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PROPERTIES AND MECHANICAL PERFORMANCE OF CEMENT MORTARS INCORPORATING COFFEE GROUNDS RESIDUES

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ABSTRACT: *Current advances in sustainability and innovation have led to research and development of new eco-friendly construction materials. Recycling or transforming waste materials, which are unlikely to end up on landfill sites, into usable materials for construction applications, will significantly reduce the demand for virgin quarry materials. Used coffee grounds, for example, are a by-product of the brewing process, an unavoidable waste product these days. Coffee production and consumption are on the increase worldwide, and particularly in Senegal with the advent of 'Touba' coffee. This coffee is specific and its use generates a significant amount of waste. The usual disposal of this organic waste in landfill sites constitutes a risk for humans and the environment. The aim of this article is to use coffee grounds to produce new, environmentally-friendly building materials. The residues were used at 2%, 3% and 5% partial cement replacement to assess the mechanical and microstructural performance of the mortars produced. The main results showed that a small quantity of coffee waste led to a reduction in the apparent density of mortars and a drop in mechanical performance (while still maintaining acceptable values).*

KEYWORDS: Mechanical, Cement, Mortar, Residue, Coffee grounds, Performance.

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INTRODUCTION

The increasing depletion of non-renewable resources, alarming pollution and significant climate change has reached a critical point. The use of man-made waste in the construction industry appears to offer considerable advantages in terms of reducing waste disposal costs, cutting greenhouse gas emissions, conserving natural raw materials, protecting the increasingly stringent environment and even improving the properties of construction materials. In recent years, construction and demolition materials such as recycled concrete aggregates, recycled glass, crushed bricks, reclaimed asphalt [1], and other wastes such as calcium carbide residues and sewage biosolids have demonstrated their suitability as recycled construction materials, particularly in the field of civil engineering [2].

In addition, a 2008 estimate shows that the world produces 7.4 million tons per year [3] of insoluble and highly organic matter (coffee grounds) waste resulting from the preparation of coffee [4]. This figure is expected to increase, particularly in developing countries, due to the growing popularity of the drink worldwide [5]. This waste has been used as a domestic agricultural fertilizer [6] or leachate absorbent [7]. Nevertheless, large-scale harvesting of coffee grounds (CG) for recycling or commercial purposes has not yet been reported. Therefore, the development of a derived building material, which makes extensive use of recycled CG, may be a means of diverting this insoluble solid from landfill.

Coffee grounds have also been widely studied as a substitute in concrete. The recovery of this type of material can help to reduce pollution and produce new construction materials ([4],[8],[9]). Several studies have already been carried out on the use of coffee waste as an aggregate in the preparation of cement mortar [10], concrete and eco-fuel clay bricks ([11],[12],[13]). In these works, the authors explored the use of lightweight aggregates based on coffee waste, as a composite material that reduces the workability, density, cost, brittleness, thermal insulation and fire properties of construction materials such as concrete, mortar or bricks. Coffee grounds are also used as an insulating additive in gypsum-based plasters, but incorporation is limited to 6% and the focus is solely on the thermal properties of the materials [14]. CG has low shear strength and high compressibility, and irrespective of the region of origin of the coffee beans tested, these engineering parameters are consistent [15]. Thus, consistent studies have shown that geopolymer-stabilized GC has an increased compressive strength that meets the strength requirements for use as a foundation material [16]. Our study focuses on the development of a new material by replacing a percentage of cement with coffee grounds, with the aim of improving the ecological and economic conditions of the building industry.

The coffee grounds used in this study come from the filtration process of the Touba coffee beverage produced in Senegal. During major events such as the Touba Maggal or during the month of Ramadan, coffee consumption increases, resulting in large quantities of waste. The lack of adhesion between the coffee grounds and the cement pastes and the inhibition of cement hydration due to the cellular nature of coffee grounds are the reasons cited. The aim of this article is therefore to study the mechanical and microstructural properties of mortars partially replaced with coffee grounds (2, 3 and 5%).

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This paper begins with an introduction, followed by a presentation of the materials and methods of characterization used in section 2. Section 3 presents the results and discussions, and section 4 concludes.

MATERIALS AND METHODS OF CHARACTERIZATION

Raw Materials

Three materials will be used in this study: cement, sand and coffee grounds.

The used cement is a CEM II/B 32.5, with an apparent density (ρ_{app} = 1020 kg/m^3), an absolute density (ρ_{abs} = 3000 kg / m^3), a Blaine fineness (3480 cm²/g) and a mineralogical composition is presented in Table 1. Figure 1 shows the XRD model of the cement used.

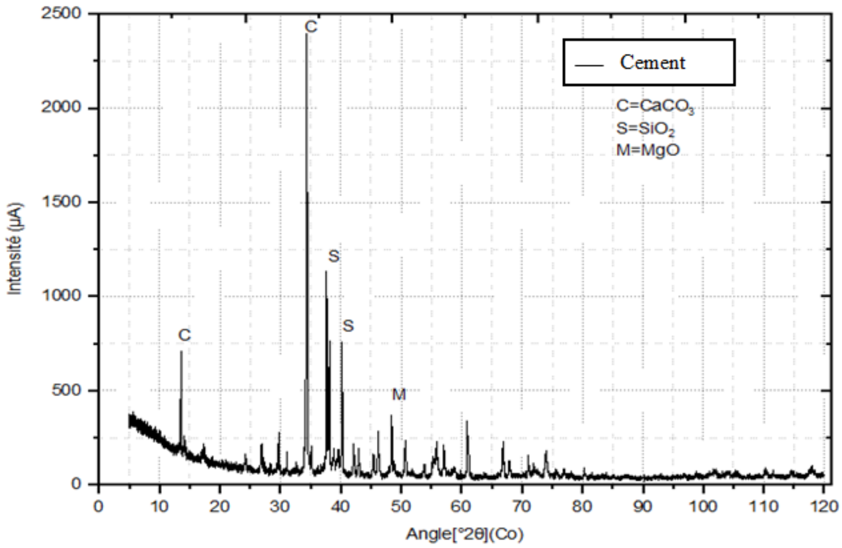

Fig. 1: XRD of cement

CEN standard sand (ISO standard sand) is natural, siliceous sand, particularly in its finest fractions. It is clean, with grains that are generally isometric and rounded in shape. It is dried and screened. The granulometric composition is determined by sieving and complies with the requirements of standards EN 196-1 and ISO 679: 2009.

Used coffee grounds were collected as domestic waste from the filtration of the Touba coffee beverage. Touba coffee, or café saff, is a drink made from Arabica coffee flavored with Selim pepper, also known as Kili, black pepper or jar. Once the juice has been extracted, the coffee residue is naturally dried to avoid molds that could compromise the integrity of the organic matter.

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Table 1: Chemical Composition of Coffee Grounds and Cement

Oxides (%)	SiO_2	CaO	MgO	Fe_2O_3	S	PAF
Cement	21.29	64.68	0.44	3.49	2.06	1.93
Coffee grounds	0.58	1.095	0.22	0.20	0.14	97.11

Properties of the GC

The size of the CG particles measured by particle size distribution shows that the material is essentially made up of fine elements with a fineness modulus of 2.29. The apparent and absolute densities of coffee grounds were determined to be 324 kg/m^3 and 1469 kg/m^3 respectively. Coffee grounds are therefore considered to be light compared with natural soils [17]. Thermal conductivity was measured using the box method, with a value of 0.086 W/mK. This characteristic of coffee grounds particles is particularly suitable for geotechnical or civil applications. In addition, scanning electron microscope (SEM) analysis using a Quanta 200 FEI showed that coffee grounds particles have angular shapes and numerous pores on their rough surfaces (Figure 2).

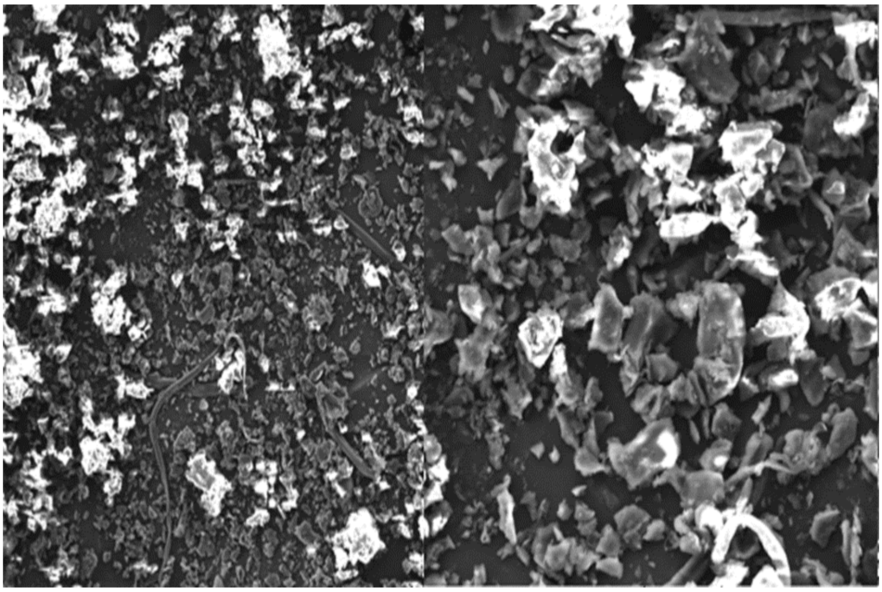

Fig. 2: SEM images of coffee grounds

This analysis also made it possible to determine the mineralogical composition shown in Figure 3. According to this analysis, K, Ca, C and O are the major elements in coffee grounds, which is consistent with the results found in [18]. The presence of the element Mg was also noted, as in the work of [19]. Traces of Au were noted as a result of spraying.

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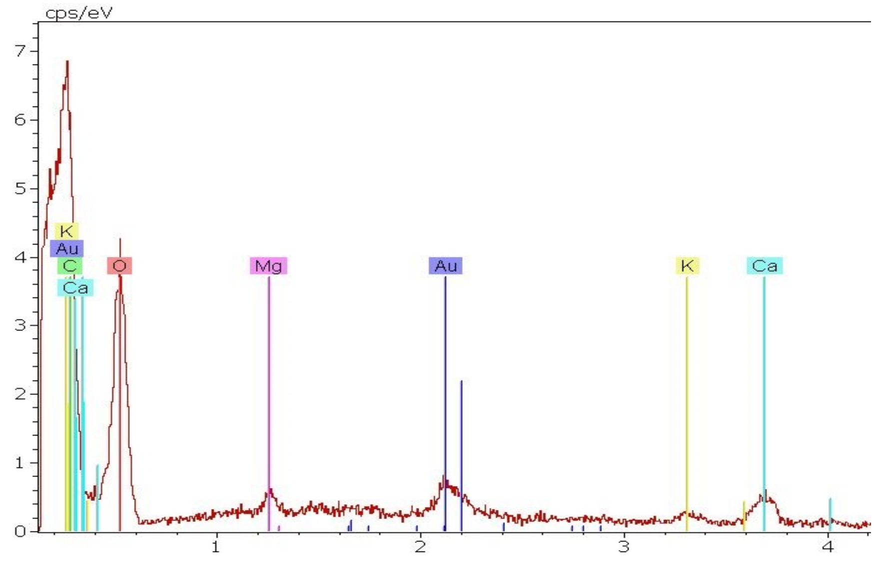

Fig. 3: SEM images composition of coffee grounds

Further XRD tests were carried out, the crystalline phase of the coffee grounds in Figure 4 shows a net detachment of calcium of about 24 as found in the work of [20].

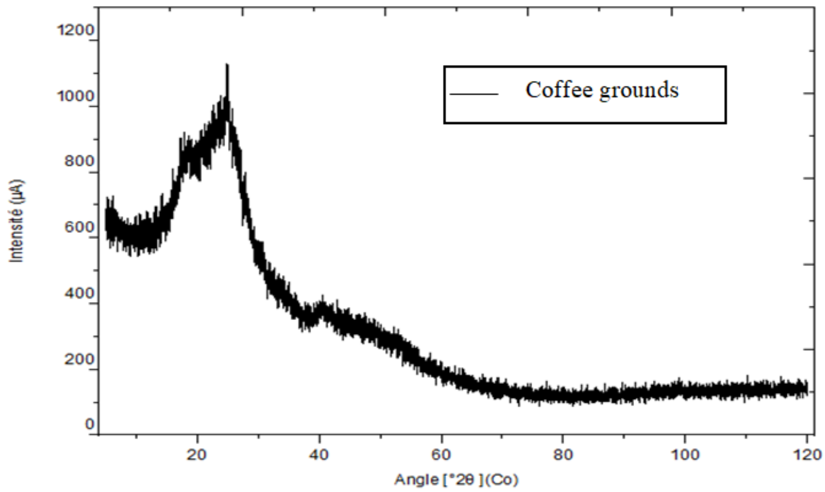

Fig. 4: XRD of coffee ground

The chemical properties were studied by infrared spectrum analysis using a ThermoFisher Scientific (max current 4.16A, DC voltage 12V) and by X-ray fluorescence using the Niton - XRF apparatus. The results obtained by analyzing the infrared spectrum show that a 3289 band corresponds to OH stretching in the carboxylic acid or various sugars, characteristic of the amine groups present in caffeine or proteins. The two bands at 2921 cm^{-1} and 2852 cm^{-1} are attributed to asymmetric and symmetric stretching of the C-H bonds of the methyl group in the caffeine molecule. A band at 1742 cm^{-1} is attributed to the carbonyl vibration (C=O) in aliphatic esters or triglycerides derived from lipids. However, coffee grounds contain compounds such as caffeine, tannins and polyphenols that are highly toxic to the environment; this is due to the abundant amounts of oxygen required to break down the organic envelope [21].

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Overall, the similarities in the IR spectra confirm the information provided by X-ray diffraction. However, elemental chemical analysis by fluorescence will help to extend this information by providing the amount of oxide in each chemical element. The figure 3 shows a pellet and the X-ray fluorescence experimental set-up.

X-ray fluorescence analysis (Figure 5) shows that in coffee grounds, the mineral components are less present with a significant loss of fire ([18], [22], [23]). The percentages of oxides are given in Table 1.

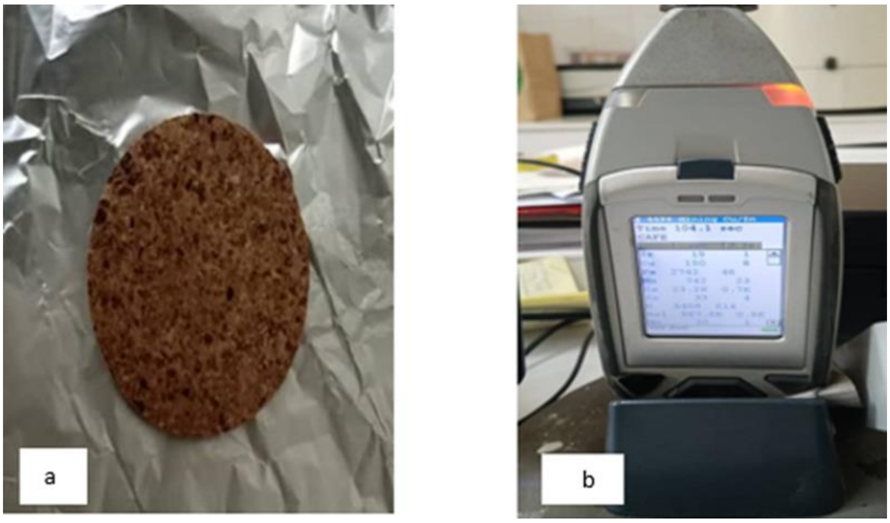

Fig. 5: Appearance of the pellet (a) and the Niton-XRF spectroscope (b)

Mechanical Characterization Methods for Cement Mortars

Pastes were prepared to determine consistency, start and end times with a W/C ratio equal to 0.27 for all mixes. The W/C ratio represents the quantity of water used in relation to the quantity of cement. Mechanical tests were carried out in accordance with standard EN 196-1 (NF EN 196-1, 1995) to determine the mechanical properties of the different types of mortar: three point bending (3 pts) on three 4×4×16 cm^3 specimens and then compression on the half-test specimens issued from the previous test.

Consistency and Setting Times of Cement Pastes

The normal consistency and the setting start and end times of the various mixes were studied using a Vicat apparatus. The mixes were first made using a mixer, then quickly introduced into a mold placed on a glass plate, without settling or excessive vibration. The mixture was then quickly introduced into a mold placed on a glass plate, without settling or excessive vibration, and the whole was placed on the Vicat apparatus plate. The needle placed on the surface of the sample is released and sinks into the paste. When it stops (or after 30 seconds of waiting), the distance 'd' between the end of the needle and the base plate is recorded. A mixture (or dough) is considered to have a normal consistency if $d = 6$ mm ± 1 mm. If $d > 7$ mm, it is considered that there is not enough water. If $d > 7$ mm, it is considered that there is not enough water and conversely if $d < 5$ mm, it is considered that there is too much water [24].

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Mechanical Properties of Mortars

Twenty-seven specimens were manufactured to study flexural and compressive strength (Figure 6a and 6b) at 2, 7 and 28 days.

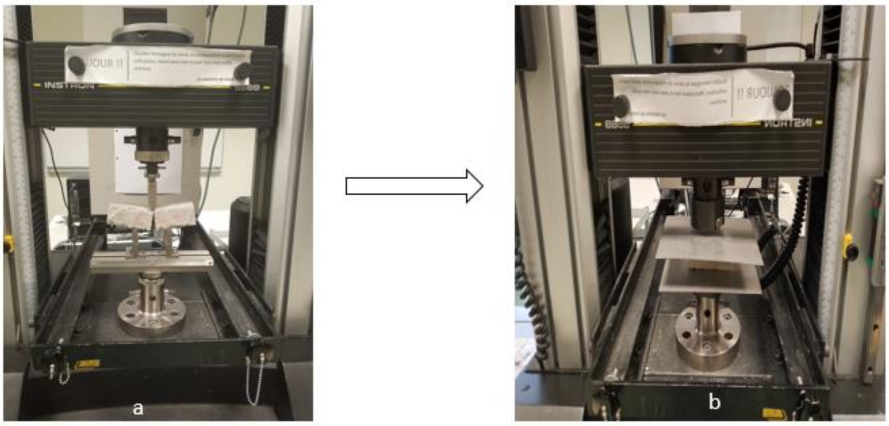

Fig. 6 (a) bending apparatus and (b) compressive device

The mixes were made in a standard mixer prescribed by standard EN 196-1 (NF EN 196-1, 1995) and poured into test specimens (4 x 4 x 16 mm^3). In order to control the mechanical behavior of the mortars, we considered the different compositions illustrated in Table 2. The following conditions were applied: a rate of replacement of cement by coffee grounds (0%, 2%, 3% and 5%), a W/C ratio fixed at 0.5. After 24 hours, the samples were demolded and placed in water at 20°C and 100% relative humidity until the day of testing [25]. Two constraints are determined:

The bending stress given by the relation:

$$\sigma_f = \frac{1.5F_f L}{b^3} \qquad \textit{Eq. 1}$$

The compressive stress is given by this equation:

$$\sigma_c = \frac{F_c}{S} \qquad \textit{Eq. 2}$$

σ_f = Bending stress

F_f = Bending force

L= Length of crest

b = Sample height

σ_c= Compressive stress

F_c = Compressive force

S = Sample surface

This procedure was followed for all compositions and tests. The different mortars produced are summarized in Table 2.

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Table 2: Composition of Mortar Mixes

Name	Cement (g)	Sand (g)	Water (g)	Coffee grounds (g)
M0	450	1350	225	-
M2	441	1350	250	9
M3	436.5	1350	252	13.5
M5	427.5	1350	255	22.5

RESULT AND DISCUSSION

Consistency and Setting Time

Replacing cement with coffee grounds increases setting time as the glass content increases. However, consistency decreases with the increase in coffee grounds in pastes made with a reduction in water requirement of around 0.2%. Studies carried out on raw coffee grounds show that the material absorbs water [26]. This may be due to the porous surface and low adhesion of the material. This behavior can have adverse effects on mortar performance.

Flexural and Compressive Strength

After 2, 7 and 28 days of immersion, a series of mechanical tests were carried out to assess the evolution of the sample's strength. The results of the bending and compression tests for the different composites are shown respectively in Figures 7 and 8.

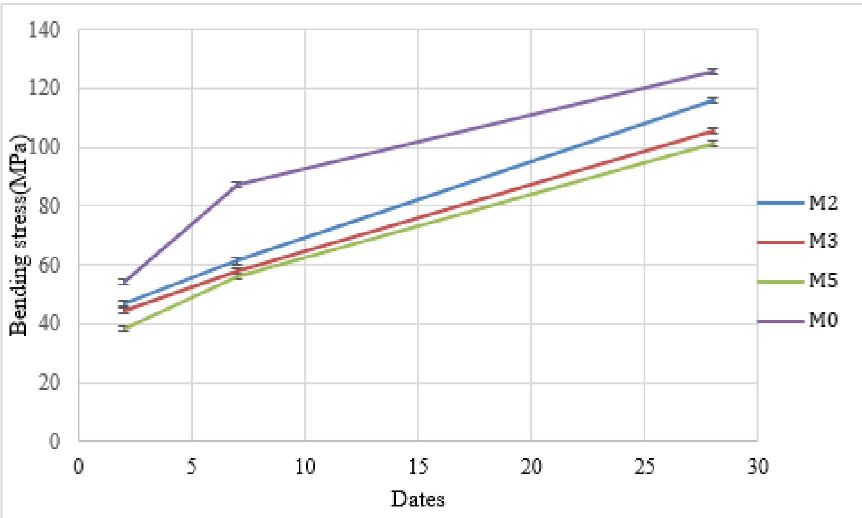

Fig. 7: Flexion strength of mortars for 2, 7 and 28 days

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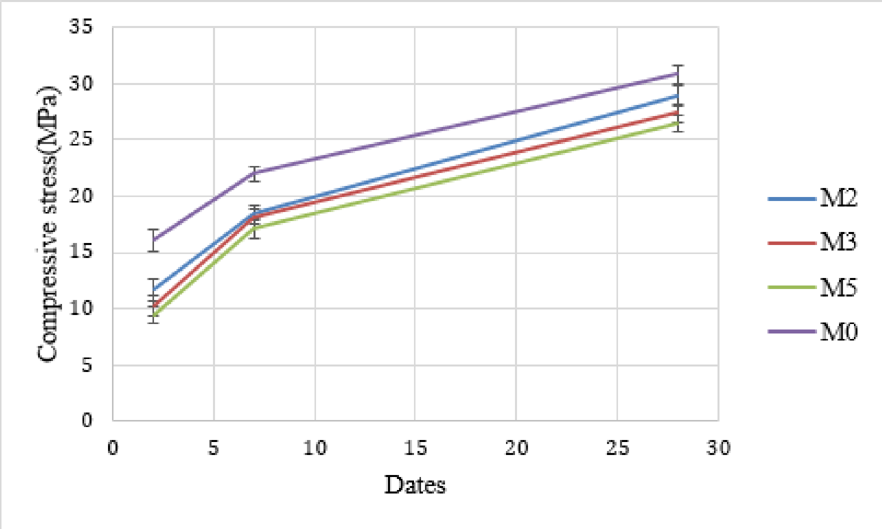

Fig. 8: Compressive strength of mortars for 2, 7 and 28 days

The curves show that the flexural and compressive strength decreases progressively with the rate of replacement of cement by coffee grounds compared with the control mortar. This trend may be linked to the porosity of the different cement mortars containing coffee grounds, which probably contributes to such deterioration in mechanical properties. The same results were obtained by Lin et al. [27] in a study on the use of coffee residues in a mortar mix as a replacement for fine aggregates. In the study by Velasco et al. [28] on the use of coffee grounds in eco-fuel clay bricks, the authors observed a 65% reduction in compressive strength, from 38 to 14 N/ mm2, when 17% coffee grounds were added. According to Quesada et al. [29], the mechanical strength of materials is partly determined by the porosity of the material, although this depends on the thickness of the clay layer. Only the sample containing 3% coffee waste showed a higher strength value, with a 4.8% reduction in bulk density and improved porosity.

In addition, when the coffee grounds content was increased from 2 to 5%, a change in mechanical performance was observed. This factor is linked to the hydration effect of the cement, which favors Portlandite. If the percentage increases from 3 to 5%, these curves tend to decrease. However, the threshold value for coffee grounds in cement mortars is 3%.

CONCLUSION

The use of used coffee grounds as a construction material is attractive because it may provide additional environmental and economic benefits. This study identifies the mechanical properties of cement mortars incorporating coffee grounds as a promising means of reducing this waste in landfill sites and the cost of construction. A series of characterization experiments were carried out with different percentages of coffee grounds (2%, 3% and 5%). Based on the studies carried out, the results showed that replacing cement with coffee grounds increases setting time and water requirements compared with the reference mix. On the other hand, consistency decreases with the level of coffee grounds in all schemes. In addition, compressive strength and flexural strength decreased with the percentage of coffee grounds compared to the control mortar. Nevertheless, the flexural and compressive strength values increase progressively with the dosage of coffee grounds. This parameter is linked to the cement

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hydration reaction, which causes denser calcium silicate hydrate bonds. The most satisfactory results are obtained for a percentage of 3 to 28 days. Although the mechanical performance of these materials is low compared with the reference mortar, their values are acceptable and satisfactory. They can therefore be considered as environmentally-friendly construction materials and used as filling mortar.

Additional studies are underway, such as tomographic analysis to observe cracks and determine pore surface by image analysis.

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