Optimizing self-compacting mortars with fillers from sustainable industrial by-products: evaluation of durability parameters

Otimização de argamassas autoadensáveis com fillers de subprodutos industriais sustentáveis: avaliação de parâmetros de durabilidade

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ABSTRACT
This study investigates the transformative potential of repurposing non-biodegradable industrial by-products, specifically glass, brick, and sanitary ceramic waste, as alternative fillers for self-compacting mortars (SCM). Positioned within the framework of sustainability and enhanced performance, we conduct an in-depth comparative analysis against traditional limestone fillers to ascertain the efficacy of these unconventional materials. Employing a comprehensive methodology, we conduct spreading tests, evaluate heat of hydration, and assess mechanical resistance. Additionally, we delve into key durability parameters, including water-accessible porosity and capillarity, to comprehensively understand the nuanced effects of diverse fillers on the characteristics of the resulting self-compacting mortars. The experimental timeline unfolds through a series of assessments, measuring compressive and tensile strengths at strategic intervals - 2, 7, 28, 90, 270, and 365 days post-application. After 270 days of maturation, our study rigorously examines durability parameters. The findings unequivocally reveal a significant enhancement in SCM performance when incorporating glass, brick, and sanitary ceramic waste as fillers, outperforming conventional limestone fillers. Of notable significance is the consistent superiority of ceramic fillers across a spectrum of metrics. This research significantly contributes to the understanding of sustainable repurposing of industrial by-products in construction. Moreover, it highlights the pivotal role played by ceramic fillers in elevating rheological, mechanical, and durability attributes of self-compacting mortars. Beyond its immediate implications, this study opens new avenues for environmentally responsible and economically viable construction materials, promising further advancements and innovation in the field.
Keywords: industrial by-products, brick, ceramic, glass, self-compacting mortars, fillers, heat of hydration, mechanical resistance, durability parameter.

RESUMO
Este estudo investiga o potencial transformador da reutilização de subprodutos industriais não biodegradáveis, especificamente resíduos de vidro, tijolo e cerâmica sanitária, como materiais de enchimento alternativos para argamassas autonivelantes (SCM). Posicionado dentro do contexto da sustentabilidade e desempenho aprimorado, realizamos uma análise comparativa aprofundada em relação aos tradicionais enchimentos de calcário para determinar a eficácia desses materiais não convencionais. Empregando uma metodologia abrangente, realizamos testes de espalhamento, avaliamos o calor de hidratação e a resistência mecânica. Além disso, investigamos os principais parâmetros de durabilidade, incluindo porosidade acessível à água e capilaridade, para compreender de forma abrangente os efeitos sutis de diferentes materiais de enchimento nas características das argamassas autonivelantes resultantes. O cronograma experimental se desenrola por meio de uma série de avaliações, medindo resistências à compressão e tração em intervalos estratégicos 2, 7, 28, 90, 270 e 365 dias após a aplicação. Após 270 dias de maturação, nosso estudo examina rigorosamente os parâmetros de durabilidade. Os resultados revelam inequivocamente uma melhoria significativa no desempenho das SCM ao incorporar resíduos de vidro, tijolo e cerâmica sanitária como enchimentos, superando os enchimentos de calcário convencionais. De significativa importância é a superioridade consistente dos enchimentos cerâmicos em uma variedade de métricas. Esta pesquisa contribui significativamente para a compreensão da reutilização sustentável de subprodutos industriais na construção. Além disso, destaca o papel fundamental desempenhado pelos enchimentos cerâmicos em elevar os atributos reológicos, mecânicos e de durabilidade das argamassas autonivelantes. Além de suas implicações imediatas, este estudo abre novos caminhos para materiais de construção ambientalmente responsáveis e economicamente viáveis, prometendo avanços e inovações adicionais no campo.

Palavras-chave: produtos industriais, tijolo, cerâmica, vidro, argamassas autonivelantes, materiais de enchimento, calor de hidratação, resistência mecânica, parâmetros de durabilidade.

1 INTRODUCTION
The Self-compacting concrete (SCC) is considered as one of the greatest technological advancements in the field of building materials [1]. In general, self-compacting concrete (SCC) is defined as a very fluid, homogeneous and stable concrete. It can flow and consolidate under its own weight, without vibration. The SCC can easily pass through gaps and between rebars, and can completely fill the formwork because it has sufficient viscosity to be handled without segregation,
blockage or bleeding [2]. SCCs are prepared with a low content of small gravel, while incorporating appropriate amounts of superplasticizers.

In order to formulate a good quality SCC, it is necessary to use a high volume of binder, with a high dosage of chemical adjuvants and a low amount of water. It is widely acknowledged that the SCC requires a large amount of powder (fillers and cement) for the preparation of about 450 to 600 kg/m³ of concrete. The resulting mixture ought to be homogeneous and cohesive [3]. In order to meet rheological requirements, it was deemed necessary to utilize fillers for the purpose of improving the workability as well as to regulate cement content and reduce the heat of hydration and prevent the cracking of concrete. It is widely admitted that limestone fillers are commonly used because they have the ability to increase the density of the granular skeleton, maintain cohesion, and enhance the resistance to segregation [4]. However, the sources of limestone fillers are limited in some areas and their transportation is quite expensive. Also, these fillers do not have pozzolanic properties that reduce the durability of concrete. An alternative solution to solve this problem is to use natural pozzolans and minerals and/or natural additives, such as natural pozzolan [5], dolomite [1], fly ash [6], pumice [7], perlite [8], zeolite [9], furnace slag [10], silica fume [11, 12], metakaolin [13, 14] [15] cane ash sugar [16, 17], and rice ash [18]. It is also important to emphasize that some industrial by-products, such as glass powder, brick powder, and ceramic powder, are currently arousing keen interest from a large number of researchers.

It is widely acknowledged that glass is made from three materials, namely silica (73%), sodium hydroxide (13%), and lime (10%) [19]. Due to its pozzolanic activity, glass can be extensively used in the composition of mortars and concretes [13]. In this context, Sandra [20] proposed a procedure for the formulation of self-compacting mortar incorporating glass powder. For this, they used a numerical model to select the best mortar mixture that exhibits maximum durability and good compactability. This mortar was obtained at minimum cost. In this regard, [21] found out that adding glass powder to SCC at 5, 10, and 15% reduced the spreading by 1.3%, 2.5%, and 5.36%, the compressive strength by 6, 15, and 20%, and the flexural strength by 2, 3, and 6.75%, respectively. Likewise, [22, 23] added glass powder at 0.3%, 0.6%, 0.9%, and 1.2% by weight of the reference SCC. They found out that adding 0.6% of glass powder can result in a 50% gain in
Ceramic and brick wastes can be collected on the production sites because 15 to 30% of the products manufactured, because not meeting the required standards, are ultimately rejected. These wastes can also be found on construction or demolition sites[24]. It is widely acknowledged that the main chemical components of ceramic powder are silica (\(\text{SiO}_2\)) and alumina (\(\text{Al}_2\text{O}_3\)). It was revealed that the massive presence of \(\text{SiO}_2\) and \(\text{Al}_2\text{O}_3\) is responsible for the pozzolanic reactivity of the ceramic powder. [25] used brick powder to replace cement and fly ash in the formulation of self-compacting concretes. They then studied the effect of brick powder on the rheological properties of SCC in the hardened state. They then noticed that the compressive strength of the formulated SCC is similar or superior to that of the control SCC. Regarding, [26], they studied the effect of brick powder on the compressive strength and viscosity properties of self-compacting mortars. They then found out that the brick powder had no effect on the workability of the mortars, but it increased their viscosity. In addition, the brick powder increased the compressive and tensile strength of the prepared SCC by 5% and 10%, for early ages. On the other hand, [27] formulated SCC by replacing cement with 0%, 5%, 10%, 15% and 20% of ceramic powder. They found out that when the rate of ceramic powder in the mixture increased, the rheology of the resulting concrete improved, while the compressive strength gradually decreased. Moreover, it was observed that the adhesion strength and density values of the specimens diminished. With regard to [28], they studied the feasibility of using bone-china ceramic powder waste (BCPW) and granite waste (GW), as fine aggregates, to replace cement in the production of self-compacting concrete (SCC). In this regard, the BCPW was added at 0%, 10%, 20% and 30%, and GW at 0%, 20%, 30% and 40%, for the preparation of the different concrete mixes. The SCC prepared using the combination of 10% BCPW and 30% GW showed maximum compressive strength.

It is worth emphasizing that the above-mentioned studies used several by-products as a substitution for cement in the formulation of concrete, but few researchers used them as fillers. In this context, it is worth mentioning that [29] investigated the possibility of replacing limestone fillers with waste brick powder (WBP) in a self-compacting mortar mixture. They came to the conclusion that when
the rate of replacement of limestone fillers by WBP increases, the SCC compressive strength decreases slightly after 7 days. However, this downward trend seems to be compensated by the pozzolanic activity of WBP and becomes stable after 28 days. It was indeed found that after 28 days, the compressive strength of mortars including WBP was equivalent to that of the reference mortar. It was also observed that the effect of the pozzolanic activity should be enhanced after 90 days.

It should be noted that, in laboratory research, the initial study on self-compacting mortars (SCMs) is essentially done for the purpose of saving time and money because the materials used in the different tests are relatively high [30]. It is worth reminding that the present study was carried out directly on self-compacting mortars. These mortars are commonly utilized as repair materials [31].

This work aims primarily to evaluate the possibility of replacing limestone fillers with glass, brick and ceramic fillers when formulating self-compacting mortars. The rheological properties, heat of hydration, mechanical properties (compressive and flexural strengths), and durability parameters (porosity accessible to water, capillarity) of self-compacting mortars were investigated as well.

2 MATERIALS AND METHODS
2.1 USED MATERIALS

Portland cement CEM I 52.5 R was used in this study. This type of cement complies with the Algerian standard NA 442 which is essentially based on the European standard EN 197-1.

The fillers studied in this work come from various recovered wastes. It is worth mentioning that, for example, the glass fillers (Gl) were obtained from green bottles that were collected from wild waste disposal centers, while the brick (Br) filler and ceramic (Cr) filler were brought from a brick factory and a sanitary ceramic factory, respectively. In addition, the limestone fillers (LS), which are the most common and most used filling agents for making SCMs and SCCs [32], were used as a control filler.

The collected brick and ceramic waste was first cleaned and next crushed using a hammer crusher. Then, they were baked for 24 hours, at temperature of
105°C. Afterwards, they were ground, using a ball mill, until the resulting powder could pass through a sieve with mesh size of 200 μm.

It should be noted that the grinding time was adjusted in order to obtain a fineness value close to that of LS fillers.

Figure 1 illustrates the different waste types, in their raw state, before shredding, and the fillers obtained after shredding.

It is worth noting that the brick fillers (Br) required a longer grinding time, while for the glass fillers (Gl), due to a lack of grinding equipment, were ground until achieving maximum fineness.

The chemical compositions and physico-chemical characteristics of the fillers and cement are summarized in Tables 1 and 2, respectively. The SEM and EDS analysis results are presented in Figure 3.

Figure 1: Different types of waste before and after shredding
Table 1: Chemical composition of fillers and cement

<table>
<thead>
<tr>
<th>(%)</th>
<th>LS</th>
<th>Gl</th>
<th>Br</th>
<th>Cr</th>
<th>CEMI</th>
</tr>
</thead>
<tbody>
<tr>
<td>CaCO₃</td>
<td>94.50</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>CaO</td>
<td>-</td>
<td>7.37</td>
<td>9.18</td>
<td>9.60</td>
<td>63.25</td>
</tr>
<tr>
<td>SiO₂</td>
<td>2.94</td>
<td>74.5</td>
<td>49.25</td>
<td>54.33</td>
<td>25.35</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>1.46</td>
<td>5.5</td>
<td>29.42</td>
<td>27.66</td>
<td>5.78</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>0.023</td>
<td>0.4</td>
<td>2.47</td>
<td>1.20</td>
<td>0.3</td>
</tr>
<tr>
<td>MgO</td>
<td>0.15</td>
<td>0.55</td>
<td>2.26</td>
<td>0.37</td>
<td>1.76</td>
</tr>
<tr>
<td>Na₂O</td>
<td>0.3</td>
<td>11.02</td>
<td>0.75</td>
<td>1.64</td>
<td>0.05</td>
</tr>
<tr>
<td>TiO₂</td>
<td>0.023</td>
<td>0.09</td>
<td>0.59</td>
<td>0.37</td>
<td>0.124</td>
</tr>
<tr>
<td>P₂O₅</td>
<td>0.026</td>
<td>0.04</td>
<td>0.17</td>
<td>0.12</td>
<td>0.078</td>
</tr>
<tr>
<td>Cl</td>
<td>0.05</td>
<td>0.003</td>
<td>0.011</td>
<td>0.005</td>
<td>0.03</td>
</tr>
<tr>
<td>K₂O</td>
<td>0.08</td>
<td>0.45</td>
<td>1.66</td>
<td>0.87</td>
<td>0.45</td>
</tr>
<tr>
<td>Mn₂O₃</td>
<td>13ppm</td>
<td>39ppm</td>
<td>0.01</td>
<td>0.02</td>
<td>38ppm</td>
</tr>
<tr>
<td>Cr₂O₅</td>
<td>10ppm</td>
<td>19ppm</td>
<td>0.04</td>
<td>0.01</td>
<td>5ppm</td>
</tr>
<tr>
<td>SO₃</td>
<td>-</td>
<td>0.04</td>
<td>0.11</td>
<td>0.04</td>
<td>2.83</td>
</tr>
<tr>
<td>L.O.I</td>
<td>43.2</td>
<td>1.28</td>
<td>2.48</td>
<td>1.46</td>
<td>2.97</td>
</tr>
<tr>
<td>(SiO₂+Al₂O₃+Fe₂O₃)</td>
<td>-</td>
<td>80</td>
<td>81.14</td>
<td>83.4</td>
<td>-</td>
</tr>
</tbody>
</table>

Source: Authors

Figure 2: SEM and EDS analysis results of fillers

![SEM and EDS analysis results of fillers](image)
Two types of sand were used in this study: a fine and siliceous sand and coarse and calcareous sand. The mixture consists of 60% of fine sand and 40% of coarse sand in order to guarantee the high fluidity and good spreading of the self-compacting mortars under study. The physical characteristics of the sands used in the mixtures are: Mf = 2.2; Apparent MV = 1305 (kg/m3); Absolute MV = 2500 (kg/m3); ES = 88.

A poly-carboxylate-based third-generation high water-reducing
superplasticizer, complying with the requirements of standard NF EN 934-2, was used in this work.

It was employed with a saturation dose of around 5% of the mass of cement in order to reduce the quantity of mixing water as much as possible and obtain better long-term mechanical results.

Distilled water was used as the mixing water in all mortars.

2.2 FORMULATION METHOD

Different fines, i.e. limestone, glass, brick and ceramic fines, were used in each preparation. The amount of water used for each type of filler was adjusted in a way to obtain a homogeneous spread, between 26 and 28 cm in thickness. The different formulations are summarized in Table 3.

<table>
<thead>
<tr>
<th></th>
<th>SCM LS</th>
<th>SCM Gl</th>
<th>SCM Br</th>
<th>SCM Cr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement</td>
<td>450</td>
<td>450</td>
<td>450</td>
<td>450</td>
</tr>
<tr>
<td>Filler</td>
<td>150</td>
<td>150</td>
<td>150</td>
<td>150</td>
</tr>
<tr>
<td>Sand</td>
<td>1200</td>
<td>1200</td>
<td>1200</td>
<td>1200</td>
</tr>
<tr>
<td>SP %C</td>
<td>5%</td>
<td>5%</td>
<td>5%</td>
<td>5%</td>
</tr>
<tr>
<td>W/C</td>
<td>40%</td>
<td>37.5%</td>
<td>35%</td>
<td>35%</td>
</tr>
</tbody>
</table>

Source: Authors.

2.3 METHODOLOGY

2.3.1 Fresh State

The fresh state was attained according to the Efnarc standard (2002) [33]. After the completion of each preparation, the spread of mortar was measured using the mini-cone, and the flow time was evaluated using the V-funnel. In addition, in order to obtain constant spreads (250 ± 10 mm) for the SCMs containing different fillers, it was decided to vary the (W/C) ratio in the mortar mixtures and to fix the amount of SP used at saturation.

2.3.2 Heat of Hydration

The heat of hydration of the mortars was evaluated in accordance with standard NF EN 196-9. The evolution of heat was followed using a semi-adiabatic Langavant colorimeter system.

In order to carry out this experiment, a quantity of 1500 g of mortar was placed in cells which were then covered with a thin layer of oil. The tests were
carried out over a period of 72 hours, with intervals of 10 minutes.

3.2.3 Mechanical Strength

In order to carry out the mechanical characterization of the prepared mortars (tensile strength and compressive strength), test specimens of dimensions (4x4x16) cm$^3$ were made, according to standard NF EN 196-1. The mechanical strength was measured at 2, 7, 28, 90 and 270 and 365 days of maturation. Afterwards, they were stored in water saturated with lime at a temperature of 20°C.

3.2.4 Porosity Accessible to Water

The porosity accessible to water was measured in accordance with to the recommendations of the standard ASTMC 642. This method adopted here consists in determining the total volume of pores accessible to water using different weightings. Sample specimens of dimensions (40x40x40) mm$^3$ were used. They were first dried at 105°C until mass stabilization. Then, after cooling, they were immersed in water for at least 48 hours. This operation was stopped only when the difference between two successive mass measurements of the sample, 24 hours apart, did not exceed 0.5%. Afterwards, the samples were soaked in boiling water in a suitable container for 5 hours for the purpose of determining the mass of the sample in the saturated state. They were then removed from water and allowed to cool for at least 14 hours. The hydrostatic weighing method was used to determine the apparent mass in water. Then, the porosity was identified as the ratio of the total pore volume to the total sample volume.

3.2.5 Capillarity

The capillary absorption test gives an idea about the porous structure and connectivity of pores in mortars. This test was carried out on mortar samples with dimensions (40x40x60) mm$^3$. The specimens were preconditioned according to the recommendations of the AFGC-AFREM test procedure (1997). The capillary absorption is calculated using the equation:

$$Q = A \cdot t \cdot \frac{S}{2.5}$$

Where Q is the amount of water absorbed (g), A is the specimen surface area in contact with water (cm$^2$), t is the time (min) and S is the sorptivity coefficient of the sample (g/cm$^2$.min$^{0.5}$).
3 RESULTS AND DISCUSSION

3.1 FRESH STATE

It is widely accepted that the mini-cone spreading is the most characterizing parameter of self-compacting mortars.

From Table 4, it can be seen that all the SCM spreads are within the interval [24 - 26] cm, which complies with the recommendations of EFNARC (2002). It was found that using Br and Cr fillers requires less water (35% of cement weight) than LS fillers which require a greater amount of water (40% of cement weight). This observation corroborates the beneficial effect of the fillers produced from industrial by-products. It should be noted that the results obtained by [29] are in contradiction with those found in this study. They indeed found out that the higher the substitution rate of brick fillers, the greater the water demand, which could certainly be assigned to the fineness differences between fillers and to their morphological structures. The reduction in water demand is likely to positively affect the mechanical strength of mortars.

Furthermore, it was found that LS fillers had the best flow time compared to the Br and Cr fillers whose mini V-funnel flow times were quite long and exceeded the limits recommended by current standards, because these two fillers can easily stick to the metal walls of the cone, which prevents their flow.

Figure 3 illustrates an example of the spreading of a self-compacting mortar with Br fillers.

| Table 4: SCM incorporating different fillers in the fresh state |
|------------------|-----------------|-----------------|-----------------|-----------------|
|                  | SCM LS          | SCM Gl          | SCM Br          | SCM Cr          |
| W/C              | 40%             | 37.5%           | 35%             | 35%             |
| Spreading (cm)   | 24.3            | 25.5            | 25.3            | 25.5            |
| Mini V-funnel (s)| 9               | 11              | 20              | 15              |

Source: Authors.
3.2 HYDRATION HEAT

Previous research, such as that conducted by [34], showed that mortars incorporating 10% of metakaolin, as cement substitution, showed a heat of hydration that is larger than that of the control mortar. Given that the sum of the oxides responsible for the pozzolanic reaction (SiO₂ + Al₂O₃) exceeds 80% in the chemical composition of the fillers produced from industrial by-products, it was deemed necessary to assess the effect of the input of waste-based fillers on the heat of hydration of self-compacting mortars.

Figures 4 and 5 illustrate the curves representing, respectively, the evolution of temperatures and the variation of the heat released during the hydration process. Table 5 summarizes the maximum temperature values T_max and the time t corresponding to T_max, as well as the quantity of cumulative heat Q_max.

<table>
<thead>
<tr>
<th>SCM</th>
<th>Q_max (J/g)</th>
<th>% Q_max</th>
<th>T°max (°C)</th>
<th>tT°max (h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SCM LS</td>
<td>260</td>
<td>-</td>
<td>52.52</td>
<td>23.35</td>
</tr>
<tr>
<td>SCM GI</td>
<td>263</td>
<td>1.15</td>
<td>52.99</td>
<td>22.51</td>
</tr>
<tr>
<td>SCM Br</td>
<td>270</td>
<td>3.85</td>
<td>54.56</td>
<td>20.84</td>
</tr>
<tr>
<td>SCM Cr</td>
<td>265</td>
<td>1.92</td>
<td>54.13</td>
<td>20.85</td>
</tr>
</tbody>
</table>

Source: Authors.

Figure 4 shows that the heat release for the SCMs incorporating brick and ceramic wastes accelerated during the first ten hours of hydration, whereas SCMs including glass waste reacted more slowly and generated a smaller quantity of heat in the first hours. However, the amounts of heat generated by the different self-compacting mortars were practically similar at the end of the hydration reactions.

Likewise, Figure 4 shows that the SCMs incorporating the brick and ceramic wastes reached their maximum temperature after 21 hours of reaction, whereas the SCMs including limestone and glass wastes attained their maximum temperature after 22.5 hours of reaction.

These findings may be due to the nucleation effect of Br and Cr fillers. It should be emphasized that the nucleation phenomenon occurs when the fillers have a high fineness, which is the case in the present study. The effect of nucleation depends on the affinity of fillers for cement hydrates. This effect increases with the fineness and the specific surface of the fillers used. This
phenomenon has previously been observed and reported by several other researchers [35-37]. These findings corroborate the results obtained from the hydration tests of Br and Cr fillers during the first hours of hydration. In this regard, the researchers [38] demonstrated that the partial substitution of cement with metakaolin (MK) enhances the hydration process due to the rapid pozzolanic reaction that occurs. This means that the reaction of MK with CH and H₂O (H) contributes to the generation of heat that is then accumulated in hydration systems. In this case, the total heat released is greater than that of the control SCM.

Based on the above findings, it can be concluded that the oxides present in the Br and Cr fillers reacted with the C-H produced during the hydration of the cement, which favored the formation of C-S-H and C-A-H. As a consequence, the amounts of released heat and accumulated heat in the system increased.

![Figure 4: Accumulated heat](image-url)
3.3 MECHANICAL STRENGTH

The compressive strength is one of the most important parameters to consider when formulating mortars. This parameter depends essentially on the cement content, the water-to-cement (W/C) ratio, and the properties of the sand and fillers used. The mechanical strength test was performed to confirm the findings of the heat of hydration tests. Previous research on cement replacement with additions of brick [39] [40], ceramic [41, 42], and glass [21, 43] confirmed that these three fillers are pozzolanic materials. Figure 6 illustrates the results relating to the compressive strength of the different mortars, at various maturities. The graph clearly shows that the compressive strengths of mortars increased over time and did not show any decrease. It was also found that mortars including Br and Cr fillers have quite significant strengths at 2 and 7 days. However, in the long term, the compressive strengths of mortars including Br and Cr fillers were much higher than that of the control mortar. Indeed, these strengths were greater by 42 and 46%, respectively, with respect to that of the control mortar. Likewise, the compressive strength of the SCM containing glass (Gl) increased significantly after 270 days of maturation. It was greater than that of control mortar by 30%. It should be emphasized that the pozzolanic reactions of Br and Cr fillers were activated prematurely, confirming their nucleation. On the other hand, the glass fillers (Gl) showed a delayed pozzolanic reaction that was activated after 28 days of maturation.
Figure 6: Compressive strength of SCMs

Source: Authors.

Figure 7 shows the tensile strength results of the different SCMs, at various maturities. The graph representing the tensile strength is similar to that of the compressive strength, which confirms that the results obtained in this work are acceptable.

Furthermore, the good performance of SCMs incorporating Br and Cr fillers may certainly be attributed to the low (W/C) ratios and to their more refined pore networks which resulted from the pozzolanic activity and the void-filling effect of these fillers [29]. It is noteworthy that the pozzolanic reactions of Br and Cr fillers were activated prematurely, which confirmed the nucleation effect due to their high fineness [35] and to the formation of C-A-H and C-A-S-H gels at young age due to the presence of Al₂O₃ [44]. On the other hand, the Gl fillers, which contain a negligible quantity of Al₂O₃, generated only second generation C-S-H which showed a delayed reaction that only took place after 15 days of maturation. These findings insinuate that the compressive strength will certainly increase at advanced ages.
It is worth noting that the compressive strengths of all SCMs incorporating industrial by-products exceeded 80 Mpa at 28 days. These mortars can therefore be considered as high performance (HP) mortars. The ACI 363R-10 Report on High-Strength Concrete states that the compressive strength of a high strength concrete should be around 55 Mpa. However, this same committee recognizes that the definition of high performance or high strength concrete should vary on a geographic basis. In areas where concrete with a compressive strength of 62 Mpa is already commercially produced, high performance concrete (HPC) with compressive strength between 83 and 103 Mpa can be utilized. In this context, it is worth mentioning the studies conducted by Ha Thanh [18] who showed that for the cement replacement range [5 % - 20%] by weight, rice ash was found to be highly efficient in improving the compressive strength of high performance concretes (HPCs); it can exceed 80 MPA at 28 days.

3.4 POROSITY ACCESSIBLE TO WATER

The amount of absorbed water and pore volume were assessed according to the ASTM C642 guidelines. The results are illustrated in Figure 8.
The water absorption values were found to be 3.59, 2.07, 2.16 and 1.73% for SCMs including LS, Gt, Br and Cr, respectively. Similarly, the void volume was 7.94, 4.58, 4.89, and 3.95% for LS-, Gt-, Br-, and Cr-based SCMs, respectively. By comparing the water absorption and void volume values for the filler-based SCMs given above with those of the control mortar, it was found that the filler-based SCMs absorb less water and contain fewer voids than the control mortar. It was also observed that these values for the mortar with Br were slightly higher than those for the mortar with Gt. Similarly to the compressive strength, it was found that replacing cement with fillers resulted in smaller water absorption and pore volume. It should be pointed out that the mortar incorporating the industrial by-product fillers absorbs half as much water as the reference mortar, which suggests that the mortar including the industrial by-product fillers is more watertight. It is also worth noting that the mortar incorporating industrial by-product fillers had a volume of voids twice as small as that of the reference mortar. Consequently, the replacement of limestone fillers (LS) by industrial by-product fillers used as pozzolans contributed to the micro-filling of pores of mortar, with the formation of a new C-S-H gel, which decreased the permeability of the SCMs.

3.5 CAPILLARITY

Figure 9 show, respectively, the cumulative weight gain as a function of time and the sorptivity coefficient of the different mixtures. The replacement of limestone fillers led to a reduction in the sorptivity of the mortars. This was more
significant in the case of SCMs including Br and Gl fillers, despite their high total absorptions. This sorptivity drop is probably due to the lack of pore connectivity which impedes water flow. On the other hand, in the case of SCM with Cr, the connectivity of the pores is clearly visible, which induced a significant capillary absorption.

Figures 9: Sorptivity plots (i versus t1/2) for SCM - Sorptivity coefficients of SCM

![Sorptivity plots](image)

Previous research [45] has reported a reduction in sorptivity in the case of mortars containing pozzolanic materials, despite the increase in total porosity. Therefore, it can be said that SCM including Br has a more refined porous structure, with smaller pores that prevent the penetration of water. Studies by [46] confirmed the refinement of the porous structure of mortars containing crushed calcined clay brick waste.

4 CONCLUSION

The above findings allowed drawing the following conclusions:

The targeted objectives have been fully achieved in this study dedicated to the impact of incorporating fillers based on pozzolanic waste. The obtained results have shed significant light on various aspects of this approach, allowing the following conclusions to be drawn:

1. Brick and ceramic fillers stand out with a lower water demand compared to limestone fillers, likely due to their fineness and distinct morphologies.
2. The nature and fineness of brick and ceramic fillers induced a nucleation effect, resulting in a significant increase in heat of hydration of binders in the early hours and accelerated development of compressive strength at an early age.

3. Supplementary Cementitious Materials (SCMs), including the three types of fillers, demonstrated a considerable increase in mechanical strength at all stages.

4. The improvement in the mechanical characteristics of industrial waste-based SCMs led to an elevation of their porosities accessible to water and capillaries.

5. Ceramic fillers outperformed other fillers in terms of performance, except for capillarity. These conclusions underscore the effectiveness of integrating pozzolanic waste-based fillers in enhancing the properties of construction materials.

5 FUTURE PERSPECTIVES:

Continuing along this research trajectory opens up exciting perspectives. Exploring the use of these fillers in self-compacting concrete would expand their application scope. Additionally, an in-depth study of rheological parameters would refine our understanding of the properties of these materials under specific conditions.

Furthermore, analyzing remaining durability parameters such as air permeability, carbonation, chloride ion penetration, and chemical attacks would provide new insights into the long-term resilience of these materials. These promising research directions contribute to broadening our understanding of pozzolanic waste-based fillers and optimizing their use in various sustainable construction contexts.
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