Volume 9, Number 4 (August 2016) p. 572 - 586 • ISSN 1983-4195
http://dx.doi.org/10.1590/S1983-41952016000400006

REVISTA IBRACON DE ESTRUTURAS E MATERIAIS
IBRACON STRUCTURES AND MATERIALS JOURNAL

Study of effect of electric arc furnace slag on expansion of mortars subjected to alkali-aggregate reaction

Estudo dos efeitos do uso da escória de aciaria na expansão de corpos de prova sujeitos à reação álcali-agregado

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Abstract

Alkali-aggregate reaction is a chemical reaction between cement alkalis and some reactive mineral present in some aggregates, leading to concrete expansion and cracking. One kind usually observed and studied in Brazil is the alkali-silica reaction, due to its fast development. There are several methods that are effective to control and mitigate this reaction, and one of them is the partial replacement of cement by mineral additions such as pozzolans like fly-ash, silica fume and slag. In this study, we propose the use of electrical steel slag as a partial replacement of cement, evaluating its effectiveness by NBR 15577:2008, employing different proportions as replacement. It seems that the electrical steel slag, despite its expansive behavior, has been effective in the control of the ASR.

Keywords: concrete expansion, alkali-aggregate reaction. alkali-silica reaction, pozzolans, steel slag.

Resumo

A reação álcali-agregado (RAA) é uma reação que ocorre entre os álcalis do cimento e alguns compostos minerais presentes em determinados agregados, gerando consequências ao concreto, como por exemplo, fissuração. A reação com maiores ocorrências registrada no Brasil é a reação álcali-sílica (RAS), devido à rapidez com que esta ocorre em função das formas minerais reativas envolvidas. Vários métodos estudados já se comprovaram eficazes para o controle desta reação, sendo um deles a substituição parcial de cimento por adições como as pozolanas, dentre as quais podem ser citadas as cinzas volantes e as escórias de origem siderúrgica. Neste sentido, este trabalho tem por objetivo o estudo da utilização da escória de aciaria elétrica como redutor da reação álcali-agregado, sendo desenvolvido com base nas orientações da NBR 15577:2008 Agregados – Reatividade Álcali-Agregado, avaliado para diferentes proporções de substituição parcial de cimento por escória. A escória de aciaria elétrica, uma pozolana não tradicional resultante do processo de produção do aço e de características expansivas, teve êxito ao reduzir a expansão da RAS.

Palavras-chave: expansão do concreto, reação álcali-agregado, reação álcali-sílica, pozolanas, escória de aciaria.

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Received: 16 Mar 2015 • Accepted: 18 Feb 2016 • Available Online: 12 Jul 2016

1. Introduction

Alkali aggregate reaction (AAR) is a chemical reaction, which occurs between alkalis from cement paste and some alkaline reactive minerals in aggregates. This reaction form a viscous hygroscopic gel that fills concrete voids leading to damage and reducing the concrete structure life span [1].

There are mainly two types of AAR, alkali-silica reaction (ASR) and alkali-carbonate reaction (ACR), according to the aggregate reactive minerals.

Alkali-silicate reaction can be classified as a specific type of ASR, for its resemblance, because low degree of crystalline silicates or amorphous silicates usually develop alkali-silica reaction while highly crystalline silicates develop alkali-silicate reaction [2]. In this sense, alkali-silicate is observed in opal, amorphous silica, chert or chalcedony, cristobalite or tridymite, natural volcanic and borosilicate glasses, when reacts with cement alkalis and calcium hydroxide. Alkali-silica reaction and alkali-silicate reaction is the most common type of AAR in Brazil, been found in several structures [3].

If properly identified, it is possible to minimize the expansion and related cracking. If the aggregate is potentially reactive, replacement may be considered, but cost must be evaluated. Reactive aggregate partial replacement may reduce the potential for expansion. Collins and Bareham [4] partially replaced a reactive aggregate by a porous aggregate, suppressing the expansion through the dilution of alkali concentrations by water absorbed in the porous aggregate. Ducman *et al* [5] also employed a porous aggregate, yet highly reactive. The porous structure of the aggregate were able to accommodate the gel produced, without causing expansion or cracks in the evaluated mortar bars.

Low-alkali cement can also minimize alkali hydroxide concentration in the concrete pore solution, reducing the potential for expansion. Nevertheless supplementary cementitious materials and external sources of alkalis like deicers and seawater, can contribute to total alkali content of concrete [6].

The expansion reduction may also be attained by chemical additions to the concrete, like lithium compounds. Qinghan *et al* [7] and Lumley [8] indicate that lithium compounds are effective to inhibit ASR expansion, because it replaces sodium and potassium alkaline ions in ASR gel, densifying it. Notice that, if insufficient lithium is used, the expansion may increase, because lithium compounds may combine with calcium hydroxide as well, producing calcium salts and lithium hydroxide, and increasing hydroxyl ions concentration in the pore solution [9]. Mo *et al* [10] say that some lithium salts do not release hydroxyl ions in the pore solution as it reacts, leading to best results.

Diamond [11] studied lithium nitrate ($LiNO_3$) as a chemical addition, and observed that it did not increase hydroxyl ions in the concrete pore solution, and was able to inhibit ASR expansion. Qian *et al* [12] observed that lithium hydroxide and lithium salts were effective to suppress ASR but started Alkali-Carbonate Reaction. Silva [13] observed that, beyond a threshold, lithium nitrate had no more influence on the ASR inhibition, and, after a 30 days test, lithium nitrate hold ASR expansion while fly-ash did not.

Mineral additions can be used as supplementary cementitious material and suppress ASR expansion [14]. The most common materials are natural pozzolans, fly-ash, slag, silica fume and rice husk ash. These materials can suppress ASR expansion and also improve some concrete properties, such as permeability, heat resistance (slower conductivity rate), smaller diffusivity (due a denser matrix) and overall durability increase [15].

Munhoz [16] verified that, as blast furnace slag, fly-ash, metakaolin, silica fume are mixed in concrete at increasing amounts, expansion due AAR is reduced. Silveira [17] had similar results with rice husk ash.

Ramachandran [18] stated that mineral additions, such as natural pozzolans, fly-ash, blast furnace slag, silica fume and rice husk ash, would only be effective to inhibit alkali-aggregate reaction according to their chemical composition (SiO_2 percentage and free alkali ions), to the mixed amount, to the aggregate type (kind of AAR) and to the cement alkali (Sodium, Potassium or Lithium).

Electric arc furnace steel slag is a by-product of steel production, without commercial value and treated like waste, because is made of impurities removed during steel refining operation. Steel slag is mainly composed by lime (calcium oxide – CaO) and magnesia (magnesium oxide – MgO), with porous structure where water migrates, reacting with free calcium oxide to form lime slurry (calcium hydroxide - $Ca(OH)_2$) that has crystalline structure and twice volume. This volume change leads to stresses, cracks and expansion [19]. Steel slag has high Calcium/Silicate ratio, which means that free calcium oxide has potential to expand when mixed in concrete [20]. Notice that the concrete expansion due AAR is dependent on Ca content [21].

Luxán *et al* [22] studied the chemical stability and the mineralogical compounds of electric arc furnace slag, stating that the studied slag may be employed as building material. Tsakiridis *et al* [23] employed steel slag as raw material for the production of cement clinker, showing that the addition of steel slag did not affect cement sintering, the hydration process during production, and had similar mechanical characteristics to usual Portland cement clinker. Qiang and Peiyu [24] also pointed out that the hydration compounds of steel slag are mainly CSH gel and lime slurry, very similar with those of cement.

Table 1 – Cement characteristics – CP V ARI RS

Property	Test method	Results	Limits NBR 15577-4
Na_2O alkali equivalent*	NBR 14 656	0.780 %	(0.90±0.10) %
Free calcium oxide	NBR NM 12	1.31 %	–
Blaine fineness	NBR NM 76	4743 cm^2/g	(4900±200) cm^2/g
Autoclave expansion	ASTM C 151	0.08 %	< 0.20%

(*) Na_2O alkali equivalent = 0,658 $K_2O\%$ + Na_2O

Table 2 – Standard sand characteristics

Property	Results	Limits NBR 7412:1982
Material passing through 0.075 mm sieve	0.0%	≤ 1.0%
Conglomerate clayey	0.0%	≤ 0.2%
Feldspar content of sieves 2.4 and 1.2 mm	2.4 %	≤ 15.0 %
Mica content of sieve 0.3 and 0.15 mm	1.9 %	≤ 2.0 %
Organic impurities	< 100 ppm	≤ 100 ppm

Source: IPT (28)

Xuequan *et al* [25] developed a cement made of clinker, steel slag and fly-ash, with cementitious properties close to Portland cement, consuming part of the alkali during hydration, which would reduce expansion due to AAR.

This paper evaluates the electric arc furnace steel slag as partial replacement of Portland cement, instead of raw material for cement clinker production, aiming to suppress alkali-silica reaction, based on the methodology established by the Brazilian standard NBR 15577:2008 [26]. Next, we present the characteristics of the material employed in this study and the techniques to evaluate it. Then, the results are presented, and finally some conclusions are drawn.

2. Materials and methods

The materials used were: high early strength Portland cement with improved resistance to sulphate attack (CP V ARI RS), with characteristics presented in Table 1 and following the features required by NBR 15577:2008; fine grained basalt with volcanic glass scattered throughout the rock; Brazilian standard sand – a reference sand that must be used for cement tests, with characteristics presented in Table 2; and electric arc furnace steel slag.

The slag has been crushed and milled in a ball mill into powder form, using only the material passing through 0.075 mm sieve. Figure 1 presents a sample employing scanning electron microscopy (SEM). One may notice that slag grain shows a round form, with particle size under 10µm, but most of it has size under 3µm. Figure 2, obtained with the aid of a laser diffraction particle size analyzer, shows that the particle size distribution of the slag is close to particle size distribution of the cement, meaning that the slag can be used as a mineral addition.

To identify the composition of the slag, an X-ray diffraction was carried out. The main compounds present were periclase (magnesium oxide), quartz (silicate), lime (calcium oxide), alkalies (potassium and sodium), dolomite ($CaCO_3.MgCO_3$) and calcite ($CaCO_3$), that can be verified through the diffractogram of Figure 3.

Table 3 shows the slag chemical composition obtained by X-ray fluorescence spectrometer, while Table 4 shows its apparent (bulk) density and volumetric instability, evaluated with Brazilian standard NBR 11582:2012 [27]. Notice that the slag did not show expansion, but it was only evaluated until 7th day.

Figure 1 – Scanning electron microscopy of crushed steel slag (1000x e 2000x)

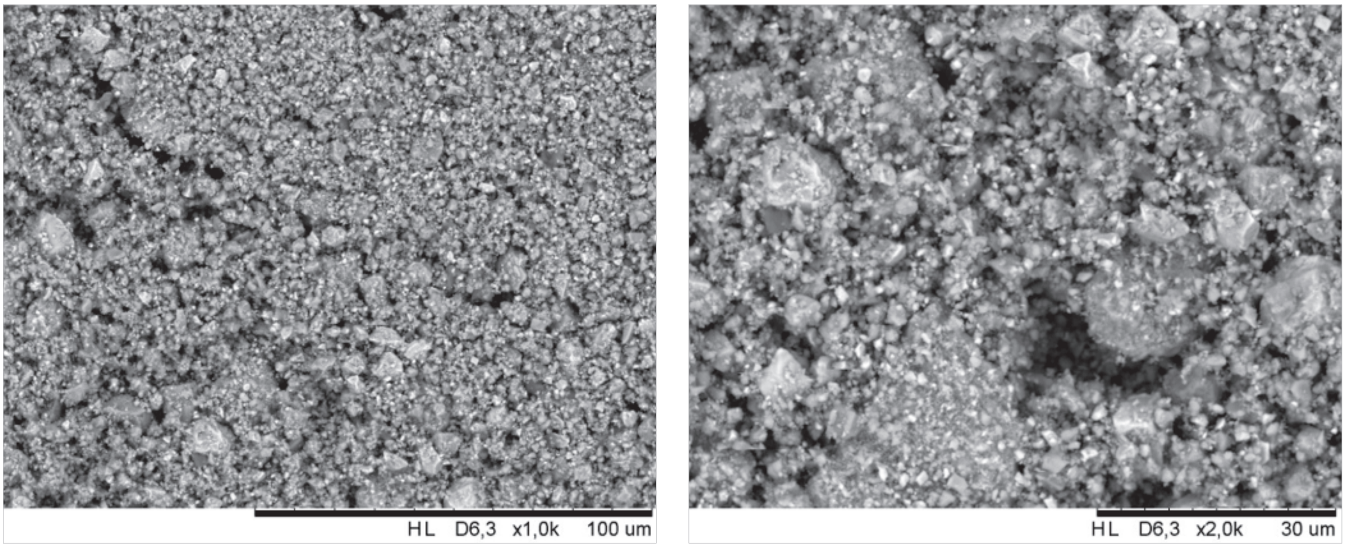


Table 3 – Steel slag chemical composition by X-ray fluorescence spectrometer

Chemical composition	Results
Fe_2O_3 (%)	30.7
SiO_2 (%)	24.1
CaO (%)	21.3
Al_2O_3 (%)	7.0
MgO (%)	6.3
MnO (%)	4.0
Cr_2O_3 (%)	1.1
TiO_2 (%)	0.9
P2O5 (%)	0.5
Na_2O (%)	0.4
K_2O (%)	0.4
SO_3 (%)	0.4
BaO (%)	0.4
V_2O_5 (%)	0.1
SrO (%)	0.1
ZrO_2, Nb_2O_5, ZnO, Cl (%)	<0.1
Basicity	1.85
Free CaO	0.97

Figure 2 – Particle size distribution of slag and cement by laser diffraction particle size analyzer

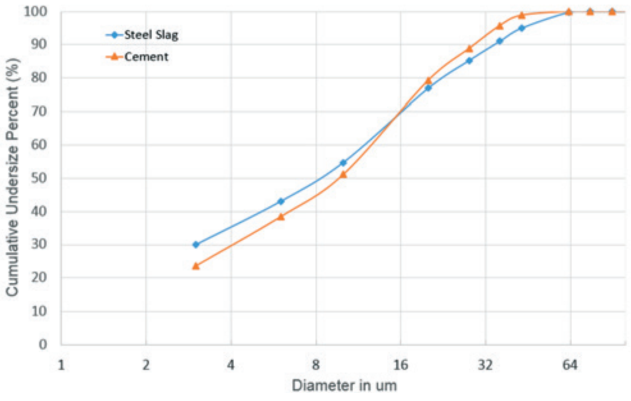
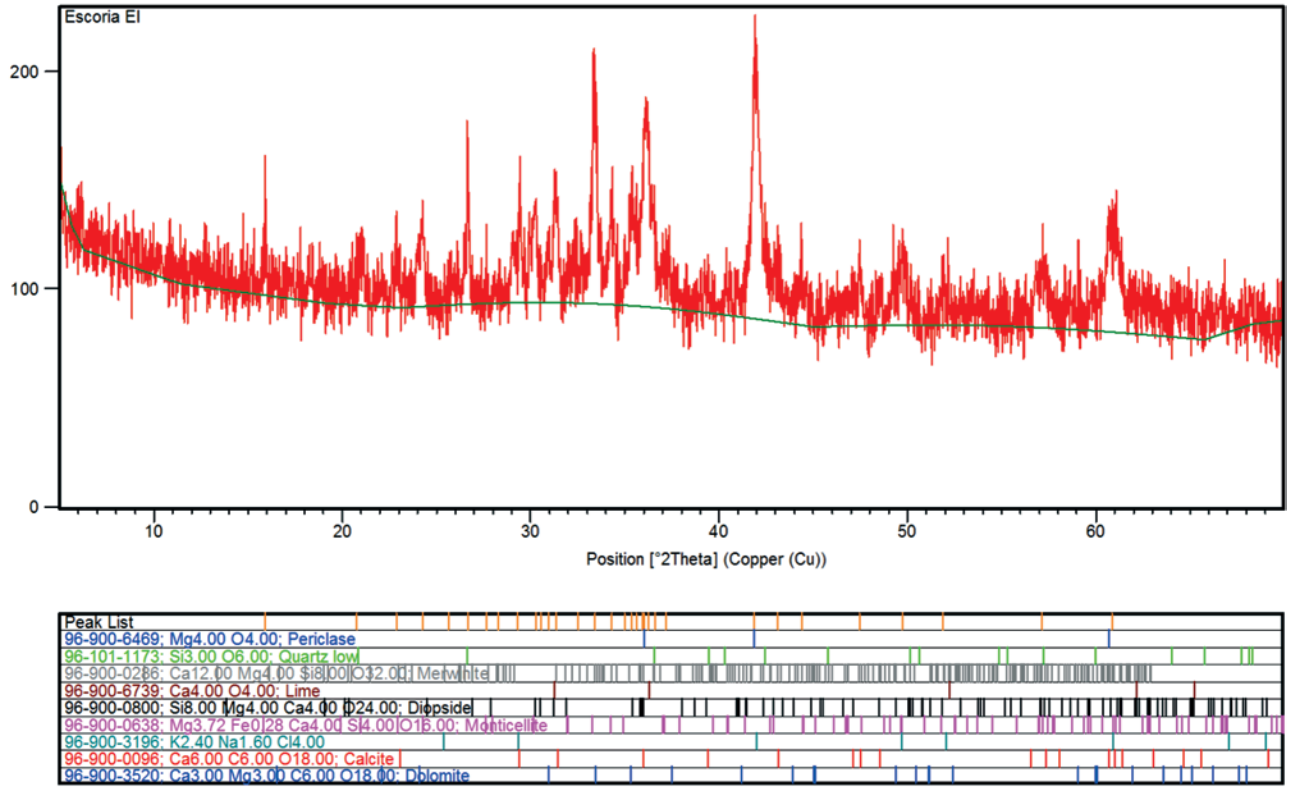


Figure 3 – Steel slag diffractogram



Following NBR 15577:2008, parts 4 and 5, three mortar bars (25±0,7 mm by 25±0,7 mm by 285 mm) were cast for each mixture, with mix design by mass of 1 part of cement, 2.25 parts of selected aggregate (either fine grained basalt or standard sand), and water/

Table 4 – Steel slag characteristics

Property	Steel slag
Apparent (bulk) density	3.76 g/cm^3
Expansibility (NBR 11582)	0 mm

binder ratio of 0.47. Twelve different mixtures were prepared containing 0, 10, 20 and 30% by mass replacement of cement by slag. Three mortars were mixed without reactive aggregate and without slag, only with standard sand and Portland cement, for reference. The cement replacement ratio is shown in Table 5.

The specimens were cured in a moisture room for a period of 24 hours. After that, mortars received identification tags and the initial length of each specimen was measured. The specimens were then stored in a climatic chamber with temperature of 80ºC immersed in distilled water. After another measurement was taken, the specimens were immersed in a 1N sodium hydroxide (NaOH) solution, at a temperature of 80ºC. Expansion rate is increased due temperature, while the sodium hydroxide solution provides enough alkaline ions. Following NBR 15577:2008, the specimens were measured at 8, 16, 22 and 30 days.

3. Results and discussion

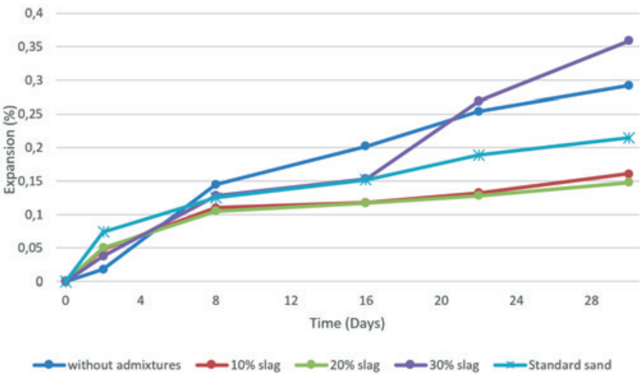
Figure 4 presents the average expansion measured in all specimens. The relative expansion is obtained by the following expression:

$$R = 100\frac{E_4 - E_5}{E_4} \qquad (1)$$

where R is the percentage reduction of mortar expansion, E_4 is the average expansion of the mortar without mineral addition (without slag - %) and E_5 is the average expansion of mortars with mineral addition (%). Results are presented in Figure 5.

Figures 4 and 5 show that slag was able to reduce expansion due AAR. Nevertheless, it should be employed with caution. Good reduction is achieved with 20% of cement replacement by slag, with expansion of 0.12% at 16 days and 0.15% at 30 days.

Figure 4 – Mortar expansion with and without steel slag



According to NBR 15577-1:2008, a mineral addition is considered effective only if expansion is under 0.10% at 16 days, which was not attained by any of the proposed replacements. It worth notice, nevertheless, that the expansion was reduced about 40%, as seen in Figure 5. Probably the basaltic aggregate is highly reactive to

Figure 5 – Percentage reduction (R) of mortar expansion, related to mortar without slag

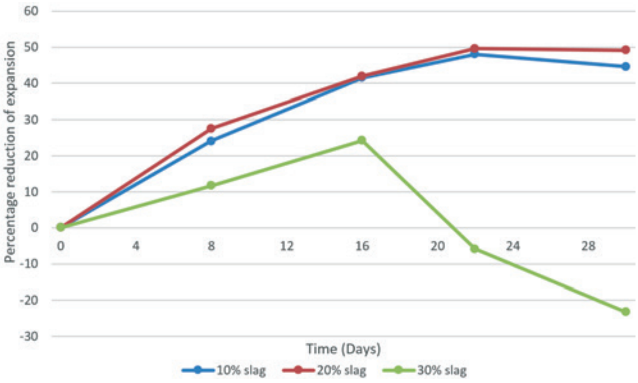
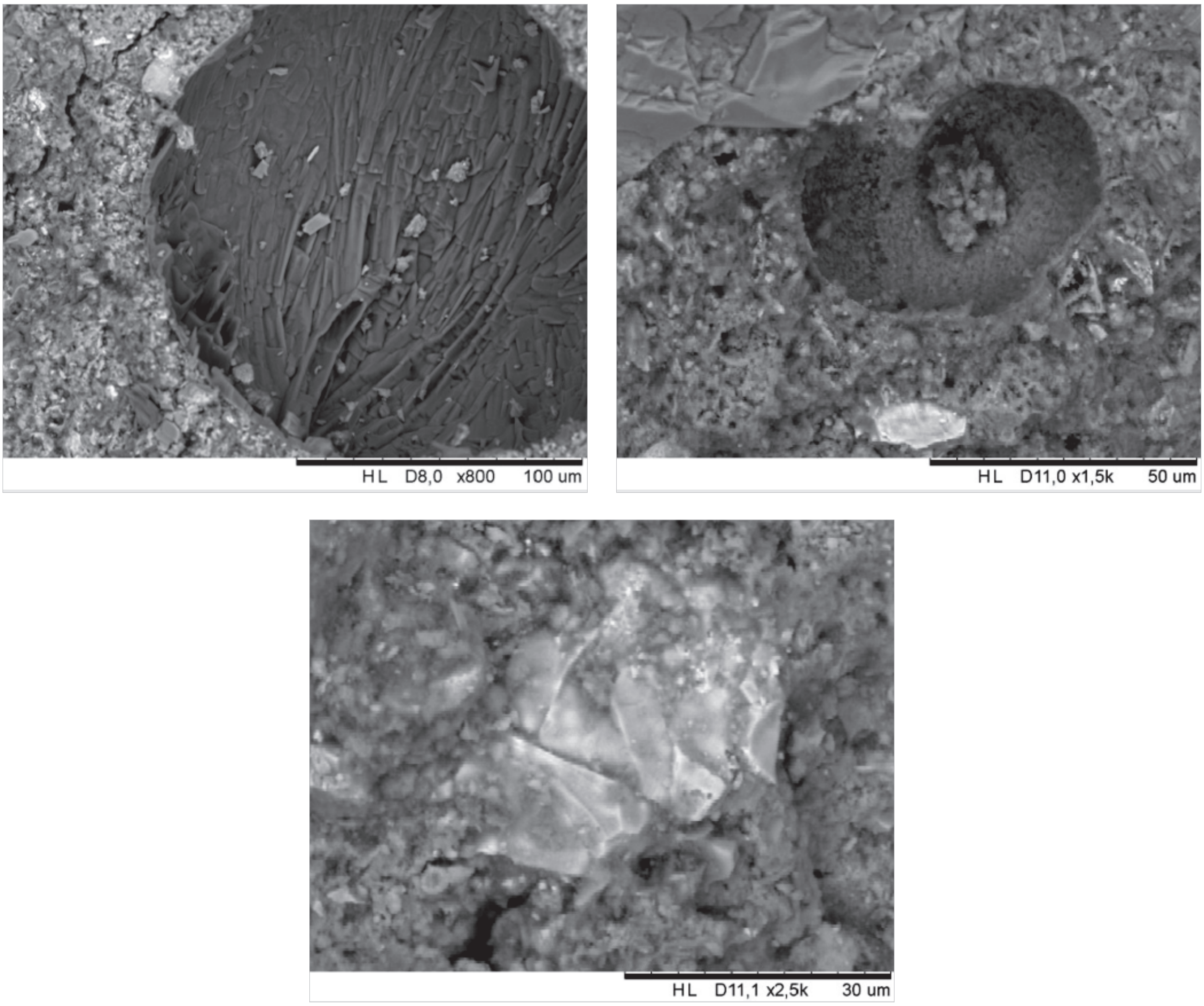


Table 5 – Cement replacement ratio

Replacement ratio	1		2.25	0.47
	Cement (g)	Slag (g)	Aggregate (g)	Water (g)
0% (Reference)	146.67	–	330.00	68.93
10%	132.00	14.67	330.00	68.93
20%	117.34	29.33	330.00	68.93
30%	102.66	44.01	330.00	68.93
Sand (no reactive)	146.67	–	330.00	68.93

Figure 6 – Microscopy of mortar specimens with 30% replacement by steel slag (800x, 1500x, and 2500x)



alkalis, and it might be interesting to test the replacement with a less reactive aggregate, as stated by the Brazilian standard.

It is also worth point out that the expansion in mortar with 30% of cement replacement by slag was reduced about 25% at 16 days, but expansion is observed after 30 days. Figure 6 shows a scanning electron microscopy made in a mortar with 30% of cement replacement. The first and second sub-image, with zoom of 800x and 1500x, show a slag grain, with reaction rim. The third sub-image shown an aggregate grain, with no reaction rim, indicating that the reaction is probably restrained, maybe even suppressed. Latter expansion could then be caused by free calcium oxide [20].

A point to be clarified remains, in which the excess calcium rather than assist in expansion as would be expected (see [21] for example), reduced the alkali-aggregate reaction.

4. Conclusions

Evaluation of the effectiveness of the use of steel slag in reducing expansion due to alkali-aggregate reaction has been studied. The fine grained basalt with volcanic glass scattered throughout the rock was highly reactive, with expansion of 0.86 mm (0.29%) at 30 days in the accelerated mortar-bar test set by Brazilian standard NBR 15577:2008.

Regarding the steel slag addition, it is observed that at 16 days there was significant reduction in the mortar expansion due AAR with 10% and 20% of cement replacement, setting almost 54% of expansion reduction. Despite it, expansion is above the limit of 0.10% set by Brazilian standard NBR 15577:2008. Furthermore, expansion still develops the end of the measurement, at 30 days, which implies that the reason behind expansion is still there.

It has been considered that the reason for the expansion is the excess of free calcium oxide and magnesium oxide, since no reaction rim or gel bags were observed in the specimens with 10, 20 or 30% of cement replacement by steel slag.

In this sense, we conclude that a steel slag with high content of calcium oxide (CaO) may have opposite effect to the expected, which may mitigate AAR yet expansion still develop due the presence of free calcium oxide and magnesium oxide.

5. Acknowledgment

Authors acknowledge UTFPR-PB for financial support and LACTEC – Institute of Technology for Development by providing the reactive aggregate. We also acknowledge prof. Dr. Caroline Angulski da Luz for the assistance in the analysis of X-ray diffraction and laser diffraction particle size analyzer.

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