



ORIGINAL ARTICLE

Use of recycled aggregates from civil construction in self-compacting mortar

Uso de agregados reciclados da construção civil na argamassa autoadensável

Fernanda Rodrigues Santos Valle^a Paulo Cesar Gonçalves^a Maria Gabriela A. Ranieri^b Mirian de Lourdes Noronha Motta Melo^c Valquíria Claret dos Santos^a ^aUniversidade Federal de Itajubá – UNIFEI, Instituto de Recursos Naturais – IRN, Itajubá, MG, Brasil^bUniversidade Federal de Itajubá – UNIFEI, Instituto de Engenharia de Produção e Gestão – IEPG, Itajubá, MG, Brasil^cUniversidade Federal de Itajubá – UNIFEI, Instituto de Engenharia Mecânica – IEM, Itajubá, MG, Brasil

Received 02 December 2020

Accepted 26 May 2021

Abstract: The utilization of wastes from demolition in civil construction in self compacting concrete (SCM) has the potential to reduce both the environmental impact and financial cost. In this context, this article aims to verify the behavior of the incorporation of recycled aggregates of civil construction in the mix designs of self-compacting mortar (SCM) in replacing cement, presenting as an interesting alternative to natural raw materials. This study used the EMMA® software to optimize the choice of percentages of fine recycled aggregates when replacing cement. The proportions chosen were 0%, 5%, 15%, and 25%, through the analysis of the granular packing curve of the respective mix designs. The proportion of 0% has in its composition cement, metakaolin, sand, superplasticizer (SP) and water. The parameters obtained, through tests in the fresh state of the mini-slump and mini-funnel V, certified the samples as SCM. The compressive strength and flexural tensile strength tests in the hardened state demonstrated a reduction in mechanical properties of the material with cement replacement. It is concluded that the waste used brick and ceramic can be added in replacement to the cement in SCM without significant loss of properties in the fresh and hardened state.

Keywords: self-compacting mortar (SCM), ceramic waste, construction waste, metakaolin, granular packing.

Resumo: A utilização de resíduos de demolição da construção civil em concreto autoadensável (CAA) tem o potencial de reduzir o impacto ambiental e o custo financeiro. Nesse contexto, este artigo tem como objetivo verificar o comportamento da incorporação de agregados reciclados da construção civil nos traços de argamassas autoadensáveis (AAA) em substituição ao cimento, apresentando-se como uma alternativa interessante às matérias-primas naturais. Este estudo usou o *software* EMMA® para otimizar a escolha das porcentagens de agregados reciclados finos ao substituir o cimento. As proporções escolhidas foram 0%, 5%, 15% e 25%, através da análise da curva de empacotamento de partículas dos respectivos traços. A proporção de 0% tem em sua composição cimento, metacaulim, areia, superplastificante (SP) e água. Os parâmetros obtidos, por meio de testes no estado fresco do *mini-slump* e mini-funil V, certificaram as amostras como AAA. Os ensaios de resistência à compressão e a tração na flexão no estado endurecido demonstraram redução nas propriedades mecânicas do material com a substituição do cimento. Conclui-se que os resíduos usados de tijolo e cerâmica podem ser adicionados em substituição ao cimento na AAA sem perda significativas de propriedades no estado fresco e endurecido.

Palavras-chave: argamassa autoadensável (AAA), resíduo cerâmico, resíduo de construção, metacaulim, empacotamento de partículas.

How to cite: F. R. S. Valle, P. C. Gonçalves, M. G. A. Ranieri, M. L. N. M. Melo, and V. C. Santos, "Use of recycled aggregates from civil construction in self-compacting mortar," *Rev. IBRACON Estrut. Mater.*, vol. 15, no. 1, e15107, 2022, <https://doi.org/10.1590/S1983-41952022000100007>

Corresponding author: Valquíria Claret dos Santos. E-mail: valquiria@unifei.edu.br

Financial support: None.

Conflict of interest: Nothing to declare.



This is an Open Access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

1 INTRODUCTION

Self-compacting concrete (SCC) is a concrete that is able to flow and compact in several forms by simply using its weight and without the need for vibration equipment [1]. In rheological terms, SCC has a significant variation in plastic viscosity that interfere in obtaining concrete with adequate fluidity and stability. Due to this parameter combination, the SCC has several advantages, such as fluidity and filling capacity [2].

In studies of Silva et al. [3], the percentage replacement of cement in SCC by masonry wastes was carried out, which caused decreased strength in the samples in relation to the reference mix design. It was observed in the results that for replacement level greater than 40%, the mechanical strength reduced, in the order of 50% in the tensile and compression strengths. However, this fact did not prevent its use because it is possible to find another purpose that is not necessarily structural for the concrete. Besides that, this replacement brings positive impacts to the environment, as raw material consumption and solid waste generated in construction and demolition are high.

One of the methods of self-compacting concrete mixes is to study the properties of self-compacting mortars (SCM). At the same time, determining the rheological characteristics of self-compacting mortars is more accurate, less labor intensive and lower costs. Therefore, the influence of modifying additives on the properties of self-compacting concrete was studied in its mortar phase. Mortar serves as the basis for the workability properties of self-compacting concrete (SCC) and these properties can be evaluated with self-compacting mortars (SCM). In fact, evaluating SCM properties is an integral part of the SCC project

The SCC is characterized by the use of a greater amount of fines and cement. In this context, this work aims to use the fines from wastes from demolition in civil construction and, at the same time, reduce the amount of cement, promoting environmental impact and cost reduction. The objective of this study is to prove the feasibility of replacing the percentage of cement in the SCC with wastes from demolition in civil construction. The brick and ceramic wastes used were ground to obtain a finer granulometry in search of better results.

2 THEORETICAL FOUNDATION

2.1 Solid construction and demolition wastes as recycled aggregates

Civil construction is one of the most active sectors of the country's economy, with around 15% of Brazilian Gross domestic product [4], representing one of the most important in the country's production. However, the consumption of raw materials and energy demanded by this sector implies a great environmental impact, being the one that generates the most solid waste. In recent decades, construction and demolition waste has attracted the attention of many researchers in all parts of the world. Only in the European community, around 3000 million tons of waste are produced annually [5]. This fact, added to the increasing difficulty in obtaining raw material for the production of concrete due to environmental and social issues, has led to the search for viable alternatives. An important alternative in the civil construction scenario is the reuse of solid waste generated by construction and demolition, whether for use as coarse aggregates to be incorporated the concrete, as fine aggregates in the production of mortars. Many challenges still need to be overcome in the proper use of recycled aggregates from civil construction, still requiring many research to consolidate this alternative.

Bravo et al. [5] researched about the durability of concrete with incorporation of recycled aggregates for construction and demolition. The incorporation of recycled aggregates demands a higher w/c ratio, in comparison with mixture that use natural aggregates, to ensure adequate workability, resulting in more porous cementitious matrices and, consequently, the entry of external agents that reduce the durability of the concrete. Another important analysis showed that carbonation resistance was the most affected with the insertion of recycled aggregates. As a result of greater porosity, the carbonation depth in concrete with coarse recycled aggregates was on the order of 22% higher than concrete with natural aggregate and, when replacing 100% of fine recycled aggregates, the increase was above 110%. It is noteworthy, however, maintaining the same compressive strength in mixture that use recycled aggregate leads to less workability, requiring the use of superplasticizers [6].

Another property of concrete affected by the insertion of construction and demolition aggregates is the reduction of the elasticity modulus, resulting in greater retraction. Butler et al. [7] analyzed the effects of the insertion of recycled aggregates from various sources on the mechanical properties of concrete and observed that maintaining the same compressive strength, equivalent to the concrete mixed with natural aggregate, the values of elasticity modulus showed a reduction of up to 19%.

Regarding mortar produced with insertion of recycled aggregates, Chen et al. [8], presented the study about the incorporation of fine recycled aggregates to replace natural sand in the mortars mixed. The authors used waste from

construction rubbles after a recycling process, which basically consisted of brick and structural concrete waste. The results showed that with addition of fine recycled aggregates the strength of the mortar was reduced and its proportion of substitution governs the percentage of resistance reduction than the w/c ratio. This is totally different from the behavior of the recycled coarse aggregate used in concrete. The use of recycled sand in the mixes composition has been studied recently. As result of crushing leftover fresh structural concrete produced in a concrete dosing plant, the use of recycled sand to replace natural sand has attracted attention. It is common for quantities of concrete ordered in dosing plants to exceed the volume required necessary in the constructions resulting in leftovers of fresh concrete and these leftovers are discarded. A solution to treat the excess concrete is to promote its return to the dosing plant for the curing process for a few days and then crush it resulting in coarse and fine recycled aggregates.

Dapena et al. [9], presented studies on the substitution of recycled sand in the production of mortars, from different substitution proportions and the w/c ratio. The results obtained in mortars with insertion of up to 20% recycled sand caused a reduction of compression and flexural strengths. For higher replacement rates, the authors identified the flexural strengths values were similar to those obtained with 20% recycled sand, when 4% superplasticizer was used in the mixture. Another recycled material from construction and demolition that may have potential in the use of concrete and mortar production is ceramic brick waste. The powder obtained from crushing clay bricks can promote a more compact mixture and, consequently, improve the structure of the mortar and reduce the size and number of pores, resulting in a stronger and denser hardened paste [10]. In other words, the finer the particle size of the recycled brick waste, the denser the microstructure of the paste matrix and the greater the compressive strength of the pastes.

2.2 Self-compacting concrete and Sustainability

According to Gomes and Barros [11], self-compacting concrete (SCC) was developed in the 1980s, in Japan, by Professor Hajime Okamura, due to the need for savings and less execution time. Currently, SCC has multiple advantages, in addition to shorter execution times, labor savings, and durability.

Despite a relatively new practice, an interesting point in self-compacting concrete (SCC) technology has grown in recent years among builders and in the construction industry in several countries [12]. This interest is due to the several advantages provided by the use of self-compacting concrete, as, for example, according to Gomes and Barros [11], SCC is easy to use in concrete parts with a high reinforcement rate, that is, difficult to access. Besides reducing labor effort during the concreting phase, which shortens the construction period. And mainly, considering a healthy work environment and environment preservation, this technology results in a considerable reduction in the levels of acoustic noise due to the non-use of vibration equipment, as well as the reduction in the use of secondary raw materials.

SCC has particular characteristics that guarantee a lower porosity index than conventional concrete due to a greater addition of fine material in the mixture, which may have greater durability and mechanical resistance [13]. Recently, several studies have been developed on CAA with the addition or substitution of fine natural aggregates with fine recycled residues, of a mineral nature or from the manufacture of products, which are usually discarded, with some examples being mentioned, such as fly ash and bark ash. rice [14], recycled rubber powder waste [15], [16], marble and granite powder [17], [18], of plastics, as polymeric waste recycled from refrigerators [19]. With respect to construction and demolition waste, there is still little work on the subject. Venkateswara Rao et al. [13], proposed the study of the durability of the CAA with the addition of fine recycled aggregates, from crushed limestone residues, replacing the natural fine aggregates. The results obtained from the CAA samples with control of the a/c ratio and incorporation of silica active showed a considerable reduction in the permeability to the chloride ion due to the lower porosity index when compared to conventional vibrated concrete samples. This reduction in porosity is directly related to the better packaging of particles within the microstructure. Omrane et al. [20] evaluated the results of the experimental analysis on the mechanical, rheological and durability properties of the CAA produced with fine aggregates and recycled coarse, from crushed concrete and with natural polozane replacing cement. The samples with 50% substitution of coarse and fine aggregates and with addition between 15% and 20% of polozane, allowed to obtain the rheological properties within the necessary limits required for self-compacting concrete.

Other researchers concluded that the incorporation of masonry wastes, with a density of 2.63 g/cm³ and an average size of 24.08 µm, as a partial replacement for cement, affects the compressive strength, reducing it as the waste increases [3]. They concluded that this reduction may be caused by the effect of dilution and low reactivity of the waste because there is less formation of hydration products as the cement is replaced, and the waste does not have high reactivity with water, resulting in decreased strength. Regarding the increased strength between the ages of 180 and 360 days, the study indicates that it may be a consequence of the pozzolanic reaction, and in the replacements of 12.5%, 25%, and 37.5% cement, reaches concrete with performances equal to or greater than the reference.

Jerônimo et al. [21], in their studies on the incorporation of ceramic waste in SCC, concluded that the cement replacement, in 20%, 30%, and 40% contributes to reducing porosity. Regarding the compressive strength, Jerônimo et al. [21] obtained a specific result of greater strength at 7 days of curing with 20% replacement. However, the other replacements showed values lower than the base mix design at this same age. In the study by Jerônimo et al. [21], at 28 and 90 days, the strength gain in relation to the reference mix design varied, respectively, from 0% to 4% and 6 to 11%, which implies a greater pozzolanic effect over time.

Sahmaran *et al.* (2006) evaluated the effectiveness of various mineral additives and chemical additives in the production of self-compacting mortar. In the work, they used four mineral additives (fly ash, brick powder, limestone powder, and kaolinite), three superplasticizers and two viscosity modifying additives. The results showed that fly ash and limestone powder significantly increased the workability of SCM samples. The same occurred with the use of polycarboxylate superplasticizers. The use of mineral additives reduced mechanical resistance in comparison with the reference samples [22].

Several other studies on SCM have been developed recently. The influence on the mechanical properties and durability SCM produced with proportional replacement of cement by pumice as a mineral additive [23]. Study of the effects of superplasticizer and silica fume on the fresh and mechanical properties of self-compacting mortars [24]. Lozano-Lunar et al. [25] evaluated the replacement of conventional fine aggregate (natural sand) with granite sludge as an alternative for SCM production.

A study using blast furnace slag was prepared and used as an additive for self-compacting mortar. Blast furnace slag was crushed and ground to nano particle size [26]. Mechanical properties increased and physical properties, such as total water absorption and porosity, decreased as the percentage of nano dust was increased. Still in the scope of replacing cement in the SCM mixtures, Matos et al. [27] used casting sand from calcined residues and observed that there was an increase in mechanical strength of about 14% in relation to samples containing limestone. Brick residues from construction and demolition as partial replacement of natural aggregates or after crushing, as fines for partial replacement of cement, represent an important socio-environmental alternative.

The use of crushed brick powder as a cement replacement material in SCM production was analyzed in Si-Ahmed and Kenai [28]. The results showed that in up to 15% substitution of cement with crushed brick powder, it has little influence on the rheological parameters of the self-compacting mortar and the compressive strength increased in the long term. It is important to note that studies of the behavior of SCM with incorporation of recycled fine aggregates for construction and demolition are largely scarce and there is a strong demand for research, since they constitute low-cost recycling materials and sustainable alternative to conventional aggregates in the manufacture of self-compacting mortar by reducing the consumption of raw materials.

2.3 Equating the packaging of EMMA® particles for the production of concrete

The compressible packaging model (CPM) appears as a dosing tool that allows the selection and formulation of the concrete constituents, which increases the compactness of the granular mixture and decreases the risk of segregation, as shown in Figure 1 [11]. These models are analytical models that calculate the overall packing density of a mixture based on the geometry of the combined particle groups.

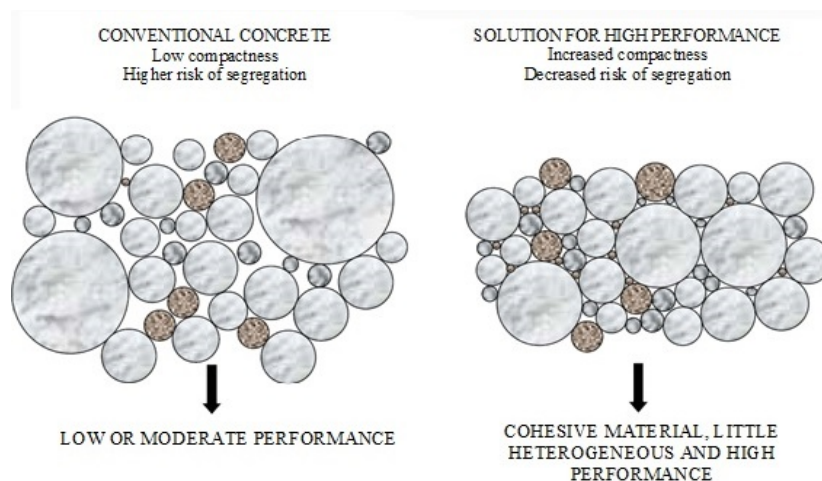


Figure 1. Packaging that seeks the concrete performance. Source: Formagini [29].

EMMA® (*Elkem Materials Mixture Analyzer*) is a software for evaluation of particle-packing, including the production of self-flowing concrete to achieve a suitable workability. Due to the limitation of conventional methods of estimating compacted unit mass for high-fine concrete, the company Elkem developed and made available this computational tool, which calculates and presents the particle size distribution of a mixture of components, in order to optimize particle packaging.

The use of the EMMA® is effective in obtaining the granular skeleton of the SCM, thus avoiding the experimental realization of several mix designs to achieve the proper characteristics of the SCC. According to Castro and Pandolfelli [30], as classics, there is the model proposed by Furnas, which considers particles individually, and the model proposed by Andreassen, which considers particles as continuous and infinitely small distributions and for this reason does not represent real situations with fidelity. Therefore, a new model was developed (Alfred Model), presenting an improvement of the previous models [30]. Alfred's model comes close to Andreassen's model when the diameter of the smallest particle in the mixture tends to zero. For this reason, Alfred's model is also known as a modified Andreassen model, and its mathematical formulation is presented in Equation 1:

$$CPFT = 100 \cdot \left(\frac{D_P^q - D_S^q}{D_L^q - D_S^q} \right) \quad (1)$$

where CPFT: percentage of particles with a diameter less than DP [%];

DP: diameter of the particle;

DS: diameter of the smallest particle;

DL: diameter of the largest particle;

q: distribution coefficient.

The model modified Andreassen, correlates a particle size distribution factor “q”, and limits the maximum and minimum particle sizes. Through computer simulations, it was found that values less than or equal to 0.37 for the distribution coefficient favor the maximum packaging of the particles, while values greater than 0.37 imply residual porosity. Also, for a mixture to have a good flow capacity, the value of the distribution coefficient must be less than 0.30 [31].

In the present work, a distribution coefficient $q = 0.28$ and a maximum diameter of 4800 micrometers were used, in order to optimize the amount of fines present in the SCM. The laser granulometric curves of cement, metakaolin, brick and ceramic, granulometric curves of sand and specific gravities materials were inserted in EMMA® *software*.

Other researchers also used EMMA® program to particle size distributions and achieve a suitable workability to concrete. In the study, the q-values for shotcreting and dry-gunning mixes are 0,27 and 0,22, respectively [32].

3. METHODOLOGY

3.1 Characterization of materials

CP V-ARI cement, used in this experiment, has a finer grinding of Portland clinker, thus adding a material with a favorable granulometry to obtain SCC. To simplify the waste nomenclature in this research, the ground brick waste was called RT (Brick Waste) and the ceramic waste was RP (Ceramic Waste).

In this case, the specific gravity, specific surface, and laser granulometry of the cement were evaluated according to current regulations. Granulometry, specific gravity, unit mass, and water absorption tests were also carried out for the sand, according to current regulations.

The additive used in the SCC is a polycarboxylate superplasticizer.

It was decided to add metakaolin to increase the percentage of fines, improving the mixture cohesion. The tests performed were specific gravity and laser granulometry. The high specific surface area improves rheological aspects by optimizing the granulometric distribution of the paste, contributing to water retention, increased cohesion, reduced exudation, and segregation [33].

The superplasticizer was also used to avoid excessive water consumption.

Finally, as the main objective is the analysis of the percentage replacement of cement by ceramic materials, it was necessary to carry out specific gravity tests for powder materials and granulometry by laser granulometer (Model MasterSizer Micro, Measuring range: 0,3 a 300 μm .), in this case the powder materials are cement, metakaolin, brick and ceramic.

3.2 Dosing and mixing method

To perform SCM, the concept of paste by the method of Gomes and Barros [11] was used, in which a w/c ratio is chosen according to the strength expected to be achieved for the concrete, and a proportion of SP and the amount of fines according to the amount of cement used.

The method of Gomes and Barros [11] has as principle the optimization of the paste and the granular skeleton separately, and the model suggests that the viscosity and fluidity of the paste lead to the concrete flow behavior. According to Gomes and Barros [11], the model is developed in three stages, obtaining the composition of the paste, determining the proportion of the mixture of the aggregates and selecting the paste contents.

According to Gomes and Barros [11], the composition of the paste is defined by the amount of cement and the relationships of the other components of the paste as a function of the cement mass. The paste volume is obtained by Equation 2:

$$V_P = \frac{C}{\rho_C} + \frac{P_a}{\rho_a} + \frac{P_{cs}}{\rho_{cs}} + \frac{P_{mtc}}{\rho_{mtc}} + \frac{P_{spl}}{\rho_{sp}} - \frac{P_{asp}}{\rho_a} \tag{2}$$

Where: C: cement mass [g];

ρ_C : specific gravity of cement [g/cm^3];

$P_a = (w/c) \cdot C$: water mass [g];

ρ_a : specific gravity of water [g/cm^3];

$P_{cs} = (cs/c) \cdot C$: mass of silicon carbide [g];

ρ_{cs} : specific gravity of silicon carbide [g/cm^3];

$P_{mtc} = (mtc/c) \cdot C$: metakaolin mass [g];

ρ_{mtc} : specific gravity of metakaolin [g/cm^3];

$P_{spl} = [(sp/c) \cdot C] \div [T_{sp} / 100]$: mass of liquid superplasticizer [g];

T_{sp} : solid content of the superplasticizer;

ρ_{sp} : specific gravity of the superplasticizer [g/cm^3];

$P_{asp} = [(sp/c) \cdot C] \cdot [(100 / T_{sp}) - 1]$: mass of water contained in the superplasticizer [g].

Then, the composition of the granular skeleton must be defined. Granular skeleton means the association of large and small aggregates that make up the concrete structure. As an adaptation and simplification of the method by Gomes and Barros [11], the coarse aggregates were disregarded of the dosing procedures so that it was possible to produce SCM. Also, according to the author, the volume of fine aggregates in relation to the total mortar volume should preferably be not less than 40% and not more than 50%.

After defining the w/c and SP/c ratios according to the desired fluidity and viscosity properties, the cement mass is calculated for the volume of one cubic meter of mortar, according to Equation 3 [11].

$$C = \frac{V_P}{\frac{1}{\rho_C} + \frac{(a/c)}{\rho_a} + \frac{(cs/c)}{\rho_{cs}} + \frac{(mtc/c)}{\rho_{mic}} + \frac{(sp/c) \cdot \left(\frac{100}{T_{sp}}\right)}{\rho_{sp}} - \frac{(sp/c) \cdot \left[\left(\frac{100}{T_{sp}}\right) - 1\right]}{\rho_a}} \tag{3}$$

Where VP is the volume of the paste previously determined.

The mixing process was carried out as proposed [34]. The materials used and the mixing process are shown in Table 1. The mixer used is in accordance with [34].

Table 1. SCM mixing process developed in this article

	Addition
1 minute	Cement, metakaolin, sand, and ground brick (or ceramic)
1 minute	80% of the total volume of water
5 minutes	20% of the total volume of water + superplasticizer
2 minutes	Rest in mortar
1 minute	Mix again in the mortar

3.3 Mortar properties

3.3.1 Properties in the hardened state

According to the standards [35] and [36], the axial compressive strength and flexural tensile strength tests were performed. Four cylindrical specimens (CP) were molded, 5 cm in diameter, and 10 cm high for the compressive test, and 3 prismatic CPs, 4 cm wide, 4 cm high, and 16 cm long for the flexural.

The flexural tensile test is subjected to a force until rupture according to Equation 4:

$$Rf = \left(\frac{1,5 * Ft * L}{40^3} \right) \tag{4}$$

Where:

Rf: flexural tensile strength [MPa];

Ft: load applied at the center of the CP [N];

L = 100 mm: distance between supports [mm].

To reduce the volume of mixing water, the ADITIBRAS® ADI-SUPER H25 superplasticizer was used, which, according to the manufacturer, had a solids content of 25%. In the Flowchart shown in Figure 2, the characterization path after the mixing of the materials is observed, both in the pasty and in the hardened state.

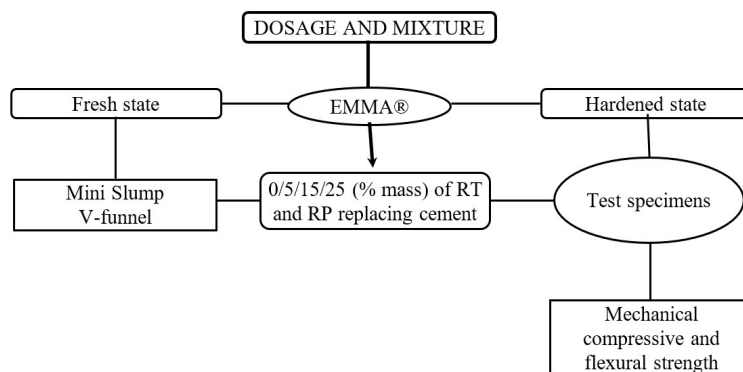


Figure 2. Flowchart on how the dosing and mixing process was carried out, both fresh and hardened.

4 EXPERIMENTAL RESULTS AND DISCUSSION

The results of the characterization tests for cement, metakaolin, sand, RT, and RP can be seen in Table 2.

Table 2. Characterization of the materials.

Material	Specific gravity (g/cm ³)	Unit Mass (g/cm ³)	Absorption (%)	Specific Surface (cm ² /g)	d50 (µm)	dmax (µm)
Cement	3.10	-	-	6.35	15.44	-
Metakaolin	2.56	-	-	-	12.40	113.20
Sand	2.57	1.45	0.37	-	983.09	-
RT	2.67	-	-	-	150.84	-
RP	2.55	-	-	-	272.45	-

Figure 3 shows the granulometric curves of the materials (cement, metakaolin, flooring (ceramic), brick, and sand) used in the mix design.

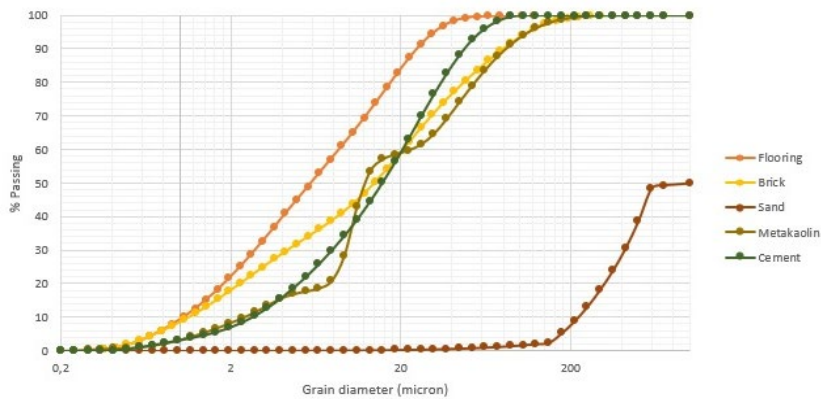


Figure 3. Granulometric curve of the materials used in the mix design.

After inserting the granulometric curves and specific gravities, the mean granulometry D50 of the materials is obtained using the EMMA®, as shown in Table 2. The EMMA® software calculates and displays the particle size distribution of a concrete mix.

Some simulations within EMMA® were carried out for the concrete mix, varying the percentages of the materials. The software generates two curves: the mix composition (blue) and the ideal one (red). It is understood that the more coincident the curves are, the greater the level of packaging of the particles and, therefore, the greater the compactness and the lower the porosity of the mixture. The base mix design (TB) curves, Figure 4 (a), and the percentages of 5%, 15%, and 25% replacement of cement by ground brick in Figure 4 (b), (c) and (d) were presented, respectively. These curves demonstrate the best packaging of the particles for the dry components, according to the granulometry, proportion and density of the materials

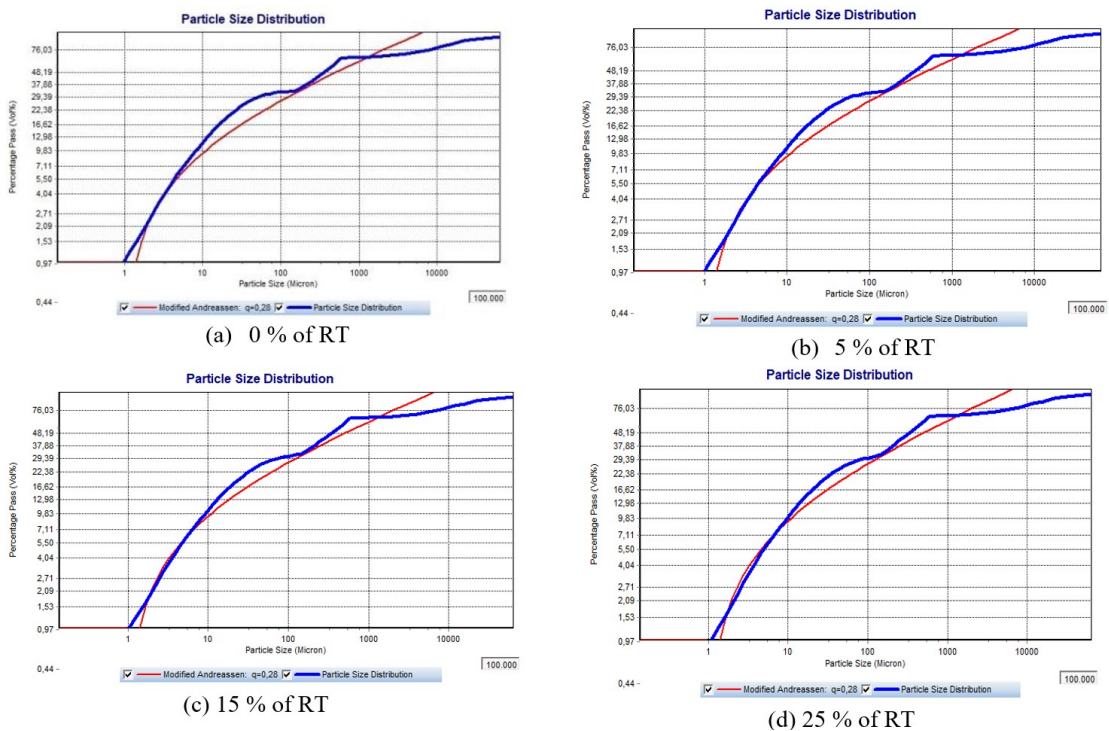


Figure 4. Packing curves of the particles obtained by the EMMA® software.

As with ground brick, percentage replacements of cement for ceramic waste of 5% to 30% were used, and also, after the analysis, replacements of 5%, 15%, and 25% were chosen, as seen in Figure 5 (a), (b), and (c).

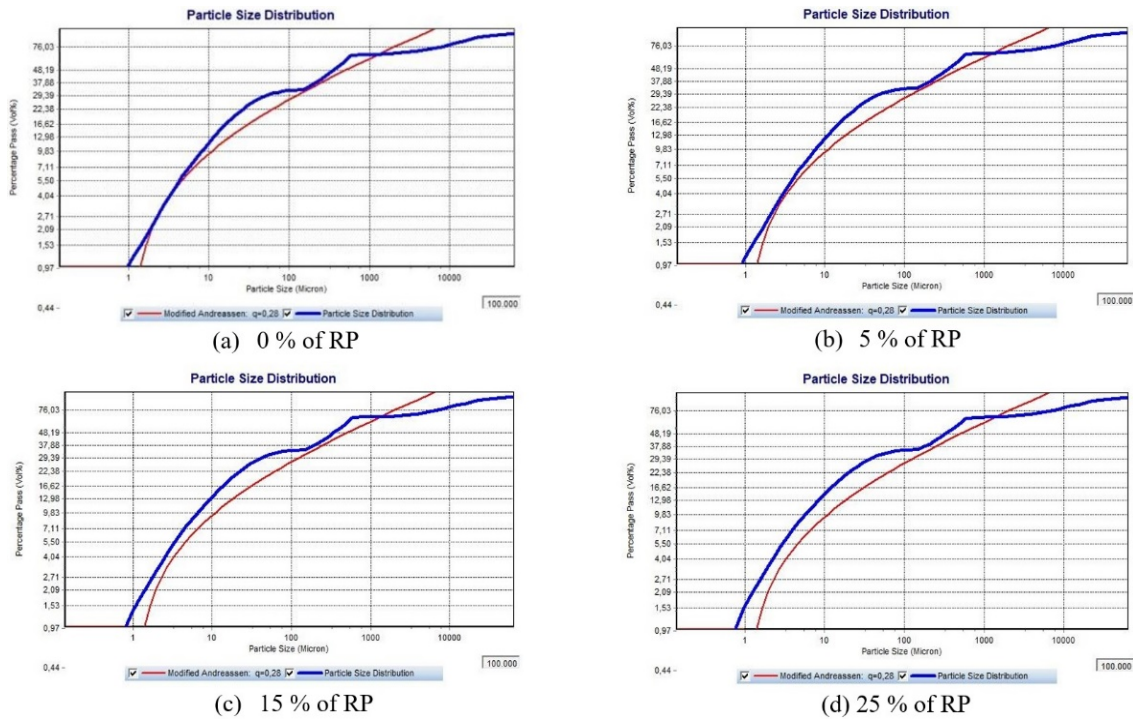


Figure 5. Packing curves of the particles obtained by the EMMA® software.

The percentage replacements of cement for the waste of 5% to 30% were studied, and the best replacements were of 5%, 15%, 25% of cement for both waste. Looking at Figures 4 and 5, it is possible to observe that, although there is an approximation with the optimal curve (Modified Andriessen) in the range of 10 to 100 μm, there is a gap in the ranges of 100 to 325 μm and 1 to 10 μm. In the graphs of Figure 4 - RT (Brick Waste) is observed for particles size from 10 to 100 μm, the passing percentage is very close to the red curve in the average of 2.7% and 1.05% respectively for any percentage studied. Making the same analysis for Figure 5 - RP (Ceramic Waste) the difference is in the order of 5.7% and 8.22% respectively. It is also observed that the shapes of the curves are similar for both materials and the different proportions. This similarity may indicate that the percentages used were small to be observed by this method. EMMA® was also used to obtain the base trace, thus decreasing the number of experimental tests to find the optimal trace. The same analysis was carried out for the base trace for the particles size from 10 to 100 μm, the percentage and the difference of passing percentage between the red and blue curves were 2.7% and 5.67% respectively.

4.1 Dosing and Mixing

The base mix design and mix designs with the addition of brick (RT) and ceramic (RP) are shown in Table 3.

Table 3. Mix designs in % of SCC with the addition of RT and RP.

Mix design (%)	Cement	Metakaolin	RT	RP	Sand	SP	w/c
0	1	5	0	0	2	0.80	0.40
5	1	5	5	5	2	0.80	0.40
15	1	5	15	15	2	0.80	0.40
25	1	5	25	25	2	0.80	0.40

The mix design, Table 4, and the percentages of 0%, 5%, 15%, and 25% replacement of cement by RT e RP were presented, respectively. After preparing the SCM, tests were carried out in the fresh test to measure the fluidity and viscosity and compare them with the characteristic range of a self-compacting mortar. The results can be seen in Table 4.

Table 4. Results of fresh experiments with the addition of ground brick (RT) and ceramic waste (RP).

Mix designs fi(%)	Mini-slump (mm)		V-funnel (s)	
	SCM range		SCM range	
	200 – 280 mm		5 – 10 s	
	RT	RP	RT	RP
0	275	275	7.72	7.72
5	255	270	7.7	5.65
15	275	280	5.63	5
25	280	280	5.52	5.16

It is concluded that all mortars are SCM since they are within the limits established by Gomes and Barros [11], both concerning the mean diameter and the flow time. There is also a decreasing result in the v-funnel test, characterizing an increase in the capacity to fill shapes and containers. It is also possible to notice an increasing result in the mini-slump test, which characterizes an increase in fluidity. The results of v-funnel and mini-slump test for RT and RP substitutions did not change significantly between themselves. The percentages of 15% and 25% were more fluid than those of 0% and 5%, that is, the more RT and RP material the more fluid is the mortar.

Figure 6 shows the result of the mini-slump test, and it is not possible to observe the phenomenon of exudation, defined as a phenomenon that results in the appearance of water on the concrete surface after it is released and densified and before the setting occurs. This phenomenon can occur due to several factors, such as for example, the increase in the water/cement ratio or the presence of pozzolanic material.



Figure 6. Mini Slump experiment.

Table 5 presents the results of the tests of compressive strength and flexural tensile strength using the two types of waste (RP and RT).

Table 5. Mean of the test results of mechanical compressive strength and flexural strength in MPa.

Mix design (%)	Compressive Strength (MPa)		Flexural Strength (MPa)	
	RT	RP	RT	RP
0	44.95	44.95	8.74	8.74
5	40.68	30.5	7.58	7.16
15	37.35	27.74	8.12	7.13
25	43.8	40.47	8.66	7.15

It is observed in the results of both tests in the hardened state that the 25% replacement of cement by ground brick does not bring significant changes in the strength values of the mortars. Concerning the base mix design, a decrease of 2.56% in the compressive strength and 0.91% in the flexural tensile is noted.

The strength results in all tested ceramic waste replacements caused lower compressive and tensile values than the base mix design. The greatest decrease in compressive strength is a mix design with 5% replacement, 38.29% in relation to the base. Comparing the flexural tensile strengths, there is the greatest decrease in the mix design with 15% replacement, with an 18.42% change. Like this work [3], a reduction in strength was also found with the partial replacement of cement by brick waste with a mean particle size of 24.08 μm smaller than that used in this work. The d_{50} or average diameter of RT and RP are 150.84 μm and 272.45 μm , respectively, the Figure 4 and 5 showed that mixtures containing RT had better results, in other words, the mixture curve (blue) approaches the optimal curve generated by EMMA®.

Regarding the results of compressive strength for initial high-strength cement, the standard [37] provides for a minimum limit of 34 MPa. In this case, the 5% and 15% with RP replaced mix designs do not have satisfactory strength results, with means of 30.50 MPa and 27.74 MPa, respectively, both below the standard. All percentages containing RT are satisfactory for the results of compressive strength.

This difference in compressive strength and flexural strength observed in both the brick and ceramic waste has also been observed in other publications. Other researchers have studied the percentage replacement of Portland CII cement by ground ceramic block waste, in 10%, 20%, 30%, 40%, and 50%, and concluded that there is a decrease in the compressive strength with the increase in the waste. However, it was realized that this difference between the strengths decreases after the age of 56 days; that is, more days of curing favor the increase of strength [38]. However, despite this decrease in difference in relation to the base in older ages, in the study of [38], there was no mix design that exceeded the values obtained by the base mix design; and the 50% replacement, regardless of age, only resulted in decreased strength.

5 CONCLUSION

The objective of this study was to prove the viability of the replacement of cement in SCM by ceramic waste and brick waste. For this research, the self-compacting concrete dosing method (SCC) was carried out, which is known to be sound based on the lowest void ratio as an ideal packaging proposal. For this, it used the EMMA® software (Elkem Materials Mix Analyzer), which calculates and presents the best granulometric distribution of a concrete mixture. And so, some simulations using EMMA® were performed in order to obtain a material with better physical and mechanical performance. Incorporations of RT and RP were performed to replace cement of 0, 5, 15 and 25% by weight. In the fresh state, all incorporated mix designs of construction waste have self-compacting characteristics. The increase in the percentages of the brick waste causes an increase in fluidity and slightly increasing the results of the mini-slump test up to the limit value of 280mm to 25% RT. The increase in the ceramic waste causes an increase in the filling capacity, decreasing the results of the v-funnel. The results found in the hardened state for ceramic waste mix designs with 5% and 15% replacement, do not have a satisfactory result of compressive strength provided by the standard [37]. The incorporation of the two waste, mainly in the 25% cement replacement, does not bring significant losses to the mechanical strength and can contribute to lesser manufacture of cement and an efficient destination of the construction waste. It is concluded that the waste used brick and ceramic waste can be added in replacement to the cement in SCM without loss of properties in the fresh and hardened state.

It is suggested the leaching test to analyze the transfer capacity of organic and inorganic substances present in the waste. This is a method used to diagnose how much of this material will be transferred to the natural environment.

ACKNOWLEDGEMENTS

The authors would like to thank ADITIBRÁS for supplying the superplasticizer admixture.

REFERENCES

- [1] H. Okamura and M. Ouchi, "Self-compacting concrete," *J. Adv. Concr. Technol.*, vol. 1, no. 1, pp. 5–15, 2003.
- [2] A. López, J. M. Tobes, G. Giaccio, and R. Zerbino, "Advantages of mortar-based design for coloured self-compacting concrete," *Cement Concr. Compos.*, vol. 31, no. 10, pp. 754–761, 2009, <http://dx.doi.org/10.1016/j.cemconcomp.2009.07.005>.
- [3] Y. F. Silva, D. A. Lange, and S. Delvasto, "Effect of incorporation of masonry residue on the properties of self-compacting concretes," *Constr. Build. Mater.*, vol. 196, pp. 277–283, 2019, <http://dx.doi.org/10.1016/j.conbuildmat.2018.11.132>.

- [4] A. Nagalli, *Gerenciamento de Resíduos Sólidos na Construção Civil*, no. 11. São Paulo: Oficina de Textos, 2014.
- [5] M. Bravo, J. Brito, J. Pontes, and L. Evangelista, "Durability performance of concrete with recycled aggregates from construction and demolition waste plants," *Constr. Build. Mater.*, vol. 77, pp. 357–369, Feb 2015, <http://dx.doi.org/10.1016/j.conbuildmat.2014.12.103>.
- [6] M. Bravo, J. Brito, L. Evangelista, and J. Pacheco, "Durability and shrinkage of concrete with CDW as recycled aggregates: benefits from superplasticizer's incorporation and influence of CDW composition," *Constr. Build. Mater.*, vol. 168, pp. 818–830, 2018, <http://dx.doi.org/10.1016/j.conbuildmat.2018.02.176>.
- [7] L. Butler, J. S. West, and S. L. Tighe, "Effect of recycled concrete coarse aggregate from multiple sources on the hardened properties of concrete with equivalent compressive strength," *Constr. Build. Mater.*, vol. 47, pp. 1292–1301, 2013, <http://dx.doi.org/10.1016/j.conbuildmat.2013.05.074>.
- [8] H. J. Chen, T. Yen, and K. H. Chen, "Use of building rubbles as recycled aggregates," *Cement Concr. Res.*, vol. 33, no. 1, pp. 125–132, 2003, [http://dx.doi.org/10.1016/S0008-8846\(02\)00938-9](http://dx.doi.org/10.1016/S0008-8846(02)00938-9).
- [9] E. Dapena, P. Alaejos, A. Lobet, and D. Pérez, "Effect of recycled sand content on characteristics of mortars and concretes," *J. Mater. Civ. Eng.*, vol. 23, no. 4, pp. 414–422, 2011, [http://dx.doi.org/10.1061/\(ASCE\)MT.1943-5533.0000183](http://dx.doi.org/10.1061/(ASCE)MT.1943-5533.0000183).
- [10] L. Zhu and Z. Zhu, "Reuse of clay brick waste in mortar and concrete," *Adv. Mater. Sci. Eng.*, vol. 2020, pp. 1–11, 2020, <http://dx.doi.org/10.1155/2020/6326178>.
- [11] P. C. Gomes and A. Barros, *Métodos de Dosagem de Concreto Autoadensável*. São Paulo: PINI, 2009.
- [12] S. Nunes, H. Figueiras, P. Milheiro Oliveira, J. S. Coutinho, and J. Figueiras, "A methodology to assess robustness of SCC mixtures," *Cement Concr. Res.*, vol. 36, no. 12, pp. 2115–2122, Dec 2006, <http://dx.doi.org/10.1016/j.cemconres.2006.10.003>.
- [13] S. Venkateswara Rao, M. V. Seshagiri Rao, D. Ramaseshu, and P. Rathish Kumar, "Durability performance of self-compacting concrete," *Mag. Concr. Res.*, vol. 64, no. 11, pp. 1005–1013, Nov 2012, <http://dx.doi.org/10.1680/mac.11.00165>.
- [14] G. Sua-Iam and N. Makul, "Utilization of limestone powder to improve the properties of self-compacting concrete incorporating high volumes of untreated rice husk ash as fine aggregate," *Constr. Build. Mater.*, vol. 38, pp. 455–464, 2013, <http://dx.doi.org/10.1016/j.conbuildmat.2012.08.016>.
- [15] W. H. Yung, L. C. Yung, and L. H. Hua, "A study of the durability properties of waste tire rubber applied to self-compacting concrete," *Constr. Build. Mater.*, vol. 41, pp. 665–672, 2013, <http://dx.doi.org/10.1016/j.conbuildmat.2012.11.019>.
- [16] N. Li et al., "Properties of self-compacting concrete (SCC) with recycled tire rubber aggregate: a comprehensive study," *J. Clean. Prod.*, vol. 236, 117707, 2019, <http://dx.doi.org/10.1016/j.jclepro.2019.117707>.
- [17] D. M. Sadek, M. M. El-Attar, and H. A. Ali, "Reusing of marble and granite powders in self-compacting concrete for sustainable development," *J. Clean. Prod.*, vol. 121, pp. 19–32, 2016, <http://dx.doi.org/10.1016/j.jclepro.2016.02.044>.
- [18] A. Boukhelkhal, L. Azzouz, B. Benabed, and A. Belaidi, "Strength and durability of low-impact environmental self-compacting concrete incorporating waste marble powder," *Build. Mater. Struct.*, vol. 4, pp. 31–41, 2018, <http://dx.doi.org/10.5281/zenodo.1134146>.
- [19] L. R. R. Silva et al., "Polymeric waste from recycling refrigerators as an aggregate for self-compacting concrete," *Sustain.*, vol. 12, no. 20, pp. 8731, 2020, <http://dx.doi.org/10.3390/su12208731>.
- [20] M. Omrane, S. Kenai, E. H. Kadri, and A. Ait-Mokhtar, "Performance and durability of self compacting concrete using recycled concrete aggregates and natural pozzolan," *J. Clean. Prod.*, vol. 165, pp. 415–430, 2017., <http://dx.doi.org/10.1016/j.jclepro.2017.07.139>.
- [21] V. L. Jerônimo, G. R. Meira, and L. C. P. da Silva Fo., "Performance of self-compacting concretes with wastes from heavy ceramic industry against corrosion by chlorides," *Constr. Build. Mater.*, vol. 169, pp. 900–910, 2018, <http://dx.doi.org/10.1016/j.conbuildmat.2018.03.034>.
- [22] M. Şahmaran, H. A. Christianto, and I. Ö. Yaman, "The effect of chemical admixtures and mineral additives on the properties of self-compacting mortars," *Cement Concr. Compos.*, vol. 28, no. 5, pp. 432–440, 2006, <http://dx.doi.org/10.1016/j.cemconcomp.2005.12.003>.
- [23] M. Karataş, A. Benli, and A. Ergin, "Influence of ground pumice powder on the mechanical properties and durability of self-compacting mortars," *Constr. Build. Mater.*, vol. 150, pp. 467–479, 2017, <http://dx.doi.org/10.1016/j.conbuildmat.2017.05.220>.
- [24] A. O. Smirnov, L. M. Dobshits, and S. N. Anisimov, "Effect of superplasticizer and silica fume on the properties of self-compacting mortars," *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 896, no. 1, 2020, <http://dx.doi.org/10.1088/1757-899X/896/1/012095>.
- [25] A. Lozano-Lunar, I. Dubchenko, S. Bashynskiy, A. Rodero, J. M. Fernández, and J. R. Jiménez, "Performance of self-compacting mortars with granite sludge as aggregate," *Constr. Build. Mater.*, vol. 251, pp. 118998, 2020, <http://dx.doi.org/10.1016/j.conbuildmat.2020.118998>.
- [26] A. A. Atiyah, S. A. Salih, and A. S. Kadhim, "Properties of self-compacting mortar containing nano blast furnace slag," *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 737, no. 1, 2020, <http://dx.doi.org/10.1088/1757-899X/737/1/012054>.

- [27] P. R. Matos, R. Pilar, L. H. Bromerchenkel, R. A. Schankoski, P. J. P. Gleize, and J. Brito, "Self-compacting mortars produced with fine fraction of calcined waste foundry sand (WFS) as alternative filler: fresh-state, hydration and hardened-state properties," *J. Clean. Prod.*, vol. 252, pp. 119871, 2020, <http://dx.doi.org/10.1016/j.jclepro.2019.119871>.
- [28] M. Si-Ahmed and S. Kenai, "Behavior of self-compacting mortars based on waste brick powder," *Curr. Mater. Sci.*, vol. 13, no. 1, pp. 39–44, 2020, <http://dx.doi.org/10.2174/2666145413666200219091459>.
- [29] S. Formagini, "Dosagem científica e caracterização mecânica de concretos de altíssimo desempenho," Ph.D. dissertation, COPPE, Univ. Fed. Rio de Janeiro, Rio de Janeiro, 2005.
- [30] A. L. Castro and V. C. Pandolfelli, "Revisão: conceitos de dispersão e empacotamento de partículas para a produção de concretos especiais aplicados na construção civil," *Ceramica*, vol. 55, no. 333, pp. 18–32, 2009, <http://dx.doi.org/10.1590/S0366-69132009000100003>.
- [31] A. L. Castro, J. B. L. Liborio, and V. C. Pandolfeg, "Review article: rheology of high performance concretes applied in building site," *Ceramica*, vol. 57, no. 341, pp. 63–75, 2011, <http://dx.doi.org/10.1590/s0366-69132011000100009>.
- [32] H. Peng and B. Myhre, "No-cement refractory shotcrete and gunning mixes," *TechTrends*, vol. 9, pp. 1–5, 2017.
- [33] E. A. Medina, "Pozolanicidade do metacaulim em sistemas binários com cimento Portland e hidróxido de cálcio," M.S. thesis, Esc. Politéc., Univ. São Paulo, São Paulo, 2011.
- [34] A. Tuam, S. Shitote, and W. Oyawa, "Experimental study of self-compacting mortar incorporating recycled glass aggregate," *Buildings*, vol. 8, no. 2, pp. 15, Jan 2018, <http://dx.doi.org/10.3390/buildings8020015>.
- [35] Associação Brasileira de Normas Técnicas, *Cimento Portland - Determinação da Resistência à Compressão*, NBR 7215, 1996, pp. 8.
- [36] Associação Brasileira de Normas Técnicas, *Argamassa para Assentamento e Revestimento - Determinação da Resistência à Tração na Flexão e Compressão*, NBR 13279, 2005, pp. 3–4.
- [37] Associação Brasileira de Normas Técnicas, *Cimento Portland – Requisitos*, NBR 16697, 2018, pp. 1–7.
- [38] F. Carvalho et al., "Influência da substituição de cimento Portland por resíduo moído de blocos cerâmicos na resistência mecânica do concreto auto-adensável," in *An. 53 Congr. Bras. Concr.*, vol. 1, pp. 1–10, 2011, <http://dx.doi.org/10.13140/RG.2.1.2114.6724>.

Author contributions: FRSV: conceptualization, methodological design, data collection and treatment, analysis/ interpretation; PCG: analysis/ interpretation, literature survey, critical review, others; MGAR: literature survey, critical review, others; MLNMM: literature survey, critical review, others; VCS: conceptualization, methodological design, supervision, analysis / interpretation, writing, critical review.

Editors: Fernando Pelisser, Guilherme Aris Parsekian.