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Compression resistance of concretes with blast furnace slag. Re-visited state-of-the-art

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ABSTRACT
A state-of-the-art revision of the BFS-PC cementing system was done, emphasizing its effect on the mechanical compression resistance of the concrete. The use of the cementing characteristics of the BFS with high levels of replacements is viable, making it possible to improve the compression resistance, and in some cases, the resistance to the corrosion of the steel; said improvement will depend on the amount of BFS and on the exposure environment of the concrete. In this work, the replacements of BFS were confirmed as beneficial, up to 70% in humid microclimates or marine environments, and up to 50% in environments susceptible to carbonation. In these ranges, higher replacement efficiency with regard to resistance to compression can be achieved.
Keywords: slag; carbonation; industrial byproducts; corrosion.

RESUMEN
Se realizó una revisión del estado del arte del sistema cementante CP-EAH, enfatizando su efecto en la resistencia mecánica de compresión del concreto. El aprovechamiento de las características cementantes de la EAH con altos niveles de reemplazo resulta viable, pudiendo mejorar la resistencia a compresión y en algunos casos la resistencia a la corrosión del acero, dicho mejoramiento dependerá de la cantidad de EAH y del ambiente de exposición del concreto. En éste trabajo se confirmaron como benéficos los reemplazos de EAH hasta de un 70% en microclimas húmedos o ambientes marinos, y hasta 50% en ambientes propensos a carbonatación. En estos rangos se puede lograr una eficiencia del reemplazo mayor con respecto a la resistencia a la compresión.
Palabras clave: escoria; carbonatación; subproductos industriales; corrosión.

RESUMO
Foi realizada uma revisão do estado da arte do sistema aglomerante CP-EAH, enfatizando seu efeito na resistência mecânica de compressão do concreto. O aproveitamento das características aglomerantes da EAH com altos níveis de substituição resultou viável, podendo melhorar a resistência à compressão e em alguns casos a resistência contra a corrosão das armaduras. As melhoras observadas dependeram da quantidade de EAH e do ambiente de exposição do concreto. Foram confirmados como positivos as substituições de até um 70% de EAH, em microclimas húmidos ou ambientes marinhos, e até 50% em ambientes propensos a carbonatação. Nestes intervalos é possível obter uma eficiência maior da substituição com respeito à resistência à compressão.
Palavras-chave: escória; carbonatação; subprodutos industriais; corrosão.

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1. INTRODUCTION

Since the earliest civilizations, the materials with a certain capacity of adherence (cementing material) have been crucial in the development and evolution of construction. Thus, throughout history, men have sought other cementing materials to obtain the best mechanical and durability properties. This evolution has led to Portland cement and reinforced concrete being the most used materials in the construction industry (Gamgbir, 2009).

On the other hand, the cement industry is one of the main sources of carbon dioxide (CO_2). It has been estimated that the CO_2 emissions into the atmosphere reach a value of 1.0 ton per Clinker ton (Cassgnabere, 2009), which is where Portland cement is obtained from after its grinding. In light of this inconvenience, man has searched for alternate materials with cementing capacities that are not damaging to the environment due to their origin and that could, when used carefully, provide advantages (Malhotra, 1996; Day, 2006). Although the quantity of residues/byproducts that are currently used is small compared to what is produced, research is being carried out worldwide to search for new applications for these as cementing materials and thus decrease the carbon footprint of the construction industry.

There are some industrial wastes that could be used as cementing materials, and would require little to no previous maintenance for their use in the mixture for concrete and/or mortar. On the other hand, there are other cementing materials of natural origin (for example, volcanic ash) that are available for their use in the mixture of concrete (Malhotra, 1996).

Some cementing materials that originate from industrial waste and that can be used as alternative materials are: fly ash, fumed silica, blast furnace slag, metakaolinite, and schist (Day, 2006), which could be used as mineral additions in the preparation of Portland cement manufactured in the plant (Modified Portland Cement, MPC); as addition in the grinding; or for the mixture of two or more types of fine materials that partially substitute Portland cement (Hydraulic Cement with Additions or Cement with cementing substitutes) used in the mixing of concrete or mortar (Kosmatka, 2004).

The first property in the concrete that has been affected by the use of cementing materials of natural or industrial origin, is the resistance to compression, assigning for this work the real resistance (f_c) obtained from the compression tests, and therefore there is a big amount of works (Cassgnabere, 2009; Bagheri, 2013; Atis, 2003; Ashtiani, 2013) that under different mixtures, conditions, origin or atmosphere, allow the use of a certain amount of these materials without notably affecting the mechanical properties of the concrete. It is complicated to think about all the uses of these materials, but there is a need to know if the tendency to decrease the f_c is constant, or what its limit is regarding the parameters of research that have been used in different investigations. Similarly, even though there are already excellent combinations of cementing materials that give rise to binary, ternary, and quaternary cements (Nedi, 2001), the availability of the materials in one zone or region alone could constitute an economic obstacle for their generalized use, especially in developing countries. Therefore, the use of binary cement manufactured in the plant could be the most practical alternative, in economic and availability terms, for the time being. The objective of this work is to re-visit the state-of-the-art on the tendencies of the compression resistance of concretes and structures that use blast furnace slag (BFS) as cementing material, as well as review the levels of replacement of Portland cement that are considered in the standards of different countries for the classification of the cements with blast furnace slag, be it mixed during the grinding or by the separate mixture of each grinded material.

2. CHARACTERISTICS OF THE BLAST FURNACE SLAG

A cementing byproduct is the secondary or incidental material that is derived from the industrial manufacturing process through a chemical reaction, which possesses the conglomerating characteristic after a certain treatment (Malhotra, 1996). An industrial byproduct that is considered waste could possess a certain pozzolanic capacity, and could be useful and marketable when finding an application for it in another industrial sector, for example, as a partial substitute of Portland cement in the construction with concrete, or also as a stone aggregate as is the case of granulated slag.

Blast furnace slag is a (non-metallic) byproduct from the manufacture of melted steel in blast furnace, which consists mainly of silicates and calcium aluminosilicates and other phases (Siddique, 2008). Certain authors (Malhotra, 1996; Lea, 1971) describe blast furnace slag as a pozzolanic material, as it does not present cementing properties onto itself unless it is combined with other cementing materials for its chemical activation. Other authors, however, indicate that it should be classified as a latent hydraulic cement, as its components are comparable to the oxides of Portland cement (lime, silica, and alumina) in different proportions (Lea, 1971).

The slag generated in the steel industry can be divided into four types according to the method used for its cooling: the blast furnace slag air cooled; the expanded or foamed slag; the palletized slag, and the granulated blast furnace slag.

The air-cooled slag does not present the same hydraulic properties as the water-cooled slag, given that by slowly cooling with the fair, its compounds have the possibility of reaching a greater degree of crystallization, which would result in a material with low reactive activity. For its part, the expanded slag is used as a light weight coarse aggregate in the manufacture of concrete with a specific low weight (Malhotra, 1996). These materials are used in the construction of roads and buildings. The type of slag used as cementing material is the blast furnace granulated material; this byproduct is obtained through the accelerated cooling of melted slag, through the application of water on its surface to form a vitreous material which could have a certain degree of activation.

The fast cooling of the melted slag with water prevents the formation of bigger crystals, resulting in a granular material that comprises almost 95% of the compound of alumina-silicate of non-crystalline calcium. Granulated slag is processed through a previous drying and is subsequently grinded through a rotating ball mill, until a very fine powder is obtained known as Ground-granulated blast-furnace slag (GBS). The granulated slag has particle sizes between 4 to 15 mm, and less than 45 μm with a superficial area of 400 to 600 m^2/kg after grinding, which could be used as latent hydraulic cement (Lea, 1971). The grinded material is a powder with a lighter color than Portland cement; the coloration it gives the concrete is lighter and provides a smoother surface when compared to the concrete with Portland cement. The specific gravity that it presents is of 3.15.

In figure 1, we show an image of MEB (SEM) taken from the literature, with the morphology of a hydrated paste comprised of a cementing system of 30% blast furnace slag and 70% of ordinary Portland cement (Li, 2011). In this same Figure, we can observe angular particles that correspond to the slag and which have not been able to hydrate after 7 days. This behavior is normal in the cements with slag, as the slag presents a lower reaction activity when compared to ordinary Portland cement.

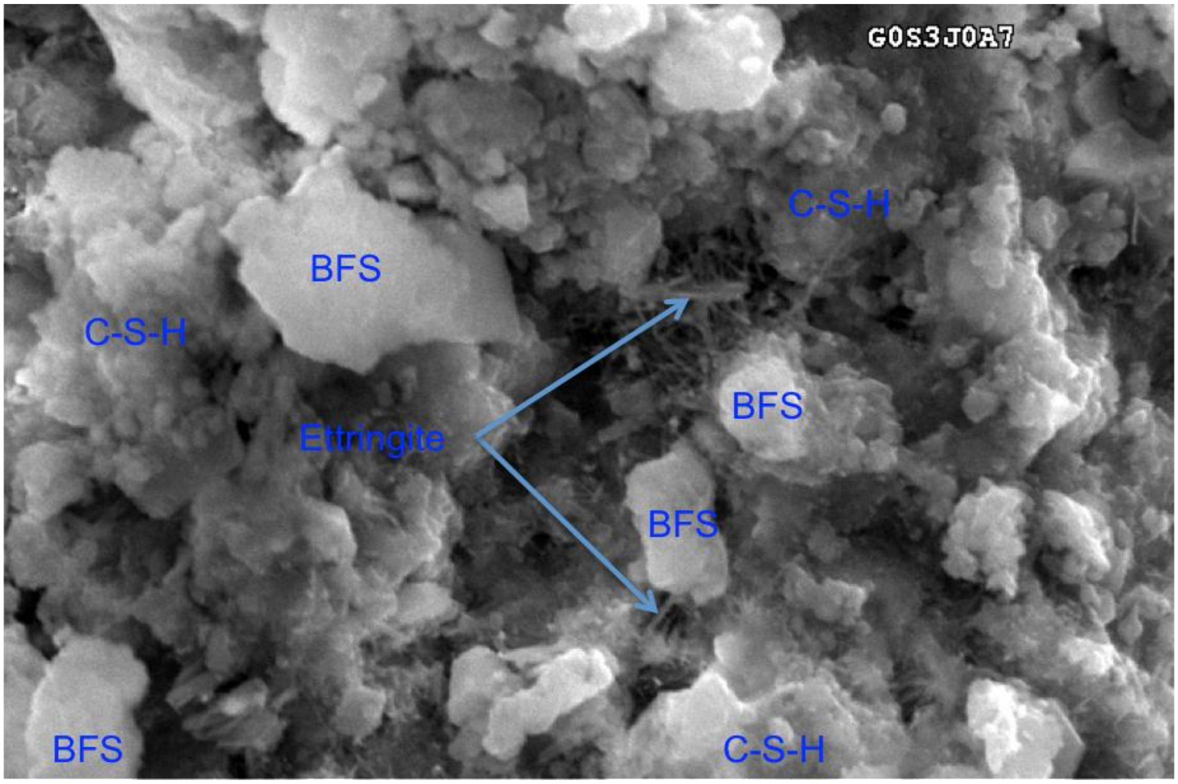

Figure 1. MEB microphotographs of hydrated pastes after 7 days, paste with 30% blast furnace slag and 70% ordinary Portland cement (BFS blast furnace slag, C-S-H hydrated calcium silicate) (Li, 2011).

The specifications for the granulated blast furnace slag as cementing material can be found in the ASTM C 989 (ASTM-C-989, 1999), where slag is classified in three degrees of resistance. These degrees are based on the activity index of the slag: grade 80 (with a low activity index), grade 100 (with a moderate activity index), and grade 120 (with a high activity index); other specifications for slag can also be found in AASHTO M 302 (ASSTHO-M302, 2000). The number of the quality designation corresponds to the compression resistance at 28 days, approximately, done in standard mortar cubes prepared with GBFS (mixture with an equal amount in mass of Portland cement). The degree of activity affects the reactive behavior in the fresh mix of concrete and the subsequent setting. On the other hand, the hydraulic activity of the slag will be determined by its chemical composition, the superficial area, and the size of the grinded slag particle (Puertas, 1993; Pal, 2003).

The chemical composition of the blast furnace slag could vary greatly depending on its origin, but to be considered a cementing material it is required that the chemical composition lies within the ranges of: CaO (30-45%), SiO_2 (30-48%), Al_2O_3 (15-25%), Fe_2O_3 (0.5-2%), and other oxides in lower quantities (Shetty, 2013). Among the chemical requirements provided by the ASTM 989 (ASTM-C-989), 2.5% and 4.0% are established as the maximum quantities of sulfides (S) and sulfates, respectively, with these quantities the presence of slag in the reinforced concrete does not represent a corrosion risk for the reinforced steel (Wang, 2010). The pulverized blast furnace slag is slightly alkaline and presents a solution pH that is within a range of 8 to 10, however, the slag leachate can exceed a value of 11, a level that could be corrosive for aluminum or galvanized steel pipes placed in direct contact with the slag (Wang, 2010).

The previously mentioned proportions of the oxide compounds will determine the basicity of the slag and its hydraulic capacity. However, for the slag to be able to truly develop its hydraulic potential, it is fundamental that its vitreous phase is largely superior to 70%. This vitreous characteristic will condition the ability of the slag to recreate the crystalline structure that will provide the concrete with its resistance and durability qualities.

As cementing material, the granulated slag has the following characteristics: it is a strong latent hydraulic cement when it is grinded, it has a high content of Na_2O and K_2O, light weight, a high permeability to water, it does not contain chlorides, and it does not produce alkali-aggregate reactions.

The replacement of cement for ground granulated slag (GBFS) will generally reduce the amount of water necessary to obtain the same shrinkage as the one obtained from a concrete with OPC. The reduction of the amount of water will be influenced by the increase in the level of replacement and by the fineness of the slag (Shetty, 2013). The typical water demand for the mixture of concrete with GBFS is approximately 3-5% less than for the concrete with Portland cement (Wang, 2004; Walker, 2011). This represents a reduction of 5 to 10 liters of water per cubic meter of concrete. For OPC replacements with GBFS within 70% and 80%, the reduction in the demand of water could be less, due to the much higher concentration of finer GBFS particles (Siddique, 2012; Oner, 2007). This behavior is due to the surface particles of GBFS being softer and having greater crystallinity than the ones of Portland cement, resulting is less water adsorption on the surface of the GBFS particles.

Among the advantages that the use of ground granulated slag has on fresh and hardened concrete are: reduction of hydration heat, refinement of the pore structure, reduction of the permeability of external agents, increase of the resistance to chemical attacks, resistance to attacks by sulfates, enhancement of the workability of the mixture, and in certain cases, it can improve the resistance to the corrosion of the reinforcement steel, as this will depend on the chemical composition of the slag. The concrete with the slag could reach a higher compression resistance for certain levels of replacement of the Portland cement. All of this, in addition to saving ordinary Portland cement in the concrete mixture (Shetty, 2013).

The incorporation of blast-furnace slag in the cementing mixture modifies the nature and characteristics of the hydrates formed, affecting the concrete capillary network, reducing the size and number of pores. This effect of the slag is shown on the concrete in its hardened state and in its durability. However, the beneficial effects of the slag on the mechanical properties and durability of the concrete will be in accordance with different factors, among which stand out the quality of the slag, the adequate design of the mixture, the placement and transportation of the fresh concrete, and the care in the time and type of curing.

Another considerable characteristic of the slags is the hydration process, which is slower than the Clinker one, as its dissolution is more difficult due to its vitreous nature as well as due to its need of a strong sulphatic (plaster, anhydrite) or alkaline (by the presence of alkali or portlandite) activation. The activation of the slag is caused by the presence of portlandite $Ca(OH)_2$ released by the hydration of the Clinker, due to the alkali in the slag and the actions of the setting regulator (plaster and/or anhydrite).

In this situation, other characteristics of the granulated blast-furnace slag, related to their hydration process, can be mentioned.

- There is no release of portlandite $Ca(OH)_2$ and we can consider the consumption of the amount released by the clinker.
- There is no formation of tricalcium aluminate (C_3A).
- The alkali (K_2O y Na_2O), that participate as catalysts in the hydration of the slags, are trapped in the crystalline net and are not in their free state.

On the other hand, as an environmental benefit, the ground granulated slag is also considered a sustainable material (Gjørv, 2000), as it is a byproduct of industrial waste and its use in concrete is acknowledged by the LEED certification (Leadership in Energy and Environmental Design) (Council U.S.G.B. 2014; Slag Cement Association). Considering this, slag may be used in concrete for superstructures, and with the right evaluation, it is also used in reinforced concrete exposed to environments with chlorides and sulfates; with the disadvantage of its slow setting, implying a greater time of execution for a certain project.

The fact that the slag added to the concrete mixture has a lower reactivity during the first couple of days, results in a considerable decrease in the compression resistance at early ages of the mixtures when compared to PC concrete mixtures. However, at subsequent ages the contrary occurs, meaning that in several cases, greater resistances than those in homologue concrete were reached (Oner, 2007; Berndt, 2009).

3. BLAST FURNACE SLAG AS CEMENTING MATERIAL IN THE REGULATIONS

The BFS can be used for the same purposes as Portland cement, as it sets and hardens due to its chemical reaction with water, therefore, it is considered a latent hydraulic cement due to having the same compounds as PC. However, in some cases, it is necessary for the slag to be mixed with hydrated lime to gain functionality (Gambhir, 2009; Lea, 1971).

The specification for the slag cement can be found in the ASTM C595 (ASTM-C595, 200) standards, where they are classified as IS and S type (Blast-furnace slag Portland cement and Slag or refractory cement), respectively.

The IS type cement is comprised of granulated blast-furnace slag (GBFS), which can be grounded along with the Clinker of the Portland cement or through separate grinding and then incorporated to the cementing mixture. The amount of GBFS in this type of cement is between 25% and 70% of the cementing mass. It is considered that the slag content of 70% of the cementing mass brings a certain benefit with regard to resistance and durability, but just up to a certain degree and in accordance with the environment where the concrete is exposed. On the other hand, if higher doses of this type are used, tests must be done on the concrete to verify the resistance, durability, and other specifications that are required for the project.

Table 1 shows the amounts of slag content considered in the standards of different countries. According to the standards presented in table 1, the European standard (UNE-EN-197, 2013) considers a level of slag of 95% in the cementing mixture, this being the highest level compared to those of the other countries shown in Table 1. As for American countries, Colombia considers up to 85% of slag in its standard, whereas Mexico considers up to 80%. On the other hand, it is important to mention that the use of high levels of slag should be subject to a certain level of verification control, due to the compatibility with other additions in the mixture, or due to the aggregates and the environmental conditions.

The use of other cementing materials, different to the traditional ones entails certain effects and changes in the fresh and hardened concrete. For the concrete mixture, a certain amount of water is needed for the hydration reaction to happen. Among its particularities, slag can diminish the

amount of water for the mixture by 1% to 10%, depending on the amount of substitution. It can also present a greater amount of tap without it having adverse effects on the concrete, but it also tends to diminish the heat of hydration when compared to Portland cement. Nevertheless, the combined use of ground blast-furnace slag and fly ash can decrease the setting time (Lee, 2013).
For the hardened concrete, the use of slag could contribute to the enhancement of the resistance to compression. However, there is the risk that the resistance of the concrete will suffer a decrease with the addition when the proper curating method and care are not applied for the cementing system used. Therefore, the development of the resistance of concrete with GBFS can be comparable to normal concrete if it is cured at a temperature of approximately 23 °C.

Table 1. Slag content in cements according to the standards of different countries.

Country and Standard	**Type of cement**	**Slag content**
European Committee for Standardization UNE-EN 197-1, 2013.	Portland Cement with slag additions Portland cement with blast-furnace slag	6 to 35% 36 to 95%%
Argentina IRAM 50000, 2000; IRAM 50001, 2000.	Ordinary PC PC with slag Composite Portland cement Blast-furnace cement	Maximum 10% of BFS 11% – 35% of BFS 35% BFS 35-75%
Chile NCH148	Refractory Portland Cement Refractory Cement	Maximum 30% BFS 30% - 70%
Colombia NTC 30	Refractory cement BFS Portland Cement	>70 of BFS 15 – 85 GBFS
Mexico NMX-C414-ONNCCE	OPC Portland Cement with blast-furnace slag Composite Portland Cement Cement with blast-furnace slag	5 6 – 60 6 – 35 61 – 80
United States (ASTM C595, 2000; AASHTO M240)	Blast-furnace Portland Cement Refractory or blast-furnace slag Cement Portland Cement modified with slag	25 – 70 of GBFS Minimum 70% GBFS < 25%
Canada CSA A362, CSA A23.5 CAN/CSA-A3001-03	Portland Cement with Blast-furnace slag Portland Cement modified with slag	25 to 40% of slag 25 – 70%
Australia AS/NZS 2350.1; AS 3582.2; AS 3972,	Binary Cement mixed with slag Ternary cement with slag and other supplementary cementing material	30 – 70% 30% - 50%

4. RESULTS OF THE EFFECT OF THE GBFS SLAG ON THE COMPRESSIONRESISTANCE

For this section, we did a collection of data from researches reported in the literature used, paying attention to the replacement levels of Portland cement with blast-furnace slag and the effect caused on the resistance to the real compression (f_c) of the hardened concrete at ages of 28 and 29 days. It is important to mention that the mixtures of the cementing material that have been investigated are comprised of the system: Portland cement and slag.
Usually, the amount of water used to prepare the concrete mixture is implicitly indicated in the water/cement (*a/c*) relation. However, for cementing systems, the amount of water is indicated by the water/material relation expressed by *a/mc*. Nevertheless, there are some cases where water is not used exclusively for the preparation of the mixture, but where some activating solution of a byproduct is required; in this case the term *s*/*mc* is used, which represents the aqueous solution with the chemical agent (alkaline solution) and cementing material.
The curing techniques for concrete after 24 h of strain could be very varied, among these are: the humid curing or water immersion curing; room temperature curing; curing with temperature (*T*) and controlled relative humidity (*HR*). The curing period will depend on the cementing system used for the concrete mixture with a slag dosage as a cement replacement.
Table 2 shows some of the results reported in the literature about the resistance to real compression f_c of the concrete at ages of 28 and 90 days, with replacements of type I ordinary Portland cement with the byproduct of GBFS. The level of replacement, the *a/mc* relation, and the compression resistance at 28 and 90 days are indicated in the table.
As can be observed in Table 2, the amount of replacement by slag is a maximum of 80% for the research reported in 2007 (Atis, 2007), this amount being within the range reported in the standards of different countries such as Mexico and Colombia. Similarly, it is also worth mentioning that the concretes with different *a/mc* relations have been investigated, all within the range of 0.28 to 0.55, also indicating that in low relations of *a/mc* it is fundamental to use some water reducing additive or superplasticizer to confer the suitable properties to the fresh state of the concrete.
According to Table 2, there is a broad range of possibilities to use BFS as a partial substitution of the cement for the manufacture of concrete mixtures, but in some cases the result does not have a good effect with regard to the mechanical resistance. It is therefore important to provide certain details regarding the resistance to compression of the concrete in relation to the amount of slag used in the OPC-BFS cementing system.

Table 2. Resistances to compression (f_c) of the concretes with cementing system type I OPC+ BFS with different levels of replacement according to different authors.

Authors	**Replacement with byproduct (%)**	**a/mc**	**f_c (MPa) 28 days**	**f_c (MPa) 90 days**	**Authors**	**Replacement with byproduct (%)**	**a/mc**	**f_c (MPa) 28 days**	**f_c (MPa) 90 days**
Kriker, 1992	0	0.50	30	35	Atis, 2007	60	0.40	53	
	15	0.50	26	39		80	0.40	43	
	30	0.50	30	33		0	0.50	52	
	40	0.50	28	36		20	0.50	51	
	45	0.50	26	38		40	0.50	46	
	50	0.50	21	29		60	0.50	40	
Kriker, 1992	0	0.60	29	31		80	0.50	27	
	15	0.60	34	37		0	0.30	73	
	30	0.60	32	39		20	0.30	70	
	45	0.60	25	33		40	0.30	66	
Amrane, 1994	0	0.55	24	27		60	0.30	68	
	15	0.55	26	31		80	0.30	54	
	30	0.55	27	33		0	0.40	66	
	50	0.55	21	29		20	0.40	63	
Ramezanian pour, 1995	0	0.50	41			40	0.40	62	
	25	0.50	40			60	0.40	59	
	50	0.50	35			80	0.40	47	
Polder, 1996	0	0.43	50			0	0.50	37	
	70	0.43	51			20	0.50	37	
Yeau, 2005	0	0.42	46	49		40	0.50	35	
	25	0.42	48	52		60	0.50	30	
	40	0.42	44	60		80	0.50	20	
	55	0.42	47	57		0	0.30	75	
Atis, 2007	0	0.40	68			20	0.30	73	
	20	0.40	69			40	0.30	76	
	40	0.40	62			60	0.30	58	
	60	0.40	54			80	0.30	56	
	80	0.40	43		Chidiac, 2008	0	0.31	61	
	0	0.50	42			25	0.31	64	
	20	0.50	36			40	0.31	70	
	40	0.50	35			50	0.31	64	
	60	0.50	28			60	0.31	64	
	80	0.50	18						

Tabla 2. Continuación.

Authors	**Replacement with byproduct (%)**	**a/mc**	**f_c (MPa) 28 days**	**f_c (MPa) 90 days**	**Authors**	**Replacement with byproduct (%)**	**a/mc**	**f_c (MPa) 28 days**	**f_c (MPa) 90 days**
Chidiac, 2008	0	0.38	76		Bilim, 2009	0	0.30	80	86
	20	0.38	86			20	0.30	82	90
	25	0.38	76			40	0.30	84	91
	33	0.38	70			60	0.30	81	92
	40	0.38	71			80	0.30	66	77
	50	0.38	79			0	0.40	64	71
	60	0.38	70			20	0.40	73	82
Bilim, 2009	0	0.30	81	85		40	0.40	66	81
	20	0.30	81	90		60	0.40	62	73
	40	0.30	82	88		80	0.40	47	55
	60	0.30	78	79		0	0.50	49	50
	80	0.30	68	76		20	0.50	50	56
	0	0.40	64	68		40	0.50	49	53
	20	0.40	66	72		60	0.50	39	49
	40	0.40	67	78		80	0.50	28	35
	60	0.40	61	75	Bouikni, 2009	0	0.43	55	
	80	0.40	53	57		50	0.43	57	
	0	0.50	51	57		65	0.43	55	
	20	0.50	53	61	Shariq, 2010	0	0.45	36	41
	40	0.50	52	58		20	0.45	31	37
	60	0.50	40	50		40	0.45	28	40
	80	0.50	25	34		60	0.45	24	29
	0	0.30	76	84		0	0.50	31	34
	20	0.30	81	87		20	0.50	27	31
	40	0.30	81	88		40	0.50	25	32
	60	0.30	73	81		60	0.50	22	26
	80	0.30	63	71		0	0.55	22	25
	0	0.40	64	71		20	0.55	20	23
	20	0.40	66	74		40	0.55	19	24
	40	0.40	67	76		60	0.55	15	19
	60	0.40	61	74	Topçu, 2010	0	0.50	34	36
	80	0.40	50	59		25	0.50	48	54
	0	0.50	54	61		50	0.50	44	45
	20	0.50	57	65	Abdelkader, 2010	0	0.50	30	34
	40	0.50	56	66		30	0.50	36	43
	60	0.50	45	58		50	0.50	30	39
	80	0.50	30	38					

Tabla 2. Continuación.

Authors	**Replacement with byproduct (%)**	**a/mc**	***f*c (MPa) 28 days**	***f*c (MPa) 90 days**	**Authors**	**Replacement with byproduct (%)**	**a/mc**	***f*c (MPa) 28 days**	***f*c (MPa) 90 days**
Johari, 2011	0	0.28	87	96	Hadjasadok, 2012.	0	0.65	36	42
	20	0.28	95	104		15	0.65	33	36
	40	0.28	88	99		30	0.65	28	40
	60	0.28	87	98		50	0.65	16	33
Lübeck, 2012	0	0.30	60	72		0	0.42	62	65
	50	0.30	59	68		15	0.42	61	63
	70	0.30	40	42		30	0.42	60	65
	0	0.42	48	59		50	0.42	53	62
	50	0.42	42	55	Li, 2012	0	0.41	48	
	70	0.42	30	38		10	0.41	48	
	0	0.55	39	48		30	0.41	47	
	50	0.55	30	40		50	0.41	46	
	70	0.55	20	31					

Figures 2 and 3 present the information shown in Table 2, corresponding to the resistance to real compression of the concrete at ages of 28 (figure 2) and 90 days (figure 3) in relation to the degree of cement replacement. Likewise, Figures 2 and 3 show the average correlation lines with the classification in three ranges of the *a/mc* relation; the values lower to 0.4, the range between 0.4 and 0.6, and the values higher to 0.6.

It is possible to observe in Figure 2, that there is a slight generalized tendency to the decrease of the resistance when the amount of slag in the cementing mixture is increased, even though it can be observed that there is a range where the resistance may be improved. The level of replacement that has been used in investigations reaches a value of 80%, but it can be observed that it is within the range of 20% to 60% that there are slightly higher values of f_c when compared with the reference concrete, that is, without slag. A similar behavior to the one of the resistance at 28 days can also be observed in the resistance at 90 days, shown in figure 3. Said graph also shows that for a longer period (concrete of older ages), the resistance f_c of the concretes with replacements of 20% to 60% tends to increase with age.

For both ages of the concretes (Figures 2 and 3), it can be observed that with cement replacement levels higher than 60% slag, the resistance of concrete is inferior to the concrete without replacement.

To determine the effect generated in the resistance f_c of the concretes for the ages of 28 to 90 days, a parameter called rate of change was determined. This parameter is a unidimensional value obtained from the fraction between the resistance f_c of the concrete with slag and the resistance f_c of the reference concrete. In the graphs of Figure 3, the rate of change (efficiency) of the concrete with slag is shown in comparison to the reference homologous concrete and in accordance with the different levels of replacement. The horizontal line indicates the rate of f_c for the reference concrete. An inferior value to said line indicates that the concrete with slag did not reach the resistance value of its counterpart without slag; whereas the values above the horizontal line mean that the concrete surpassed or improved the resistance of the concrete without slag.

Similarly to what was observed in Figures 2 and 3, Figure 4 shows that there is a known and expected tendency for the decrease of the resistance of the concrete f_c with the increase of the level of replacement of the cement with slag in the cementing system, making it consistent with what is reported in the literature (Abdelkader, 2010).
As before, the range in which a better effect on the resistance can be appreciated is between 20% to 60%, where similar or slightly superior values of f_c are reached with regard to the reference concrete; this effect is more distinct in the graph shown in Figure 5 for the 90 day-old concrete. Furthermore, it can be observed in Figure 4 that replacements higher than 60% have a decrease in the improvement of the f_c resistance. Similarly, this effect can also be seen at the age of 90 days, making it consistent with the observations in Figure 2 and 3.
According to the results reported by Ahmend Hadjasadok et al. (Hadjasadok, 2012), it can be observed that for the same *a/mc* relation, the resistance f_c is reduced when the level of replacement of the OPC is increased, but for an equal quantity of slag the f_c resistance is increased when reducing the *a/mc* relation.

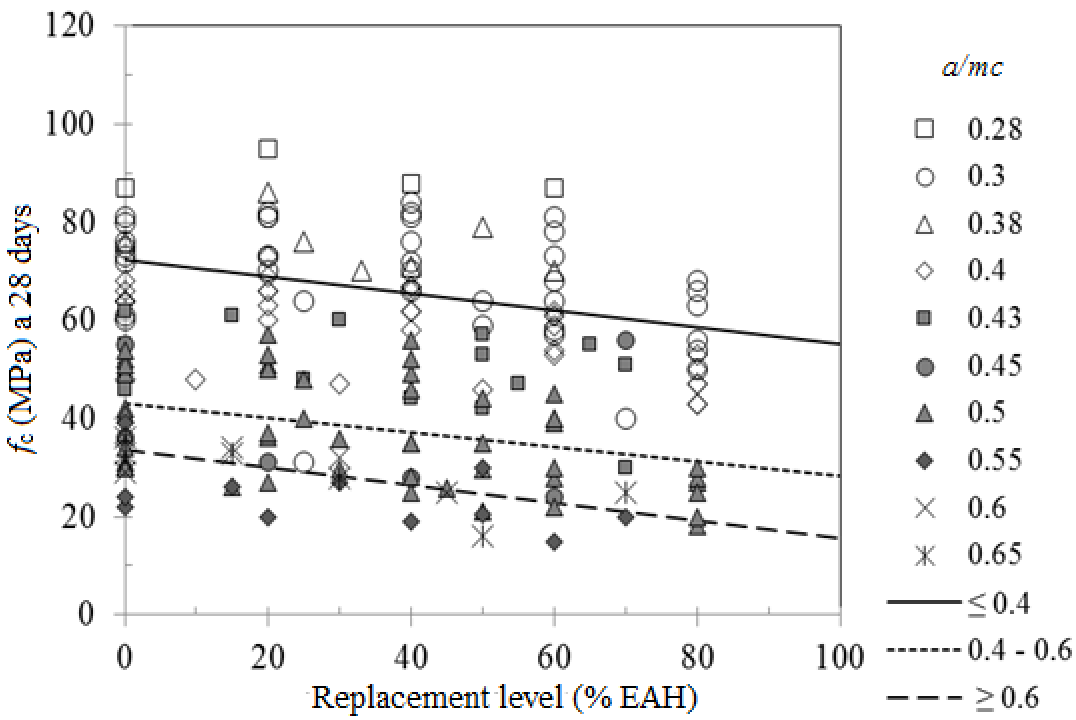

Figure 2. Data reported in the literature (Table 2) regarding the resistance to real compression (f_c) of the concretes with slag and tested at 28 days.

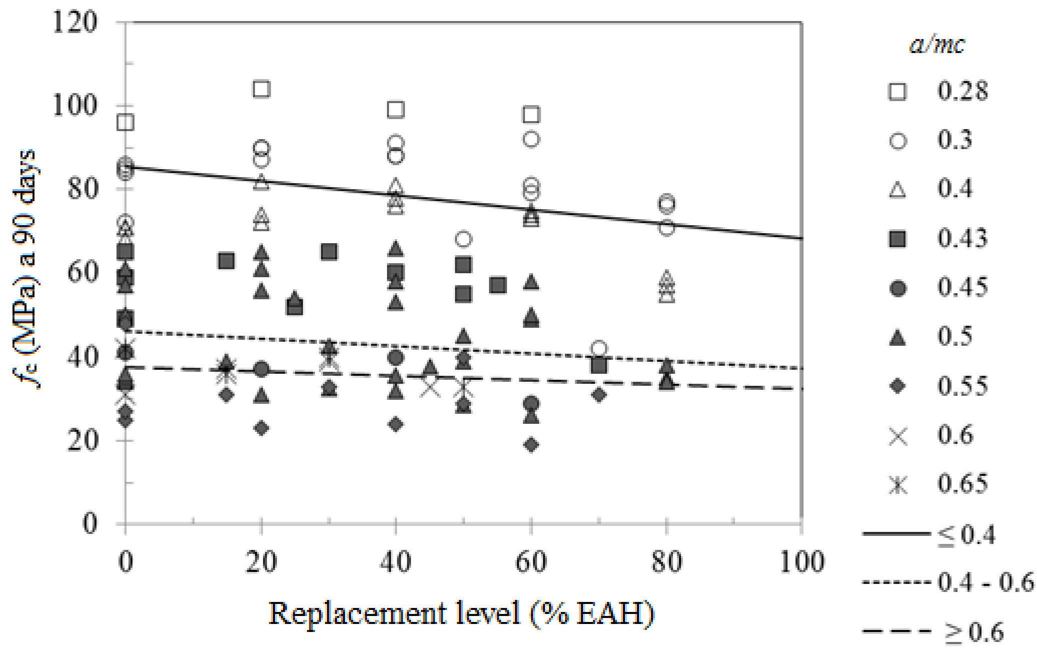

Figure 3. Data reported in the literature (table 2) regarding the resistance to real compression (f_c) of the concretes with slag and tested at 90 days.

On the other hand, Figure 5 shows that at an age of 90 days, the concrete acquires a higher resistance when compared to an age of 28 days (Figure 4). This observation was also presented in the works of Iker Bekir Topcu and Raif Boga (Topç, 2010), in which they also conclude that with replacements of 25% of GBFS to the cementing system there is a higher compression resistance for the concrete with underwater curing and during 28 days, as well as at 90 days. It is also worth mentioning that at 50% the resistance diminishes in similar curing times, this effect with a similar replacement level was observed by Bougara (Abdelkader, 2010). For their part, Chidiac and Panesar (Chidiac, 2008) concluded that the f_c resistance of concrete with slag is decreased with an increase in the replacement level of cement.

The behavior observed in the delay for the improvement of mechanical resistance in concretes with slag is thought to be due to the cementing steel byproduct taking more time to activate than conventional cement.

These characteristics have also been mentioned in other investigations carried out on pastes (Sanchez, 2011), on mortar (Hwang, 1991), and on concrete (Lee, 2013), having a similar result in the decrease of resistance at early ages, as consequence of the delay in the hydration time of the supplementary cementing material. This behavior causes a decrease in the precipitation rate of the most stable reactive products, which contribute to the mechanical resistance.

Due to the resistance being related to the phases formed in the pastes, we mention one of the results of the researches done by Chao-Lung Hwang y Der-Hsien Shen (Hwang, 1991) on pastes with OPC – GBFS systems, with replacements of 10% to 40% and three water-cementing material relations of 0.35, 0.47, and 0.59, bringing us to the conclusion that for a certain *a*/*mc* relation, a high GBFS content will require a longer setting time for the paste.

However, according to the investigation done by Martínez Aguilar et al. (Aguilar, 2010), they report that the f_c in pastes with GBFS could be improved with the activation of the slag through a type of alkaline sulfate (Na_2SO_4 or K_2SO_4 mixed with Al_2SO_4) or through a sulphatic source such as Fluorogypsum (Fy, $CaSO_4$), which is also another industrial byproduct, even though they also mention that in some cases the f_c at 90 days was lower than at 28 days. The authors link said effect to the formation of unstable phases (ettringite and gypsum) in the internal structure of the cementing paste, which results in an imbalance (expansion) at subsequent ages.

In accordance with the foregoing, it can be said that for a constant content of slag, the setting time will change proportionally to the *a/mc* relation. This will lead to better results in the compression resistance at subsequent ages than those for a conventional concrete, which would lead to a higher hydration rate for the chemical compounds of the cementing material.

To appreciate the effect caused by the slag in hardened concrete throughout time, the frequency of change in the resistance of concrete was determined in accordance with three ranges of the rate of change: those concretes with BFS that presented a change <1 with regard to the reference concrete; those that did not present any change or change rate, which were considered equal to 1; and those that presented changes >1; this was done for both ages of the concretes. The foregoing is shown in Figure 6 through a graph of frequencies of a representative sample of the resistance data of concretes with slag analyzed in this work, which achieve rates of change that are lower, equal, and higher than 1 *fc*. In said Figure 6, it can be clearly observed that for the rate of change <1 there is a decrease in the frequency of the rate of change for the BFS concretes when going from 28 to 90 days of age, whereas for the rate of change >1 there is an increase in the frequency. This means that the incidence in the rate of change <1 for the concrete with BFS at 28 days is higher than for the reference concrete. Whereas the rate of change values >1, which are represented by the BFS concretes and which surpass the resistance of the reference concrete, have a greater incidence in the rate of change for those concretes that have more than 90 days of age. This is related to the above statements, as the slag has a slower hydration process than the OPC, therefore, it requires a longer time to reach the optimal hydration and thus develop compounds and more stable chemical phases that interfere in the improvement of the compression resistance of the concrete. Considering this, it is believed that in this situation the hydration characteristics are a conditioning factor for the development of the resistance and which interfere in the decrease of the resistance, in addition to the type of activity of the slag and the implementation of the curing of the concrete.

As mentioned in the above paragraphs, for the OPC + Slag system applied to hardened concrete, this could produce an effect on the resistance that surpasses that of the design at an age of 28 days of curing, according to the literature reports (Topç, 2010; Yeau, 2005). Prior to that age, the GBFS concretes presented lower f_c when compared to those of the reference concrete, but this can be overcome at later ages, with this behavior being present for all the levels of replacement. This result is due to the chemical secondary reactions and to the slow hydraulic reaction of the slag, which contributes to the densification of the micro-structure of concrete. The results presented by Chidiac and Panesar (Chidiac, 2008) confirm the above, plus the initial hydration rate is slower in concrete with GBFS than with OPC. Therefore, over the course of 7 to 28 days, the concrete with GBFS (60%) starts gaining resistance, making it similar or superior to the concrete with OPC.

With these results, it can be said that the possibilities of using a byproduct will be determined by the quality requirements of the concrete, understood as the mechanical resistance and durability properties. It is worth mentioning that the compression resistance is not an absolute parameter in selecting a certain concrete for any determined construction. Therefore, with the information presented above, it can be predicted that with the increase in the dosage of BFS in the cementing system, resistances to compression comparable to a conventional PC concrete can be obtained, but with the notion that this will happen at later ages as with a normal concrete.

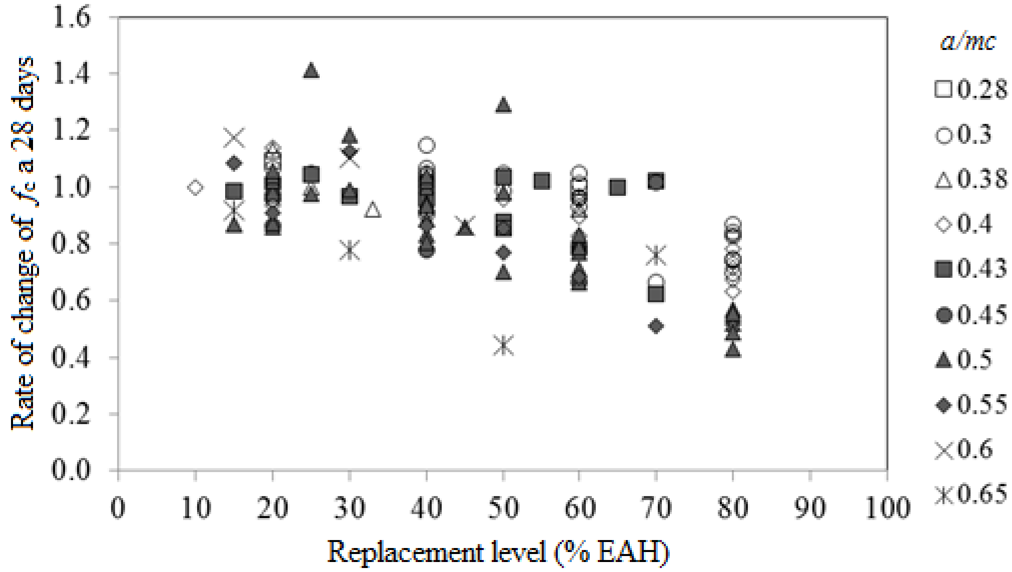

Figure 4. Rate of change (efficiency) of the resistance to real compression f_c of the concretes with slag, at 28 days.

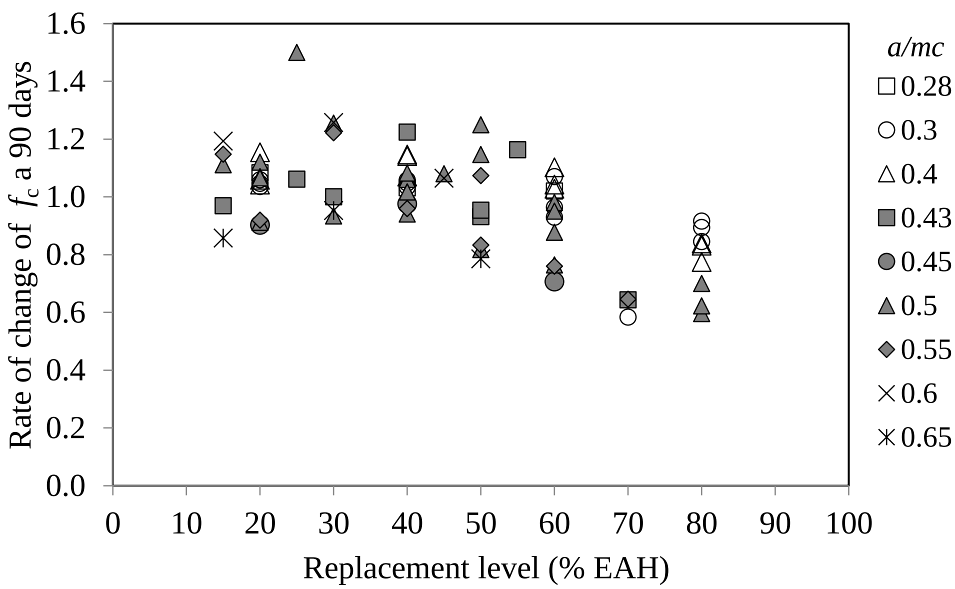

Figure 5. Rate of change (efficiency) of the resistance to real compression f_c of the concretes with slag, at 90 days.

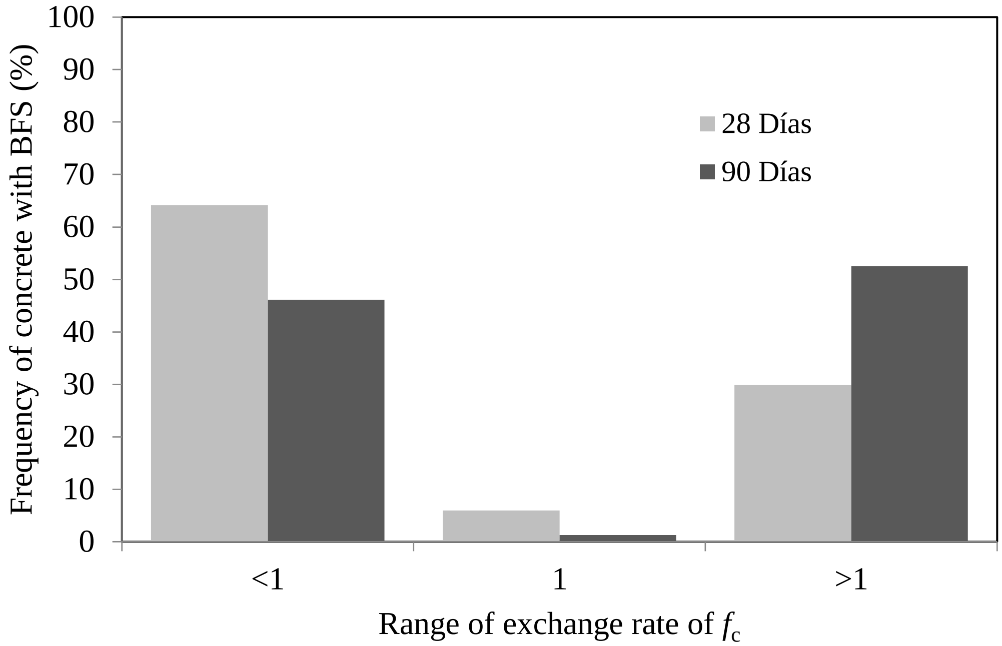

Figure 6. Frequency of the number of concrete samples with BFS related to the rate of change (efficiency) of f_c when compared to the reference concrete.

It has been previously observed that the incorporation and the increase in the level of slag in the mixture of concrete can have a beneficial effect on the mechanical properties of hardened concrete, but conditioned to a certain degree of replacement and to a certain age. As a counterpart, it can be said that the concrete elaborated with a high percentage of slag is very sensible to the conditions of curing, generating a premature drying on the surface of concrete, which would lead to the increase of permeability, in addition to the fact that the hydration of the cementing material is reduced, which would decrease the mechanical properties of resistance for the hardened concrete.

In a similar manner to the conventional concrete, the curing during the first hours following the hardening of concrete with a OPC+GBFS cementing system is highly essential, as this influences the development of the compression resistance, the decrease of porosity, and the high resistance to the penetration of chlorides. Under this premise, Ramezanianpour and Malhotra (Ramezanianpour, 1995) provide the results of their research with the replacement levels found in Table 2 and with a standard continuous humidity curing, corroborating that the concretes that were not cured showed poor performance with regard to the development of the mechanical resistance, as well as greater porosity and a weak resistance to penetration of chloride ions. It is worth pointing out that even when concretes were cured for 2 days, a significant improvement was seen with regard to their resistance in comparison with the concrete with no curing treatment. Therefore, the importance of curing the concrete with the OPC + BFS cementing system is reaffirmed, given that as it has already been mentioned, the hydration reaction of the slag is slower than that of the cement.

An important parameter in the prediction of the resistance of concrete with slag through the Feret model (Feret, 1982) is the efficiency coefficient of the slag. In the hydration time of the cementing system, the slag tends to improve its coefficient until reaching an optimal value when compared to Portland cement, but it has also been seen that it could decrease afterwards (Abdelkader, 2010). Therefore, efficiency will depend on the level of replacement, as it has been observed that with a 15% of slag, the activation is complete and there is 67% more efficiency than with regular cement.

Whereas for the high levels of replacement (50%), the efficiency of the slag decreases or manages, in the best of cases, to be comparable to cement (Abdelkader, 2010).
In Osborne's research, (Osborne, 1999), in studies conducted on structural elements with cementing mixtures with 30%, 50%, and 70% slag, good results have been achieved on the resistances to real compression f_c and when exposed to moderately aggressive environments; the results of which are shown in Table 2. On the other hand, the author states that the carbonation rate and the permeability of gas species are similar to concrete with a regular cement, however, he considers concrete with high levels of slag and exposed to open-air to be highly susceptible, making these factors highly aggressive in places with a dry environment. Nevertheless, he points out that by taking special care of the coating for the reinforcement steel, and limiting the amounts of slag for environmental situations with a high risk of carbonation, the effect could be lessened, thus limiting the level of slag replacement to a maximum 50%. For considerably humid environments and in the presence of chlorides, a level of up to 70% may be used (Osborne, 1999)**.**
Considering the foregoing, it can be said that the proper curing of the concretes with blast-furnace slag should be considered as a fundamental factor for hydration, thus guaranteeing a good performance in the mechanical resistance and durability properties.
Consequently, it can be said that the use and the level of replacement of the blast-furnace slag in the cementing systems for concrete is defined in accordance with the design characteristics of the concrete mixture, both fresh and hardened, and on the environment to which the structural elements shall be exposed.

5. CONCLUSIONS

After re-visiting the state-of-the-art on the *fc* in concretes with blast-furnace slag, we were able to confirm that, through the experience of different authors who evaluated different conditions and types of slag, the level of replacement could be significantly high. However, when surpassing by 50% this level, a strict quality control plan would be necessary in the preparation and combination of other additives that contribute to the improvement of the mechanical resistance; otherwise, there may be adverse effects to the expected results.
The maximum replacement level recommended by several authors and in accordance with the results obtained by others, is of 70% slag in environments with little carbonation aggressiveness, otherwise it must be limited to a maximum of 50%.
The concrete where cement is partially replaced by BFS will require a longer hydration time to guarantee the desired f_c, with the curing of concrete being of major significance.

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