFD incorporation as being 6%. This being the percentage that obtained the greatest value for this parameter with 96% for the granular base, thereby allowing it to meet the minimum value required by INVIAS for a class A granular base. Moreover, it was determined that with a higher percentage of BFD, the resistance of the material decreased. Similarly, for the granular sub-base material, a CBR value of 42% was obtained for the mixture with 6% of BFD incorporated. These findings can be attributed to the greater specific gravity of BFD and the greater quantity of water necessary to compact it and reach the maximum dry density.

With the addition of BFD to the granular material, the susceptibility to erosion due to water contact is reduced. It slowed the degradation and the failure of the test cylinders in the hydrolytic stability test, a property which benefits the durability of the road surface structure in cases where the granular layers become subjected to the presence of water be that due to the water Table or because of water infiltration from the surface. With the utilization of BFD as a material in the granular layers of road surfaces, a contribution is made to environmental development as this diminishes the accumulation and inadequate disposal of the material.

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