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Porosity Analysis of Mortars Incorporating Glass Powder and Coffee Grounds Using X-Ray Tomography

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Abstract: ***The environmental burden of cement production and unmanaged waste such as glass and coffee grounds presents a dual challenge. This study evaluates the effect of partially substituting cement with glass powder (5–25%) and coffee grounds (2–5%) on the porosity and water absorption of mortar. Using X-ray computed tomography and DragonFly 3D software, the internal pore structures were analyzed non-destructively. Results show that glass powder significantly reduces porosity and water absorption, suggesting improved microstructural integrity. Conversely, the inclusion of coffee grounds leads to increased porosity and water uptake, likely due to their organic and porous nature. The findings support the potential of glass powder as a sustainable additive in mortar while calling for further research into optimizing the use of coffee grounds.***

Keywords: glass powder, coffee grounds, X-ray tomography, cement replacement, mortar porosity

1. Introduction

Cement is the most widely used construction material in the world. However, its production requires a large amount of energy, resulting in the release of significant amounts of carbon dioxide (CO_2).

With growing industrial development and various human activities, industrial waste production is increasing and accumulating in larger areas, requiring the constant search for new sites for its disposal.

In this context, reusing waste materials such as glass waste and coffee grounds as a partial substitute for cement represents a promising solution. This approach reduces waste accumulation while limiting the environmental impact of cement production.

Porosity is a fundamental parameter influencing the physical and mechanical properties of cement-based materials, including strength, durability, and permeability. Accurate characterization of the pore structure is therefore essential for understanding and optimizing the behavior of these materials.

Several studies have shown that X-ray tomography is a powerful non-destructive technique for the three-dimensional analysis of porosity in cementitious materials. Kim et al. [1] used the tomograph to observe the distribution of pores. Their work demonstrated that X-ray tomography allows detailed visualization of internal voids, facilitating the identification of the porous microstructure. Stein et al. [2] also studied porosity in concrete samples using micro-tomography, highlighting a heterogeneous distribution of pores and the presence of air voids of different sizes. For their part, Henry et al. [3] applied complementary image analysis techniques to accurately quantify the morphology and connectivity of pores in high-strength cement pastes. Furthermore, Lanzón et al. [4] highlighted the significant influence of low-density mineral additions on the porosity of mortars, with notable adverse effects on mechanical strength and capillary absorption. These studies confirm the importance of porosity as a key factor in the performance of cementitious materials.

The objective of this study is to characterize in detail the internal physical properties, including the evolution of porosity and water absorption of mortars based on glass powder and coffee grounds. To do this, tomography proves to be the most suitable analysis tool, due to its ability to detect and quantify variations in the porous structure in a non-destructive manner and at high resolution of the internal structure of the materials. This study is significant as it concurrently evaluates two commonly discarded waste products using high-resolution tomography, offering an innovative methodology to promote sustainable material use in construction.

This study begins with an introduction, then describes the materials and characterization methods in Section 2. The results and discussions are presented in Section 3, while Section 4 is devoted to the conclusion.

2. Materials and Methods

2.1. Materials

This section presents the various materials used in this study: cement, sand, recycled glass powder, and coffee grounds.

a) Cement

CEM II 32.5 cement was used, characterized by an apparent density of 1020 kg/m³, an absolute density of 3000 kg/m³ and a Blaine fineness of 3480 cm²/g.

b) Sand

Building sand is a French sand used to make mortar and concrete. The sand has a grain size of 0/4 with a water absorption coefficient of 0.7%. These grains are rolled.

c) Glass Powder

To produce the glass powder in our study, glass bottles were collected from the Mbeubeuss landfill (Dakar, Senegal). They were placed in saturated water for 24 hours to remove labels and all impurities. After drying, the used glass particles were manually broken into small parts. The parts were then ground into powder using a Los Angeles ball mill (G-128-424305/02). The microstructure of the powder shows that the material is glassy in nature and irregular in shape (Figure 1).

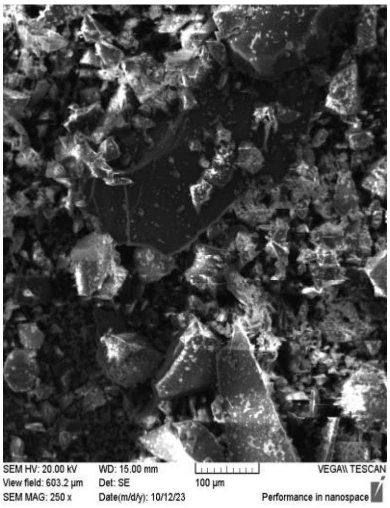


Figure 1: Microstructure of glass powder

d) Coffee grounds

In Senegal, coffee grounds (Touba coffee) are a solid organic residue, largely generated by the consumer and service sectors in recent years. They were collected as domestic waste from the filtration of the Touba coffee beverage. After juice extraction, the coffee residues were dried naturally to prevent mold, preserving the structural integrity of the residue. The morphology of the coffee grounds showed that these particles are porous, wrinkled, and serrated (Figure 2).

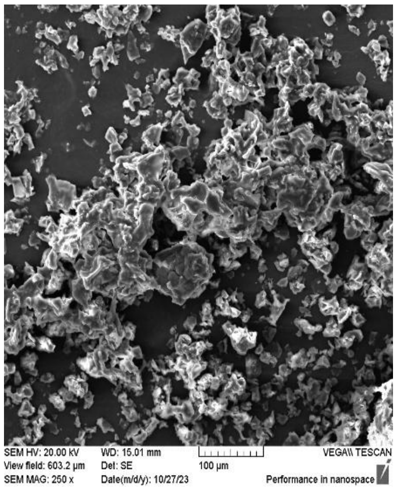


Figure 2: Microstructure of coffee grounds

2.2 Preparation of mortar samples

This study evaluates the porosity of 18 mixtures replacing CEM II type cement (32.5) with glass powder with percentages of 5, 10, 15, 20 and 25 % and coffee grounds with percentages of 2, 3 and 5 %. Mortar samples 4 x 4 x 4 cm^3 (Figure 3) were made to carry out this study.

Figure 3: Mortars made from glass powder with 25 %

2.3. Method for determining porosity

a) Tomography and measurement conditions

X-ray computed tomography is an analytical method that allows the acquisition, i.e., the acquisition of multiple 2D images taken from various angles around the rotation axis of the sample. These images are then digitally reconstructed to generate a three-dimensional volume faithfully representing the internal architecture of the material, including defects, inclusions, and porosity.

For this study, measurements were performed using an EasyTom XL-150 industrial tomograph manufactured by RX Solutions (Figure 4).

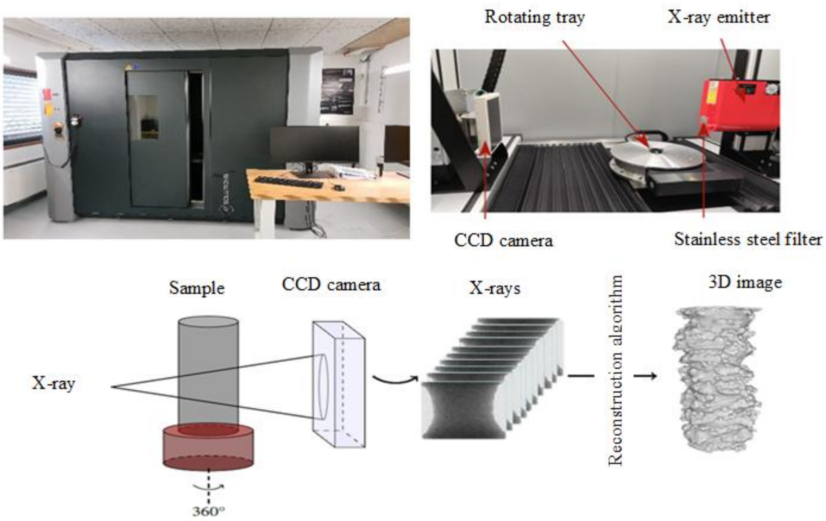


Figure 4: Presentation and diagram of the operating principle of an X-ray tomograph a-… b-… and c-…

b) Image processing and reconstruction

The X-ray images obtained during sample rotation are then processed by RX Solutions' X-AFT64 software to perform the 3D reconstruction phase (Figure 5). Correction filters were applied to eliminate low-energy photons, correct beam hardening artifacts, and adjust for any sample positioning drifts during acquisition.

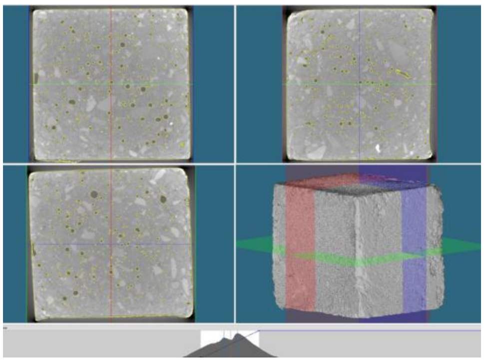
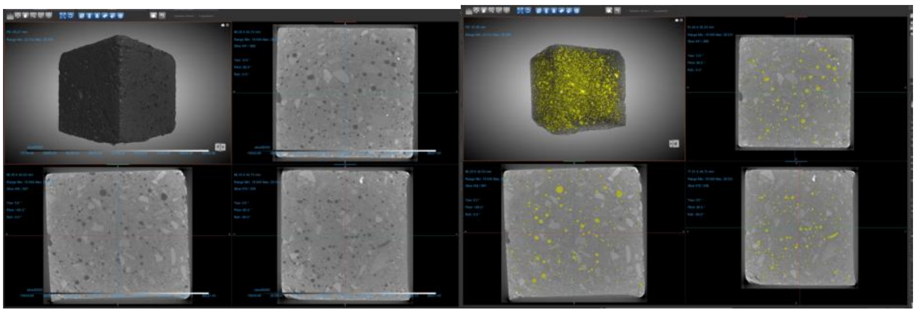


Figure 5: Example of 3D reconstruction of a mortar

c) Segmentation and quantification of porosity with Dragonfly 3D software

Once the reconstruction was complete, the volumetric images were exported to Dragonfly 3D software [5], a powerful tool for visualizing and analyzing scientific images. The first step is to segment the data: this operation allows us to distinguish different phases (including the void of interest) by normalizing the intensity of the gray levels (Figure 6a).

Next, a binarization threshold process is applied to isolate the pores, i.e., the low-density areas. This approach allows us to generate a three-dimensional mesh of the volume, from which quantitative measurements such as the percentage of porosity are extracted (Figure 6b).



(a) (b)

Figure 6: Porosity measurement by Dragonfly 3D a) Segmentation setup b) Detected porosity colored in yellow

2.4 Determination of water absorption

The objective of the test is to determine the amount of water absorbed under specific conditions. The test was carried out by measuring the amount of water absorbed by a sample for a specific period. The specimens used in this test were kept for up to 28 days. After the curing period, the principle is to determine the change in mass of an immersed mortar sample to a constant mass, i.e. mass M_1, after drying at 105 °C, i.e. mass M_2. The water absorption Abs is expressed as a percentage of the dry mass and is calculated by equation 1:

$$Abs = \frac{M_1 - M_2}{M_2} 100 \qquad Eq\ 1$$

M_1 : wet mass of the sample (g),
M_2: dry mass (g),
Abs: percentage water absorption (%).

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3. Results and discussion

3.1 Results on Porosity

The total porosity results of the mortars are presented in Figures 7 and 8 for mortars containing glass powder and coffee grounds, respectively.

Porosity decreased with higher glass powder content, but increased when coffee grounds were used. The highest total porosity values were then observed for mortars containing 5 % glass powder and 5 % coffee grounds after 28 days of curing for the types of mortars studied.

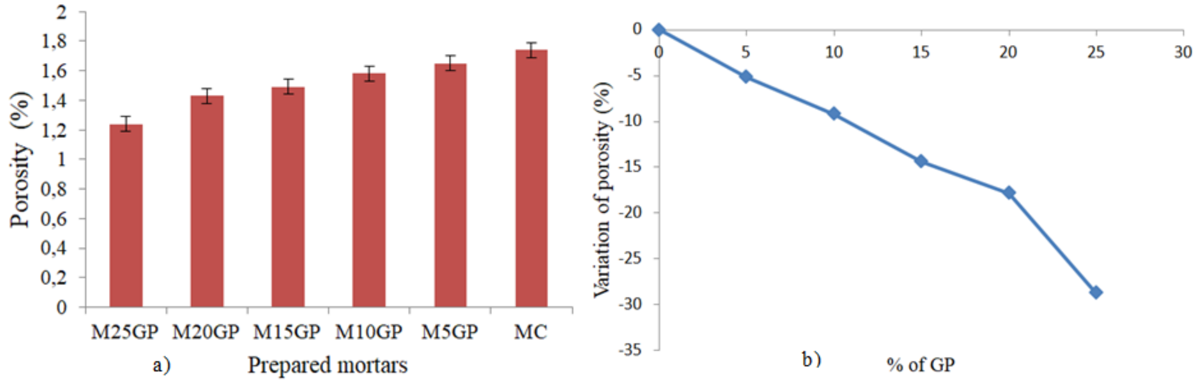

Figure 7: a- Porosity of glass powder (GP) mortars with CM: control mortar b- Variation of porosity as a function of GP percentage

The progressive decrease in porosity with increasing glass powder percentage observed for mortars (Figure 7) could be related to the development of clinker hydration [5] and pozzolanic reactions of glass powder [6]. As products of these reactions, solid phases would form, reducing the total pore volume of the material. The higher overall porosity values observed for glass powder mortars could be explained by the delay in pozzolanic reactions of glass powder compared to cement hydration [7]. For the of these reactions, requires sufficient Portlandite for effective pozzolanic reactions; therefore, more time would be needed to observe the effects of adding glass powder on the evolution of the microstructure [8].

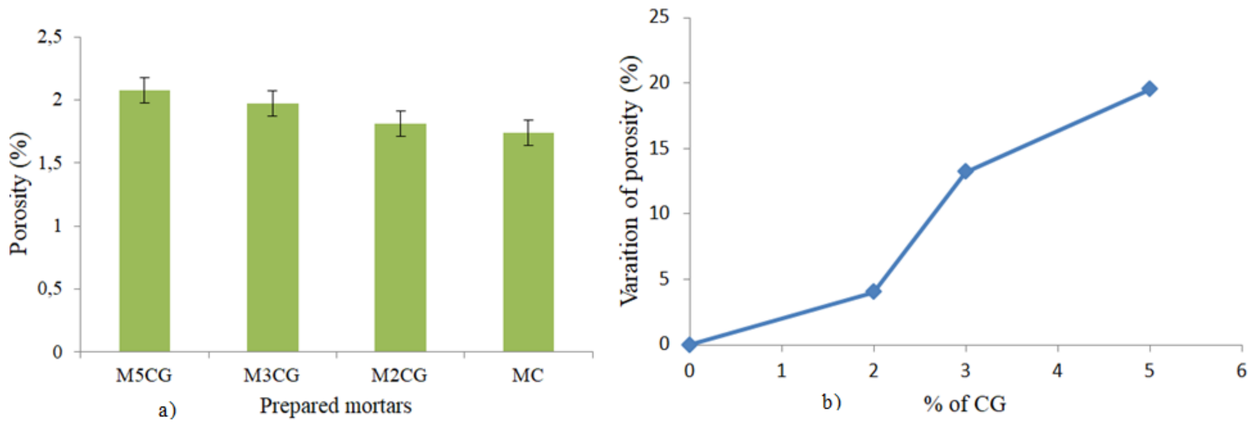

Figure 8: a- Porosity of coffee grounds (CG) mortars with MC: control mortar b- Variation of porosity as a function of CG percentage

From Figure 8, it is possible to observe a difference in terms of porosity between the control mortar and all the coffee grounds mortars. There is an increase in porosity with the increase in the coffee grounds content. This can be related to poor adhesion between the surfaces of the coffee grounds particles and the cement paste. According to Saeli et al. [9], increasing the amount of coffee grounds decreases the density due to the porous nature of the material. Thus, the samples become more porous, which leads to greater absorption and retention of water inside the material. In the work of Chung et al. [10], the addition of coffee grounds showed a slightly higher porosity than the reference samples. The porosity demonstrated by the samples was still around 3.4%, therefore, it should not be a problem according to existing studies [11], [12].

3.2 Results on water absorption

The results obtained on the water absorption of each mortar are expressed, in percentage, in the form of the average of the measured values (3 times) of each mortar. The quantities of water absorbed by the mortars made with glass powder and coffee grounds at the age of 28 days are given respectively in figures 9 and 10.

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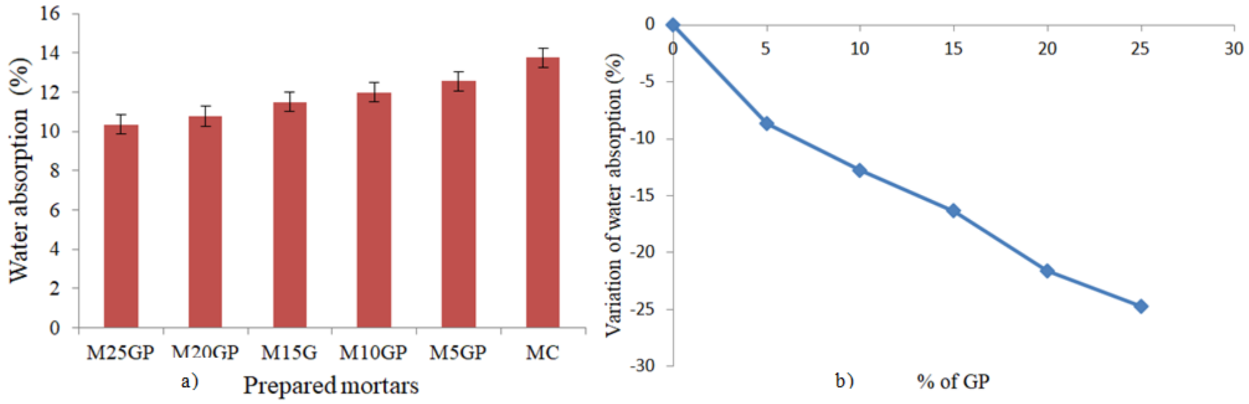

Figure 9: Water absorption of glass powder (GP) mortars with MC: control mortar b- Variation of water absorption as a function of GP percentage

The results show that the absorption of the control mortar (CM) is higher than that of the mortars made with glass powder (Figure 9). Substituting cement with glass has a significant effect on water absorption. As the substitution rate increases, water absorption decreases. This decrease is more pronounced for the mixture containing 25 % glass, at around 3.29 %.

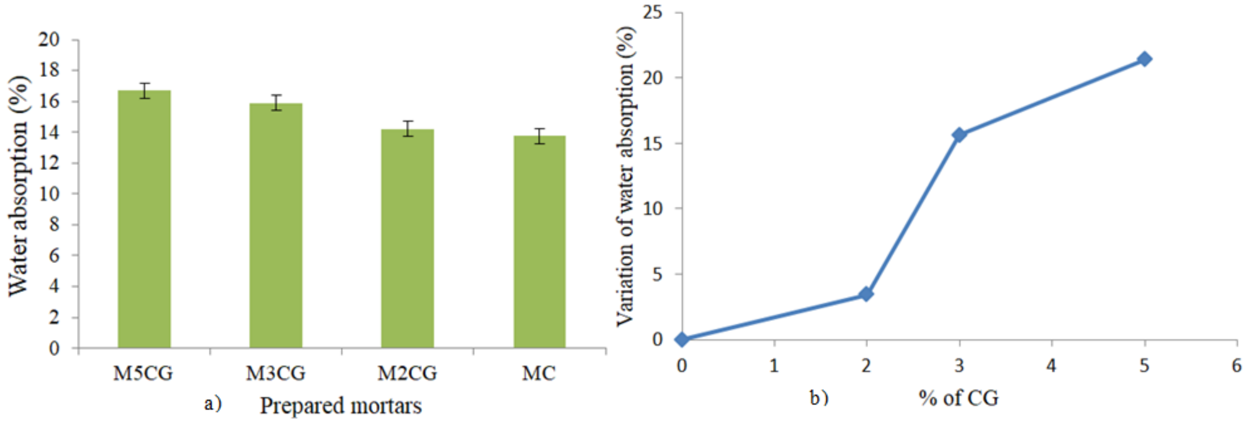

Figure 10: Water absorption of coffee grounds (CG)-based mortars with CM: control mortar b- Variation of water absorption as a function of CG percentage

Figure 10 shows that all mortars incorporating coffee grounds have higher water absorption than the control mortar, and the higher the rate, the higher the water absorption (2.94 %). This is related to the porous nature of coffee grounds, which creates voids within the material, but also to the lack of adhesion between these particles and the cement paste. Thus, mortars containing organic matter, even when treated, tend to exhibit higher water absorption results than reference mortars [13]. Raw coffee grounds, due to their organic nature and fibrous structure, can introduce additional voids into the mortar matrix.

These voids increase the open porosity, facilitating water penetration and, consequently, water absorption. According to Arulrajah et al. [14], mortars made with coffee grounds have high water holding capacity. Technically, the water absorption of coffee grounds varies depending on particle size, moisture content and image processing techniques.

3.3 Measurement of porosity and water absorption

Porosity is one of the main factors influencing the water absorption capacity of a cementitious material. Higher porosity generally corresponds to a larger volume of interconnected pores, facilitating water penetration and retention within the material [15]. Water absorption is directly related to open porosity, i.e., externally accessible pores and their connectivity.

In mortars where porosity is reduced, by adding pozzolanic materials such as finely ground glass powder, the reaction products (mainly C-S-H) fill part of the pores. This densification of the matrix limits water migration paths, resulting in a significant reduction in water absorption [16]. In contrast, the incorporation of porous or organic materials such as coffee grounds increases the overall porosity of the mortar, leading to higher absorption [9], [17]. Controlling porosity is therefore essential to improve the durability of cementitious materials, particularly in environments exposed to humidity and aggressive agents.

4. Conclusion

This study highlighted the impact of partially substituting cement with glass powder and coffee grounds on the porosity and water absorption of mortars. Using the EasyTom XL-150 X-ray tomograph, it was possible to characterize the internal structure of the samples with high accuracy, visualizing the distribution and interconnection of pores in three dimensions. The results showed that:

- The substitution of glass powder significantly reduced

porosity and water absorption, attributed to its pozzolanic reactivity and the progressive densification of the matrix.
- The substitution of coffee grounds, due to their porous structure and limited interaction with the binder, increase total porosity and, consequently, water absorption.

Regarding optimization, the results suggest that glass powder is partially optimized, but would merit testing at substitution rates above 25 %, or even combinations with other additives to maximize its effects. For coffee grounds, pretreatments (washing, drying, finer grinding) or hybrid blends could limit the observed negative effects.

From an environmental perspective, the reuse potential is real: Glass powder comes from a common waste product (glass bottles), which is often not recovered in some countries. For example, with annual mortar consumption estimated at several million tons, a 10 to 25 % substitution could recover tens of thousands of tons of glass per year. Coffee grounds, although more limited in volume, remain an abundant organic residue in urban areas. Its inclusion in construction materials would contribute to a localized circular economy model.

The tomography approach has been essential for non-destructively and reliably quantifying porosity in modified mortars. It offers a powerful tool for optimizing the formulation of cementitious materials by integrating recovered waste, while ensuring the sustainability of mechanical and water performance. This work innovates by simultaneously evaluating these two by-products in a single experimental approach, through the systematic application of X-ray tomography coupled with analysis using DragonFly 3D software. Compared to other studies that focus only on mechanical or environmental performance, our research highlights the interaction between fine particles and porosity, providing an understanding of the microstructural behavior of the effects induced by these additions. Thus, the integration of advanced imaging techniques such as tomography paves the way for a better understanding and control of the internal properties of innovative construction materials.

Following these studies, the evolution of porosity will be monitored when the mortar is subjected to a compressive force, in order to observe how the degradation induced by mechanical stress influences the porous structure. This approach will allow a better understanding of the link between damage, mechanical behavior and microstructural evolution of modified mortars.

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