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Evaluation of the use of blast furnace slag as an additive in mortars

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Abstract

Clinker is the raw material used in the manufacture of cement. However, this material is very harmful to the environment, since it is estimated that for every ton of clinker produced, about 1.0 ton of CO_2 is released into the atmosphere. For this reason, alternatives were sought for the use of other materials that are less harmful to the environment. This has led to the use of industrial by-products with the aim of increasing their use and thus reducing the amount of carbon released into the atmosphere. Blast furnace slag is a by-product used in the manufacture of some cementitious products. The aim of this research is to conduct a study on the use of slag as an additive for cement or concrete. The mortar samples were tested according to Brazilian, American and European technical standards. Physical, chemical and compressive strength tests were carried out which confirmed the possibility of using the slag without chemical or thermal activation.

Keywords: sblast furnace, clinker, cement, GGBFS, mortar.

1. Introduction

The production of clinker, the raw material for cement, is harmful to the environment, emitting about 1.1 tons of CO_2 emissions for each ton of clinker produced. Considering this scenario, new alternatives for the use of materials that are less harmful to the environment were necessary, leading to the increasing use of industrial by-products, and consequently, reducing the amount of carbon released into the atmosphere.

There are several industrial residues that can be used as cementitious materials, additives for concrete or mortar and require little or no pretreatment for their use. The Granulated Blast Furnace Slag (GBFS) is a raw material used in the production of some cementitious products. Blast furnace slag consists of calcium silicates and aluminosilicates and other phases (Sultan *et al*., 2018; Yeung *et al*., 2020; Hadj *et al*., 2021; Priya *et al*., 2021; Cardoso *et al*., 2021c; Cardoso *et al*., 2022b; Colangelo *et al*., 2021; Jayarajan *et al*., 2021).

There is a wide variety of slag from all types of steel products and in this context it can be said that slag produced in blast furnace fueled by metallurgical coke is a by-product produced during the production of cast iron in blast furnaces and is formed by the chemical combination of iron ore impurities with limestone, dolomite and coal ash. In the production of cast iron, the slag, which has a lower density (about 3.15 g/cm^3), floats on the denser cast iron (about

7.86 g/m^3) and after production, the slag is sent to coolers and slag granulators. The granular slag has a particle size between 4 and 15 mm and has dimensions of less than 45μm and a surface area of 400 to 600 m^2/kg after grinding, which can be used as latent hydraulic cement. Specifications for granulated blast furnace slag as a cementitious material can be found in ASTM C989, where granulated blast furnace slag is divided into three strength grades. These grades are based on an activity index of the slag: grade 80, 100 and 120 (low, moderate and high activity index, respectively). (Zhu *et al*., 2020; Prusty *et al*., 2020; Qureshi *et al*., 2020; Mohammed *et al*., 2021).

The chemical composition of blast furnace slag may vary depending on its origin, but to be considered a cementitious material, the chemical composition must be in the following ranges: CaO (30-45%), SiO_2 (30-48%), Al_2O_3 (15-25%), Fe_2O_3 (0.5-2%), and other oxides in smaller amounts. According to the chemical requirements of ASTM C989, 2.5% and 4.0% are set as maximum amounts for sulfur (S) and sulfates, respectively; at these amounts, the presence of slag in reinforced concrete does not pose a corrosion risk to the reinforcement. As a cementitious material, granulated slag has the following properties: it is a strong latent hydraulic cement when ground, has low Na_2O and K_2O content, low density, high water permeability, does not contain chlorides, and does not produce alkaline aggregate reactions. The replacement of cement with ground granulated blastfurnace slag (GGBFS) generally reduces the amount of water required to produce the same amount of concrete (Hwang *et al*., 2019; Wang *et al*., 2019; Wang & Jia, 2019; Sriniva & Reddy, 2020; Cardoso *et al*, 2021b; Hammad *et al*., 2021; Stocker *et al*., 2021; Jithendra, *et al*., 2021; Selvarani & Preethi, 2021; Li *et al*., 2021; Cardoso *et al*, 2022).

The main advantages of using ground granulated slag in fresh concrete are: lower heat of hydration, lower permeability to external agents, greater resistance to chemical attack, resistance to sulfate attack, better workability of the mix and greater corrosion resistance of the reinforcement. We also have the main advantage of reducing the amount of clinker in the mix (Onoue *et al*., 2017; Xie *et al*., 2019; Poloju & Srinivasu, 2021; Medeiros *et al*., 2021; Munjal *et al*., 2021; Narsimha *et al*., 2021).

There are numerous researches on the chemical and thermal activation of blast furnace slag. However, the scientific articles that consider blast furnace slag as active in cements after its manufacture are few. Blast furnace slag has always been considered a secondary product in the steel production process. When considering the new world scenario, in which the reduction of carbon dioxide emissions and the appropriate use of by-products of the production processes have made the control of chemical composition and the appropriate use of slag interesting for the steel sector, the main objective of this research was to accomplish a study of the use of ground granulated blast furnace slag as an addition to cement or concrete without chemical or thermal activation, considering the technical standards of different countries for the classification of cement with blast furnace slag.

2. Experiment

The material used in this research was a sample of 100 kg of granulated blast furnace slag that was collected from a stockpile, adopting the criteria recommended by ASTM E-300. Regarding the moisture test, performed in accordance with the ASTM C566 standard, it was necessary to dry the slag in an oven (105 ± 5) °C for 24h, until a constant mass was obtained. After the moisture test, according to the ASTM C29 standard, the calculation of the specific mass g/cm^3 of the granulated blast furnace slag sample was performed.

The ASTM C136 technical standard was used as a reference to determine the particle size composition, maximum characteristic dimension and fineness modulus of the granulated slag sample. Chemical analyses by X-ray fluorescence spectroscopy were performed on the granulated blast furnace slag sample and the results are shown in Table 1.

Table 1 - Chemical analysis of the blast furnace slag sample (%).

CaO	SiO_2	Al_2O_3	MgO	Fe_2O_3	TiO_2	K_2O	MnO	Na_2O	S	Cl	Others
43.77	34.82	12.21	5.27	0.55	0.48	0.43	0.31	0.25	1.15	0.006	0.754

During the chemical analysis, the amount of insoluble residue and loss on ignition (LOI) was also determined, according to the ASTM C114 standard, also using the X-ray fluorescence spectroscopy technique.

The evaluation of the degree of vitrification and refraction index was made using a polarized transmitted light optical microscope, by counting the partially and totally crystallized grains. The refractive index is an optical characteristic intrinsic to the substances, varying according to its crystalline arrangement and chemical composition. It is a very useful tool in identifying minerals or qualifying slag as to its basic or acidic nature. This test was accomplished using as a reference the procedure code 52504001 of the Brazilian Portland Cement Association.

Then, the granulated slag was ground in a ball mill for 4h 50 min at a speed of 750 rpm to reach a specific area and fineness close to that of Portland cement. The grinding material was composed of steel grinding bodies with diameters between 20 and 77 mm. After grinding, the samples were submitted to the fineness determination test by means of the Blaine permeabilimeter, which consists of determining the time it takes for a given amount of air to pass through a compact amount of material. To evaluate the performance of the blast furnace slag, three new types of experimental cement were prepared from an ASTM C150 type I industrial cement, in which 0%, 20% and 50% of ground blast furnace slag were added, replacing the cement mass. Table 2 exemplifies the cement/slag ratios. After the preparation of the three samples of experimental cement, the physical characterization tests were accomplished according to Table 3.

Table 2 - Cement/Slag ratio.

Identification	Mass of materials (kg)	
	Cement	GGBFS
(S1)	50	0
(S2)	40	10
(S3)	25	25

Table 3 - Physical characterization tests.

Essay	Technical standard ASTM
Fineness - residue on the 45μm sieve (%)	C430
Specific mass (g/cm^3)	C029
Specific area (cm^2/g)	C204
Normal consistency paste water (%)	C187
Start timing of setting (min)	C191
End timing of setting (min)	C191
Incorporated air content	C185

Regarding the evaluation of the hydraulic activity index of the slag, four different types of mortar were produced using the new experimental cement. Table 4 presents the trace of the mortars produced.

Regarding the fine aggregate used in the composition of the mortar, sand in Graded Ottawa Sand granulometry was used as specified by the ASTM C778 technical standard (section 4.2) and the amount of water used was necessary to obtain a mortar with a consistency index equal to (110 ± 5) %, as specified in the ASTM C109 technical standard (section 8.3).

Table 4 - Mortar composition.

Identification	Mass of Materials (g)			
	Cement	GGBFS	Sand	Water
(S1) Standard	1000	-	2750	500
(S2)	800	200	2750	490
(S3)	500	500	2750	480
(S4)	300	700	2750	460

Sample 2 and Sample 3 correspond, respectively, to 20% and 50% by mass of cement replacement, according to the ASTM C989 standard and as described above in Table 2. Regarding Sample 4, which was made according to the technical standards ASTM C595 and ASTM C311 with 70% of the cement being replaced by the slag, it was possible to evaluate the activity index with Portland cement. Regarding the binder, an industrial cement (ASTM C150 Type I) was used, with an alkaline equivalent content of 0.89%, meeting the limit for activity testing prescribed in the technical standard ASTM C989.

The same applies to compressive strength greater than 35 MPa at 28 days. Regarding the preparation of the specimens, cylindrical and standardized molds of (5x10) cm were used using mechanical compaction, by means of a vibrating table, in order to reduce the variability in the process. After the molding step, the specimens were kept in a humid chamber for a period of 24 hours, being then unmolded and kept submerged in a tank containing potable water until the moment of being prepared for the tests. A total of 72 samples were molded to perform the compressive strength test, with 18 samples for each group (samples 1 to 4) that were broken at 3, 7, and 28 days of age. For the compressive strength test, all specimens had their ends rectified, in order to ensure parallelism between them. For the test of resistance to axial compression, the Universal servo-electric machine with a capacity of 300 kN was used, with a special universal joint suitable for the specimen and a load cell with a 300 kN full-scale and a loading speed of (0.25 ± 0.05) MPa/s was used, as specified in the technical standard ASTM C109.

The mechanical method (axial compressive strength) is the most time-consuming and most accurate method for calculating the hydraulic activity index of slag and cement. This method aims to control the quality of the slag when used as an addition to cement and the manufacture of this cement. The methods for predicting the slag's hydraulicity can be based on chemical composition (through the use of chemical modules), microstructure (through the verification of the degree of vitrification by X-ray diffraction or microscopy), and by its own hydration (through the accelerated soda test). In this study, the mechanical method was chosen and the Equation (1) used to calculate the hydraulic activity index is presented.

$$HAI = \frac{f_c^{er}}{f_c^{r}} \text{ x } 100\% \quad (1)$$

Where, f_c^{er} is the average of the compressive strength of the specimens (at the respective age) molded with mortar prepared with a mixture of standard Portland cement (samples 2 to 4) and slag, in MPa, and f_c^{r} is the average of the compressive strength of the specimens (at the respective age), molded with mortar prepared with standard Portland cement (sample 1), in MPa.

The expandability in an autoclave was evaluated according to the ASTM C151 normative procedure and for this purpose, prismatic specimens of dimensions 2.5 cm x 2.5 cm x 25 were prepared, which were previously cured for 24 h. Initially, measurements were taken at a pressure of 2MPa and a temperature of 216ºC for 3 hours. After the necessary time, the prismatic bars were removed from the autoclave and again measured in the axial direction, with precision, and then the expansion resulting from the internal process was evaluated. The limit for normal cases when the expansion assessment is accomplished through this process is around 0.8% of the initial size. Regarding the sulfate resistance test, the ASTM C1012 test method was used for the determination of the dimensional variation of prismatic mortar specimens (25x25x285 mm) immersed in a sulfate solution.

The prismatic specimens were molded according to ASTM C109 and were cured until they reached a compressive strength of 20±1 MPa (measured by means of cubic specimens made of the same mortar) and later they were immersed in a solution of 352 moles of Na_2SO_4 (50g/L). As prescribed by this method, the bars were immersed in the sulfate solution when their strength reached the value of 20±1 MPa, which was measured using cubic mortar specimens (molded simultaneously with the prismatic bars). The mortars used were the same as described in Table 4 and the container used to store the bars in solution was hermetically closed.

The measure of dimensional variation was calculated at the ages of 7, 14, 21, 28, and 56 days. Expansion results are relative to the initial measurement (taken before the bar comes into contact with the sulfate solution), expressed as a percentage. At each test age, the solution was removed and new solution was added to the container containing the bars. The calculation of the dimensional variation at each age was performed according to Equation (2).

$$\Delta L = \frac{L_x - L_i}{L_g} \quad (2)$$

Where, ΔL = dimensional variation of bar length at age x; L_x = Prismatic bar length at age x; L_i = Length of the prismatic bar and L_g = Nominal length of the instrument (250 mm).

3. Results and discussions

First, the results of the physical and chemical analysis of the granulated blast furnace slag sample are presented. The sample moisture content of 2.3% meeting the requirements of ASTM C566. The physical granulometric test accomplished according to ASTM C566 presented a specific mass of 1.27 g/cm³, a fineness modulus of 2.36, and a maximum characteristic dimension of 2.36 mm. The sample presented an expected particle size distribution for granulated slag, before the grinding process.

There is no ASTM specification limiting this particle size distribution, which would only be of importance if the slag was intended for use as fine aggregate, partially replacing natural sand. The density test in the loose state according to ASTM C29 showed a value of 1270 kg/m³, compatible with the expected granulated blast furnace slag without grinding, with no ASTM standardrequirements for this property. Table 5 shows the results of the granulometric test.

Table 5 - Physical analysis of the blast furnace slag sample.

Retained percentage (by mass)		
ABNT sieve Nominal opening (mm)	Blast furnace slag (GBFS)	
	Individual (%)	Accumulated (%)
4.75	0.0	0.0
2.36	0.8	0.8
1.18	18.0	18.8
0.6	39.4	58.2
0.3	30.5	88.7
0.15	7.3	96.0
<0.15	4.0	100
Total	100.0	-
Especific mass (g/m³)	1.27	
fineness module	2.63	
Maximum characteristic dimension (mm)	2.36	

Regarding chemical tests, slags that exhibit a refractive index higher than 1.63 correspond to those of a basic nature and obey the hydraulicity index $[(CaO+MgO+Al_2O_3/SiO_2) > 1]$. On the other hand, slag with refractive index values between 1.61 and 1.62 correspond to acidic slag $[(CaO/SiO_2 < 1)]$ (Cardoso *et al*., 2021a; ABCP, 2021).

The results indicate a basic composition slag, which indicates that it has a good hydraulic potential. The only chemical requirement by ASTM C989 is restricted to limit chlorides to 2.5%. The tested sample meets this prescription. Regarding the chemical modules shown in Table 6, all are met for the specifications for granulated blast furnace slag of the European standard EN197-1, EN197-4 and the Brazilian standard NBR 16697.

The sample showed no loss on ignition (LI) and also showed a high degree of vitrification of 98% and a refractive index of 1.65 < IR < 1.66, favored by adequate cooling conditions in the cooling and slag granulation equipment. This property implies a slag with high hydraulic potential. The faster the cooling (sudden cooling), the greater the degree of vitrification and the greater the hydraulic potential of the slag. The rapid cooling and the consequent obtaining of an amorphous slag is the first indication of the technical feasibility of using slag in cement manufacturing. This process also aims to avoid the decomposition of alite ($3CaO.SiO_2$), which is the main phase of Portland cement clinker (Wang *et al*., 2019).

Another important factor for the use of slag in cement manufacturing is the formation of the mineralogical phases Akermanite ($Ca_2Al_2SiO_7$) and Gehlenite ($Ca_2Mg(Si_2O_7)$. The hydration of cement can be considered as the ideal mineralogical phase for the hydraulic activity of slag. The formation mentioned occurs after the hydration of CaO and after the formation of intermediate compounds ($3CaO.SiO_2$ and $2CaO.SiO_2$). The entire process starts with the reaction of CaO with the SiO_2 of the residue that releases heat to the system (Hammad *et al*., 2021).

There is no American normative specification in ASTM C989 and ASTM C595 or in the Brazilian standard, only indicating that the material is of a glassy nature. On the other hand, the European standard EN197-1 establishes that the minimum glass content (Chemical Components) is 2/3 of the total mass and, therefore, the studied sample meets this requirement. The Basicity indices (binary, ternary and quaternary), active module, hydraulic module, and chemical components were calculated according to the equation presented in Table 6 due to the requirements of the European standard EN197-1.

Table 6 - Chemical analysis of the blast furnace slag sample.

Nomenclature	Essay	Results (%)
LOI	Loss on Ignition	0.000
IR	Insoluble Residue	0.490
Cl	Chlorides	0.006
Na_2O	Soluble Sodium Oxide	0.006
K_2O	Soluble Potassium Oxide	0.016
BBI	Binary Basicity Index	1.267
	$[(CaO)/(SiO_2)]$	
TBI	Ternary Basicity Index	1.408
	$[(CaO + MgO)/(SiO_2)]$	
QBI	Quaternary Basicity Index	1.043
	$[(CaO + MgO)/(Al_2O_3 + SiO_2)]$	
AM	Activity Module	0.351
	$[(Al_2O_3)/(SiO_2)]$	
HM	Hydraulic Module	1.759
	Chemical Components	
CC	$[(CaO + MgO + Al_2O_3)/(SiO_2)]$	83.86
	$[(CaO + MgO + SiO_2)]$	

After the blast furnace granulated slag grinding process, the residue retained in the 45μm sieve was 8.3% according to ASTM C430, the calculated specific mass was 2.91 g/cm^3 according to ASTM C29, and the specific area was 4000 cm^2/g, according to ASTM C204, which also met the requirements of the standard.

The density of residues directly influences the degree of compaction of the matrix in mortars and concretes; therefore, it is important to analyze the density to understand the properties of the residues. Table 7 presents the results of the physical characterization of the three samples of experimental cement.

Sample 3 (cement + 50% GGBFS) had a specific area below that stipulated by ASTM C185. This was due to the particles present in the slag, which are not easily ground. This smaller specific area, which means larger particles, compromised the compressive strength values, being the most important property of the cement for the age of three and 7 days; however, for the age of 28 days, the result was satisfactory, obtaining values of resistance to compression greater than that established by the standard for all tested ages. All other results are in accordance with American, European, and Brazilian regulatory procedures.

Table 7 - Physical analysis of the blast furnace slag sample.

Technical standard	Essay	Cement	Cement + 20%GGBFS	Cement + 50%GGBFS
ASTM C-430	Fineness - residue on the 45μm sieve (%)	0.4	1.9	4.3
ASTM C-29	Specific mass (g/cm^3)	3.05	3.02	2.97
ASTM C-204	Specific area (cm^2/g)	5670	5230	4640
ASTM C-187	Normal consistency paste water (%)	29.1	27.6	25.7
ASTM C-191	Start timing of setting (min)	115	168	204
ASTM C-191	End timing of setting (min)	144	209	235
ASTM C-185	Incorporated air content	8.0	7.5	7.3

The uniaxial compression tests, performed according to ASTM C33 and ASTM C109 technical standards, with the addition of 0%, 20% and 50% of slag, presented the results in the three mixtures for ages 3 and 7 lower axial compression strength with additions of 20% and 50% slag. This result was expected because the slag reacts more slowly than the clinker. Table 8 shows the comparative results of the compressive strength of the specimens.

Regarding the hydraulic activity index, the test result according to ASTM C989 allowed classifying the slag as "*grade 120*" when ground with a specific area of 4000 cm^2/g, while, referring to the activity index with Portland cement performed according to ASTM C311, presented a value of 85.5% and therefore higher than the minimum specified value of slag for addition to the cement of 75%, according to ASTM C595.

Table 8 - Compressive strength test result (average of 6 samples).

Samples	mean + standard deviation		
	3 days	7 days	28 days
(S1) 100% Cement + 0% GGBFS	33.5 ± 0.5	37.0 ± 0.5	40.8 ± 0.8
(S2) 80% Cement + 20% GGBFS	28.6 ± 0.5	36.2 ± 1.1	41.6 ± 1.0
(S3) 50% Cement + 50% GGBFS	22.7 ± 0.8	29.9 ± 1.4	42.2 ± 0.9
(S4) 25% Cement + 75% GGBFS	19.3 ± 0.3	24.7 ± 0.2	34.9 ± 0.5

For sample 4, the physical characterization tests were not performed, as shown in Table 7, and the only test performed was the compression strength test to assess the cement activity index after the addition of the maximum slag content (75%) as allowed in technical standard. Table 9 presents the hydraulic activity indices in the respective ages and cement mixtures:

Regarding the expansion test in an autoclave, the results were satisfactory; that is, below 0.8%, for the contents of 20 and 50% (by mass) of slag addition, presenting values significantly lower than the maximum limit of 0. 8% prescribed by ASTM C595. Table 10 shows the results of the autoclave expansion tests performed on the samples.

Table 9 - Activity index.

Samples	Hydraulic Activity Index (%)		
	3 days	7 days	28 days
(S1) 100% Cement + 0% GGBFS	-	-	-
(S2) 80% Cement + 20% GGBFS	85.4	97.8	102.0
(S3) 50% Cement + 50% GGBFS	67.8	80.8	103.4
(S4) 25% Cement + 75% GGBFS	57.6	66.8	85.5

Table 10 - Autoclave expansion.

Samples	Normal consistency paste water (%)	Autoclave Expansion (%) mean and standard deviation
(S1) 100% Cement + 0% GGBFS	29.1	0.03 ± 0.01
(S2) 80% Cement + 20% GGBFS	27.6	0.04 ± 0.02
(S3) 50% Cement + 50% GGBFS	25.7	0.01 ± 0.01

The mortar samples, when evaluated by the method prescribed by ASTM C1012, presented expansion values at 56 days in a sodium sulfate solution of less than 0.007%, indicating that the mortars presented high resistance to sulfates, as specified by ASTM C595. Figure 1 illustrates the results obtained. Table 11 illustrates the characteristics of the granulated blast furnace slag, after all tests. have been accomplished.

Table 11 - Granulated blast furnace slag characteristics.

PROPERTY	VALUE	TEST METHOD	STANDARD PRESCRIPTION
CaO	43.74%		
SiO_2	34.99%		
Al_2O_3	12.20%		
Fe_2O_3	0.56%		
MgO	5.23%		
Na_2O	0.26%		
K_2O	0.41%		
TiO_2	0.49%	ASTM C114	maximum 2.5% (ASTM C114)
MnO	0.30%		
S (Sulfide sulfur)	1.17%		
IR (insoluble residue)	0.49%		
LOI (loss on ignition)	0.0%		
Cl (Chloride)	0.006%		
Na_2O (water soluble)	0.006%		
K_2O (water soluble)	0.016%		
Basicity index - $(CaO + MgO)/SiO_2$	1.40	-	>1 (EN 197-1); No ASTM requirements
Activity Module - Al_2O_3/SiO_2	0.35	-	-
Hydraulic Module $(CaO + MgO + Al_2O_3)/SiO_2$	1.75	-	-
Chemical Components $CaO + MgO + SiO_2$	83.96%	-	>2/3 (EN197-1); No ASTM requirements
Granulometry (mm)	0 - 2.36 mm		-
Fineness modulus	2.63	ASTM C136	-
Moisture	4.8%	ASTM C566	-
Color	White-yellow	Visual	-
Glass Content	98%	Microscopy	>2/3 (EN197-1); No ASTM requirements
Inert content (%)	0.5%	ASTM C114	-
Bulk Density (kg/m^3)	1.27 g/cm^3	ASTM C29	-
Hydraulic Activity Index			ASTM C989
(7 days)	89%	ASTM C989	>70 grade 100; >90 grade 120
(28 days)	113%		>90 grade 100; >110 grade 120

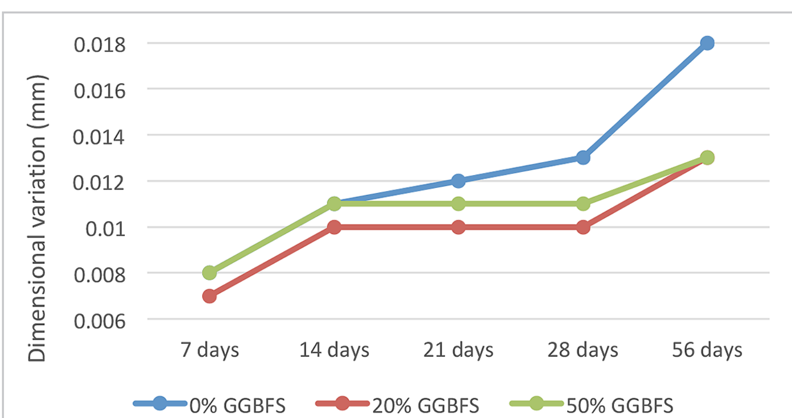

Figure 1 - Dimensional variation of specimens.

4. Conclusions

According to the proposed conditions and the results obtained in this study, it can be concluded that:

• Regarding the chemical composition, we concluded that the analyzed slag has a basic composition and has a high hydraulic potential without chemical or thermal activation;

• The chloride content in the analyzed sample met the requirements of ASTM C989 maximum limit;

• The chemical modules analyzed meet the specifications of European, Brazilian and American standards;

• The mineralogical composition showed a high degree of vitrification, implying a high hydraulic potential.

• The European standard EN197-1 establishes that the minimum glass content is 2/3 of the total mass and, therefore, the studied sample met this requirement;

• The result of the Hydraulic Activity Index test according to ASTM C989 allowed classifying the slag as Grade 120, when ground with a specific area of 4000 cm^2/g;

• The Activity Index with Portland Cement was above the minimum value specified according to technical standards ASTM C311 and ASTM C595;

• Regarding the axial compression tests, as expected, the slag reacted slower than the clinker, however at 28 days the results were superior to the standard cement.

• After the expansion tests in an autoclave, the types of cement containing 20% and 50% of slag presented values below the maximum limit prescribed in the ASTM C 595 standard;

• The cement samples showed expansion values in sodium sulfate solution below the limit specified by ASTM C 595;

• Recycling and the use of steel residues have advantages in terms of sustainability and can be considered positive factors for the environment, thus enabling the reduction of degraded areas due to their disposal and the preservation of natural resources.

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