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Spent Coffee Grounds from Touba Coffee (Senegal): Physico-Chemical Characterization and Effect of Partial Cement Replacement on the Mechanical and Thermal Properties of Cement-Based Composites

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ABSTRACT

Spent coffee grounds from Touba coffee, widely consumed in Senegal, are usually landfilled. This study characterized spent coffee grounds collected in Dakar and evaluated the replacement of cement by these grounds, from 5 to 35 % by mass. The grounds had a bulk density of 438 ± 7 kg/m³, an absolute density of 650 ± 27 kg/m³, a natural water content of 15.2 % and a water absorption of 91.7 ± 4.5 % (both relative to the dry mass), and sieving showed a uniform, poorly graded material. Specimens (4 × 4 × 16 cm, three per content) were tested at 28 days. The specimen mass decreased from 493 ± 12 g to 217 ± 6 g between 0 and 35 % replacement. The flexural strength decreased from 7.10 ± 0.41 MPa to 2.23 ± 0.21 MPa at 5 % and was not measurable from 15 %. The compressive strength decreased from 57.3 ± 2.2 MPa to 32.8 ± 0.6 MPa at 5 % and 16.3 ± 0.2 MPa at 10 %, and was nil at 35 %. The thermal conductivity fell from 0.94 to about 0.14 W/m·K. The loss of strength exceeded the reduction of the cement mass, which points to effects other than binder dilution, such as water absorption by the grounds. Raw spent coffee grounds therefore suit non-structural insulating uses rather than load-bearing ones, unless pretreated.

Key words: Spent coffee grounds; Touba coffee; cement replacement; mechanical strength; thermal conductivity; lignocellulosic biomass; Senegal

INTRODUCTION

Brewed coffee is one of the most widely consumed hot beverages worldwide, and the spent coffee grounds (SCG) left after brewing are commonly treated as organic waste and sent to composting plants or to incineration.[1] In Senegal, coffee consumption is increasing, particularly with the advent of Touba coffee, whose preparation generates a significant amount of waste that is usually disposed of in landfills.[2] Touba coffee is a spiced coffee, traditionally prepared from roasted coffee ground with Guinea pepper (*Xylopia aethiopica*, known locally as djar) and sometimes cloves.[3]

SCG is a lignocellulosic residue. A recent chemical analysis of SCG reported 30.2 wt% cellulose, 25 wt% hemicellulose and 12 wt% lignin.[4] This organic and porous nature has led several authors to test SCG in construction products. In lightweight clay ceramic aggregates, 10, 15 and 20 wt% of red clay were replaced by SCG before firing.[1] In fired clay bricks, up to 17 % of SCG could be added while keeping a compressive strength above 10 N/mm², and the thermal conductivity was reduced by up to 50 %.[5] More generally, agricultural wastes have been reviewed as ingredients of sustainable construction materials,[6] and their incorporation in fired clay bricks yields lighter bricks with a lower compressive strength.[7]

In cement-based materials, replacing 2, 3 and 5 % of the cement by SCG from Touba coffee reduced the apparent density and the mechanical performance of mortars, although the values remained acceptable.[2] Raw SCG replacing 2 to 8 % of the cement had an adverse effect on the compressive strength and on the degree of hydration, which was attributed to its organic compounds,[8] and the presence of SCG reduced the compressive strength and delayed hydration with two types of cement.[9] By contrast, SCG modified by hydrothermal carbonization increased the compressive strength of mortar by up to 35 % and improved its thermal insulation by up to 34.7 %.[10]

These studies cover small replacement levels and give little information on the properties of the residue itself. To the authors' knowledge, the physical properties of SCG from Touba coffee have not been documented in detail, and the effect of replacement levels up to 35 % on cement-based composites has not been reported for this residue. The aim of this study was therefore to characterize the density, natural water content, water absorption, particle size distribution, thermal behaviour and crystallinity of SCG from Touba coffee, and to quantify the effect of replacing 5 to 35 % of the cement on the specimen mass, the flexural and compressive strengths and the thermal properties, in order to relate the behaviour of the composites to the properties of the residue.

MATERIALS AND METHODS

Materials

The SCG, the waste recycled in this study, were collected in November 2025 from Touba coffee preparation points of sale in the Parcelles Assainies district of Dakar, Senegal. Because Touba coffee is brewed from a blend of coffee and Guinea pepper,[3] the residue studied here is a mixture of spent coffee and spent spice. The binder was a Portland cement of strength class 32.5 R, and the mixing water was tap water from the public network. *The SCG were stored in the laboratory before testing.*

Characterization of the SCG

The bulk density was determined by reading the volume occupied by 200 g of loose SCG (three tests) and expressed as the mass divided by the volume. The absolute density was determined by volume displacement: the initial volume and the total volume after introduction of 300 g of SCG were recorded, and the density was calculated as the mass divided by the volume change (three tests). *The liquid used for the displacement was water.*

The natural water content was determined by oven drying on two specimens. The SCG were kept for 24 h under ambient laboratory conditions, weighed to 0.01 g, and dried in an oven at 105 °C for 24 h, until two successive weighings differed by 0.01 g or less. The water content w was calculated as the mass of evaporated water divided by the dry mass, expressed as a percentage.

The water absorption was determined on three specimens of 50 g of oven-dried SCG. The specimens were immersed in distilled water at room temperature, removed at intervals (5 min, 10 min, 1 h, 5 h and 24 h), lightly wiped and weighed, until two successive weighings differed by 0.01 g or

less. The water absorption was calculated as the mass of absorbed water divided by the dry mass, expressed as a percentage.

The particle size distribution was determined by dry sieving of a 500 g sample on sieves of 2, 1, 0.63, 0.315, 0.16 and 0.063 mm, after drying at 45 °C for 24 h. D10, D30 and D60, the particle sizes below which 10, 30 and 60 % of the mass passes, were obtained by linear interpolation of the cumulative passing curve on a logarithmic size scale. The coefficient of uniformity Cu = D60/D10 and the coefficient of curvature Cc = $D30^2/(D10 \times D60)$ were then calculated. The particle size distribution was also measured by laser diffraction on two samples.

The thermal behaviour was examined by thermogravimetric analysis coupled with differential thermal analysis and differential scanning calorimetry (TGA-DTA/DSC), and the crystallinity by X-ray diffraction (XRD).

Preparation of the composites

The SCG replaced the cement by mass at 5, 10, 15, 20, 25, 30 and 35 %, and a control without SCG was prepared. The mixtures contained cement, SCG and water only, without sand. The cement and the SCG were first dry-mixed for 2 min, and the water was then added gradually under constant stirring, following the standard procedure for mortar mixing, until a homogeneous, fluid and uniform paste was obtained. The initial water-to-binder mass ratio, the binder being the cement plus the SCG, was 0.40 (663.55 g of water for 1658.87 g of solids per batch). From 25 % of SCG, additional water (168.39, 182.55 and 209.52 g at 25, 30 and 35 %) was added to offset the water absorption of the SCG. The mixtures were cast in standardized prismatic molds of 4 × 4 × 16 cm. The specimens were cured in a humid chamber (20 °C, 95 % relative humidity) and tested at 28 days.

Mechanical tests

The mass of each specimen was recorded before testing, in steps of 10 g. The flexural strength was determined by three-point loading of the prisms resting on two supports, with the load applied at mid-span, and was calculated as $3FL/(2bd^2)$, where F is the maximum load, L the span (100 mm) and b and d the section dimensions (40 mm). The compressive strength was determined at a constant loading rate of 2 kN/s with a mechanical press and was calculated as the maximum load divided by the loaded area of 40 × 40 mm. Three specimens per SCG content were tested in each test. *The specimens were cast in steel molds for 4 × 4 × 16 cm prisms. Both tests were carried out in a mechanical compression press, using a dedicated flexural fixture for 40 × 40 × 160 mm prisms for the three-point bending test and a compression fixture with 40 mm platens for the compressive test.*

Thermal tests

The thermal conductivity and the thermal effusivity were measured by the hot plate method, in transient regime.

Statistical Methods

Results are reported as the mean ± sample standard deviation, and the individual values are shown in the figures. Three specimens were tested for each SCG content, and for the densities and the water absorption of the SCG, and two for the water content. The association between specimen mass and compressive strength was assessed with the Spearman rank correlation coefficient on the 24 specimens. Because the specimen mass and the SCG content vary together, this correlation is descriptive and does not establish causality. Because of the small numbers of replicates and of the zero values at high SCG contents, no inferential comparison between contents was made.

RESULT

Physical properties of the SCG

The bulk density of the SCG was 438 ± 7 kg/m³ (range 430-444 kg/m³, n = 3) and the absolute density, measured by volume displacement, was 650 ± 27 kg/m³ (range 632-682 kg/m³, n = 3) (Table 1, Figure 1A). The natural water content was 15.17 ± 0.30 % of the dry mass (15.38 and 14.96 %, n = 2), which corresponds to 13.2 % of the wet mass (Figure 1B). The water absorption was 91.7 ± 4.5 % of the dry mass (range 87.0-96.0 %, n = 3) (Figure 1C): the SCG could therefore retain nearly their own mass of water.

Table 1: Physical properties of spent coffee grounds from Touba coffee (mean ± sample standard deviation, and range of the individual tests)

Property	Method	n	Mean ± SD	Range
Bulk density (kg/m³)	Volume of 200 g of loose material	3	438 ± 7	430-444
Absolute density (kg/m³)	Volume displacement (300 g)	3	650 ± 27	632-682
Natural water content (% of dry mass)	Oven drying	2	15.17 ± 0.30	14.96-15.38
Water absorption (% of dry mass)	Immersion in distilled water (50 g)	3	91.7 ± 4.5	87.0-96.0

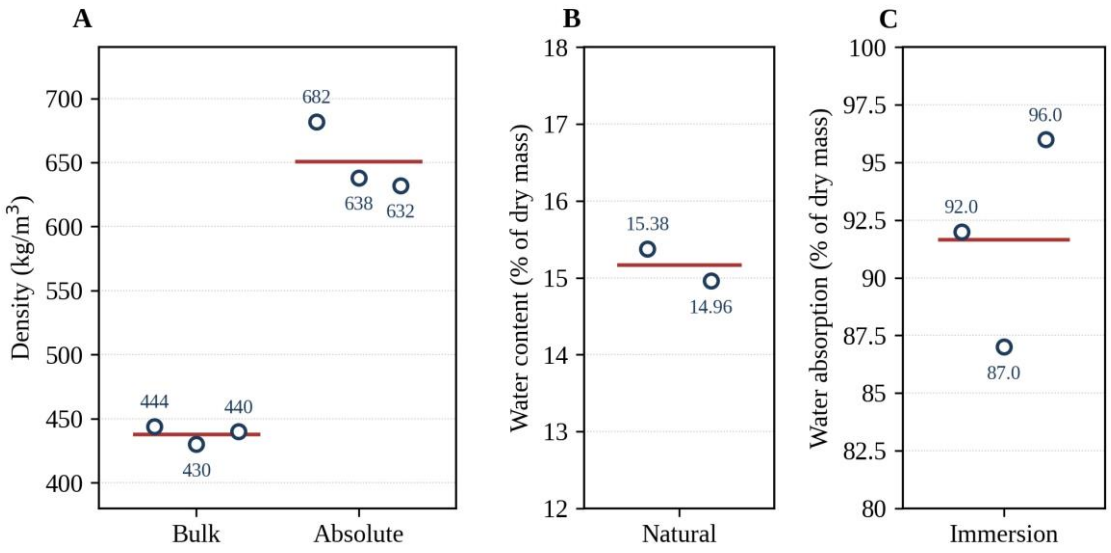


Figure 1: Individual test results for (A) bulk and absolute density, (B) natural water content and (C) water absorption of spent coffee grounds from Touba coffee. Open circles: individual tests; red lines: means.

The sieve analysis (Figure 2) showed that 90.4 % of the SCG passed the 2 mm sieve and only 1.0 % passed the 0.063 mm sieve. D10, D30 and D60 were 0.19, 0.33 and 0.52 mm, respectively, giving Cu = 2.7 and Cc = 1.1 (Table 2). The median size D50 was 0.44 mm. Laser diffraction on two samples gave finer characteristic sizes: Dx10 of about 34 µm, Dx50 of about 320 µm and Dx90 of 750-760 µm (Table 2, Figure 3).

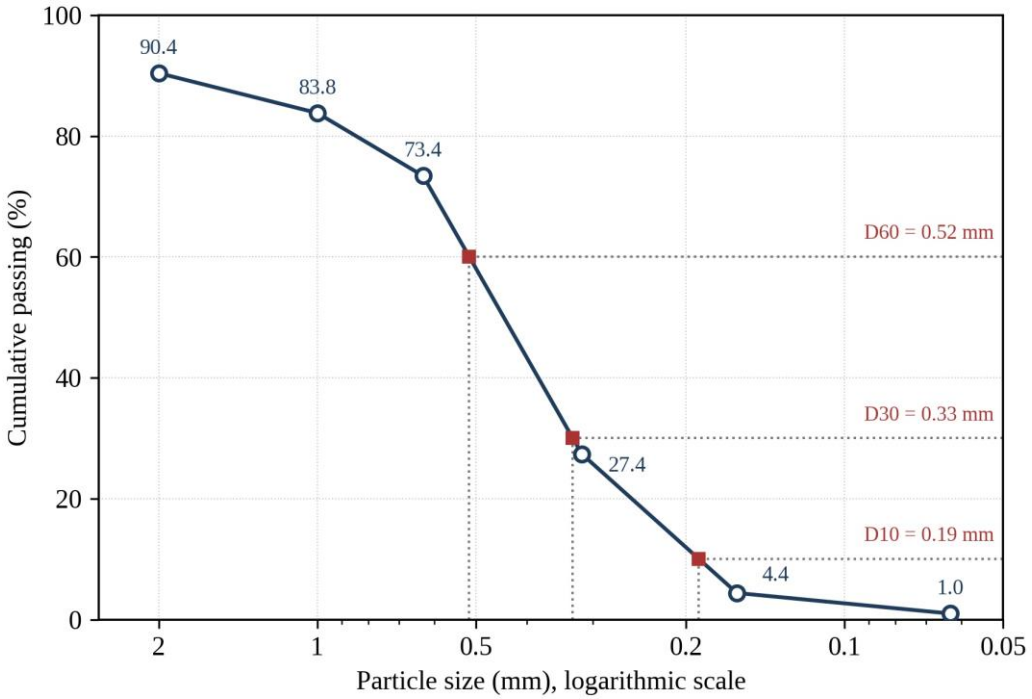


Figure 2: Cumulative particle size distribution of spent coffee grounds from Touba coffee obtained by dry sieving (percentage of the total mass passing each sieve). Red squares indicate D10, D30 and D60, obtained by linear interpolation on a logarithmic size scale.

Table 2: Particle size characteristics of spent coffee grounds from Touba coffee

Method	D10 (mm)	D30 (mm)	D50 (mm)	D60 (mm)	D90 (mm)	Cu	Cc
Dry sieving	0.19	0.33	0.44	0.52	1.9	2.7	1.1
Laser diffraction (n = 2)	0.034	n.a.	0.32	n.a.	0.75-0.76	n.a.	n.a.

n.a.: not available. For laser diffraction, the values are Dx10, Dx50 and Dx90 (volume based).

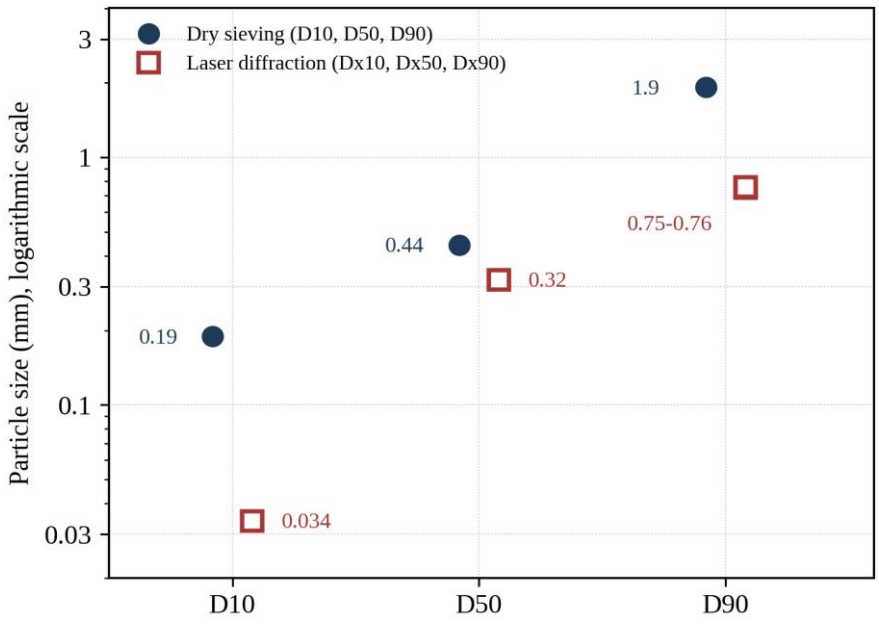


Figure 3: Characteristic particle sizes of spent coffee grounds from Touba coffee obtained by dry sieving (D10, D50, D90) and by laser diffraction (Dx10, Dx50, Dx90). The two laser values for Dx90 are shown as a segment.

The TGA-DTA/DSC analysis showed a multi-stage decomposition (Figure 4). A first mass loss of less than 10 % occurred between 25 and 150 °C and was attributed to the evaporation of free and adsorbed water. A marked mass loss between 200 and 350 °C was attributed to the decomposition of hemicellulose and to the onset of cellulose pyrolysis, the main decomposition of cellulose occurred between 300 and 450 °C, and a slow decomposition of lignin between 400 and 600 °C led to a carbonaceous residue. These ranges are consistent with the temperature ranges reported for the pyrolysis of hemicellulose (220-315 °C) and cellulose (315-400 °C), lignin decomposing over a broad range. [11,12]

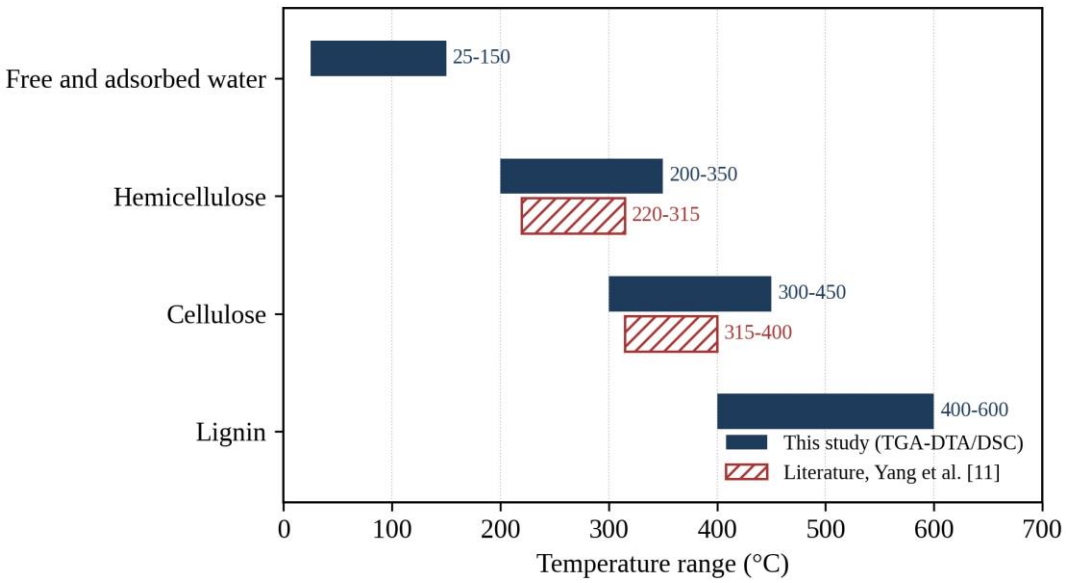


Figure 4: Temperature ranges of the mass-loss stages observed by TGA-DTA/DSC for spent coffee grounds from Touba coffee (this study) and ranges reported for the pyrolysis of hemicellulose and cellulose in the literature. The bars show ranges, not thermogram curves.

The X-ray diffractogram showed broad peaks, with a broad maximum around 2θ = 22.5° and a sharper peak near 2θ = 35°, which indicates a low degree of crystallinity, consistent with the predominantly amorphous organic matrix of a lignocellulosic residue.

Specimen mass

The specimen mass decreased steadily with the SCG content, from 493 ± 12 g for the control to 460 ± 0 g at 5 %, 400 ± 0 g at 10 % and 217 ± 6 g at 35 %, that is 44 % of the control mass (Table 3, Figure 5).

Table 3: Specimen mass and mechanical strength at 28 days as a function of the spent coffee grounds (SCG) content (mean ± sample standard deviation, n = 3)

SCG content (%)	Specimen mass (g)	Flexural strength (MPa)	Compressive strength (MPa)	Compressive strength (% of control)
0	493 ± 12	7.10 ± 0.41	57.3 ± 2.2	100.0
5	460 ± 0	2.23 ± 0.21	32.8 ± 0.6	57.2
10	400 ± 0	0.16 ± 0.02	16.3 ± 0.2	28.5
15	340 ± 0	n.m.	5.2 ± 0.7	9.0
20	293 ± 12	n.m.	2.4 ± 0.2	4.2
25	260 ± 0	n.m.	0.75 ± 0.07	1.3
30	240 ± 0	n.m.	0.04 ± 0.01	0.1
35	217 ± 6	n.m.	0	0.0

n.m.: not measurable (maximum load recorded as zero).

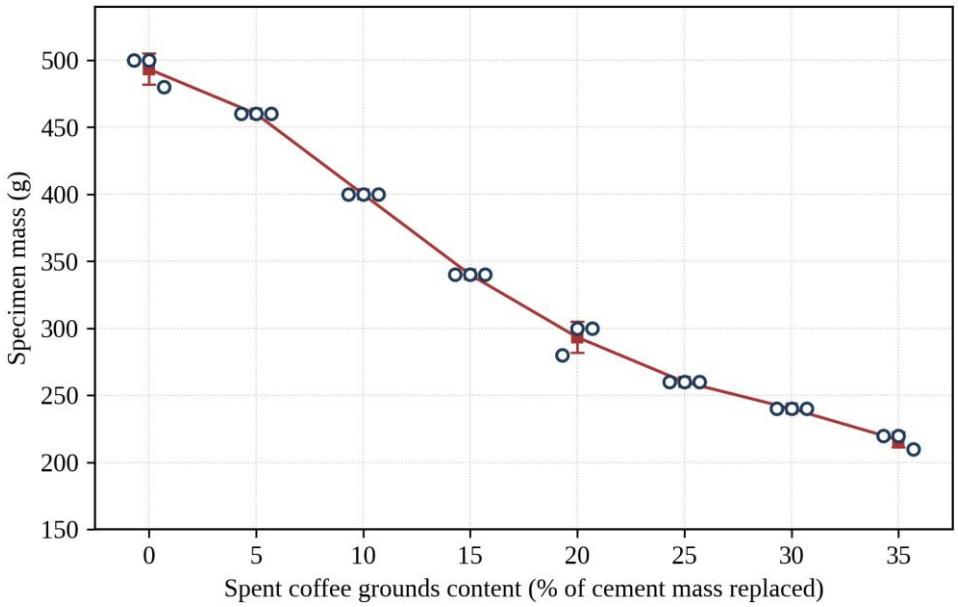


Figure 5: Mass of the specimens as a function of the spent coffee grounds (SCG) content. Open circles: individual specimens; red squares and bars: mean ± sample standard deviation.

Flexural and compressive strengths

The flexural strength of the control was 7.10 ± 0.41 MPa. It decreased to 2.23 ± 0.21 MPa at 5 % and 0.16 ± 0.02 MPa at 10 % SCG, and it was not measurable from 15 %, the recorded load being zero (Table 3, Figure 6A). The compressive strength of the control was 57.3 ± 2.2 MPa. It decreased to 32.8 ± 0.6 MPa at 5 % (57.2 % of the control), 16.3 ± 0.2 MPa at 10 % (28.5 %), 5.2 ± 0.7 MPa at 15 %, 2.4 ± 0.2 MPa at 20 % and 0.75 ± 0.07 MPa at 25 %, then 0.04 ± 0.01 MPa at 30 %, and was nil at 35 % (Table 3, Figure 6B).

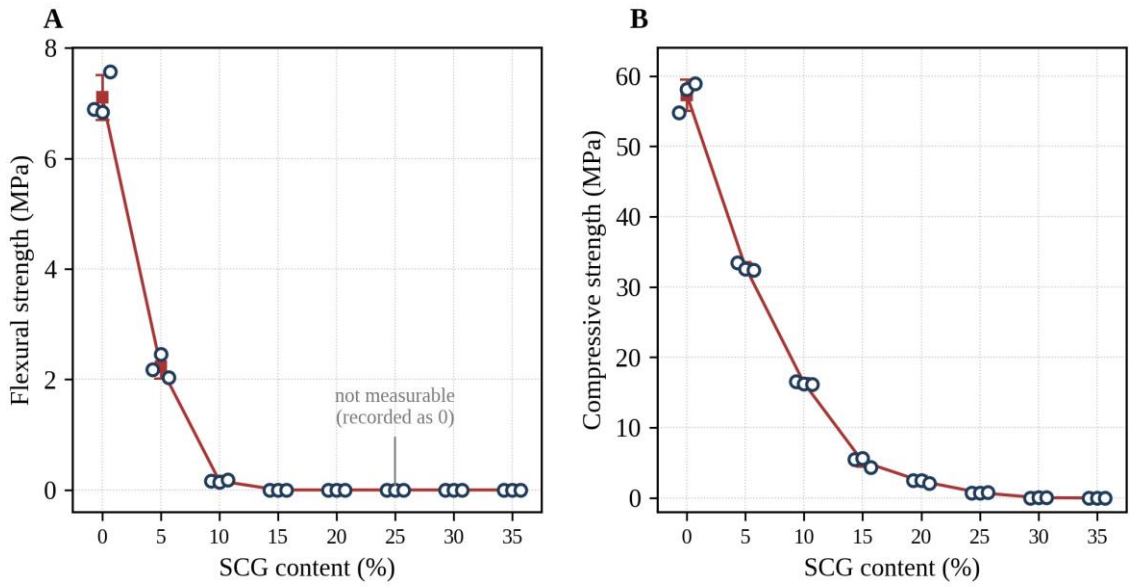


Figure 6: Flexural strength (A) and compressive strength (B) at 28 days as a function of the spent coffee grounds (SCG) content. Open circles: individual specimens; red squares and bars: mean ± sample standard deviation.

The compressive strength was strongly and monotonically associated with the specimen mass (Spearman ρ = 0.99, n = 24) (Figure 7). A loss of 6.8 % of the specimen mass at 5 % SCG was already accompanied by a loss of 42.8 % of the compressive strength.

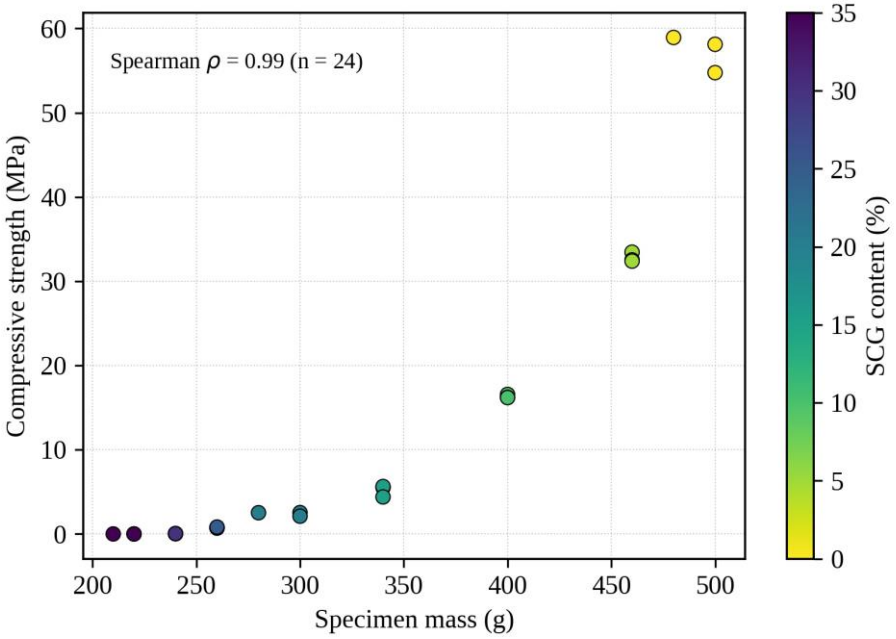


Figure 7: Compressive strength as a function of the specimen mass for the 24 specimens. The colour indicates the spent coffee grounds (SCG) content.

Thermal properties

The thermal conductivity decreased from 0.94 W/m·K for the control to 0.34 W/m·K at 10 % SCG and stabilized around 0.14 W/m·K from 30 %. The thermal effusivity decreased from about 1400 $W \cdot K^{-1} \cdot m^{-2} \cdot s^{1/2}$ for the control to about 900 at 5 % and about 400 at 35 % SCG (Figure 8).

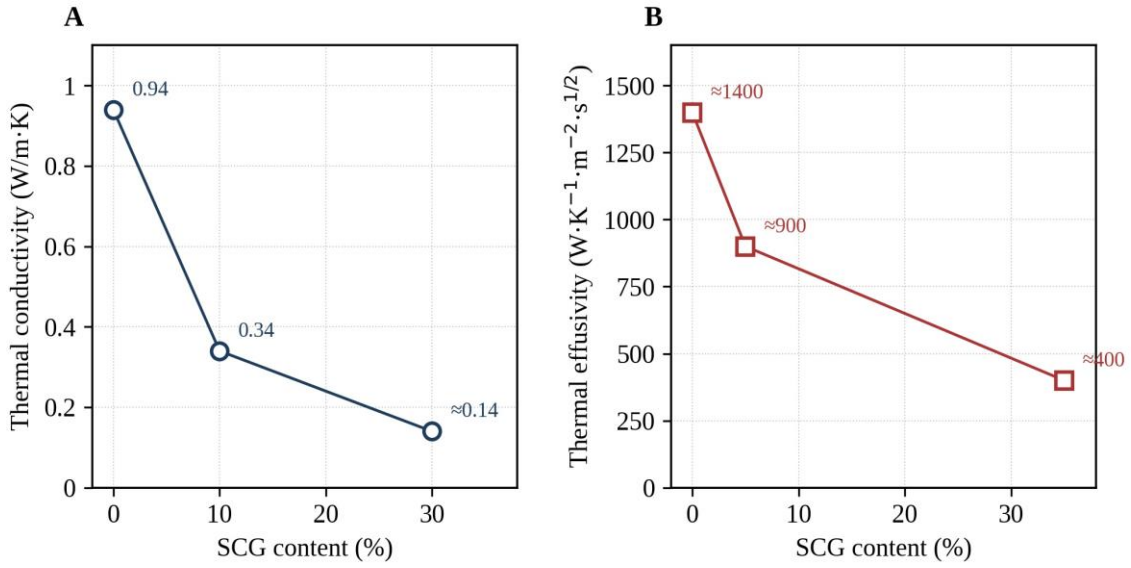


Figure 8: Thermal conductivity (A) and thermal effusivity (B) as a function of the spent coffee grounds (SCG) content. Symbols: reported values; the lines join the reported points only.

DISCUSSION

The SCG are a light, uniform and highly absorbent residue. The bulk density of 438 kg/m³ and the ratio between the bulk and absolute densities (0.67) indicate that about one third of the bulk volume is occupied by voids between particles, if the absolute density is taken as the particle density. This interpretation must be made with caution, because a density measured by volume displacement is lower than the density of water and may be affected by air trapped between and inside the particles; a skeletal density measured by helium pycnometry would be needed. The natural water content of 15.17 % is far below the water absorption of 91.7 %, so that the SCG, even in their natural state, could still take up about 76 g of water per 100 g of dry mass. The natural water content depends on the drying history: freshly collected SCG contained 65 wt% of water and 7 wt% after 48 h of drying at about 20 °C,[1] both on a wet mass basis, whereas the SCG studied here contained 13.2 % on the same basis, which is comparable to an air-dried residue.

The SCG are also a poorly graded, sand-size residue: about 63 % of the mass lies between 0.315 and 2 mm. By analogy with the Unified Soil Classification System, a coefficient of uniformity below 6 corresponds to a poorly graded granular material; this classification was developed for mineral soils and is used here only as an indicative descriptor. The laser diffraction sizes are finer than the sieve sizes, which may reflect the different measurement principles (a sieve aperture and a volume-equivalent sphere) and the dispersion of agglomerates; both sets of values are reported pending clarification of the dispersion conditions.

The loss of strength of the composites cannot be explained by the dilution of the binder alone. At 5 % replacement, the cement mass was reduced by 5 % whereas the compressive strength was reduced by 42.8 %, and at 10 % the cement mass was reduced by 10 % whereas the compressive strength was reduced by 71.5 %. Other effects must therefore contribute. The high absorption capacity of the SCG compared with their natural water content may make part of the mixing water unavailable to the cement, the organic compounds of the SCG may disturb hydration, (8, 9) and the lower specimen mass indicates a more porous and less dense matrix, which was strongly associated with the compressive strength. The present data do not allow these contributions to be separated, and hydration and microstructure analyses (calorimetry, scanning electron microscopy, porosimetry) are needed.

These findings are consistent with the literature on raw SCG in cement-based materials. Thiam et al. [2] reported lower apparent density and mechanical performance for 2 to 5 % replacement of the cement by SCG from Touba coffee, and Chen et al. [8] and Pushpan et al. [9] also observed lower compressive strength with raw SCG. In the present study the strength loss became severe at higher contents, with no measurable flexural strength from 15 % and no compressive strength at 35 %. The comparison is qualitative, because the binders, mixes and specimens differ between studies. Fired clay bricks tolerate larger SCG contents (up to 17 %),[5] which may be related to the decomposition of the organic matter during firing, since the TGA results show that the organic matter decomposes between 200 and 600 °C. By contrast, SCG modified by hydrothermal carbonization increased the compressive strength of mortar,[10] which suggests that a pretreatment of the SCG is a promising way to overcome the negative effect of the raw residue.

The thermal conductivity decreased by about 85 % between the control and 30 % SCG, which shows the insulating potential of the residue. At 10 % replacement, the composite retained a compressive strength of 16.3 MPa while its conductivity was reduced by about 64 %, so that this range appears the most interesting for non-

structural insulating elements. This suggestion requires confirmation with a complete thermal dataset. The main limitations of the study are the small number of specimens (three per content), the incomplete description of the mixes and of some test conditions, the recording of the specimen mass in steps of 10 g, the incomplete thermal dataset, the absence of microstructural analysis, and the presence of spent spice in the residue. Future work should add the chemical composition of the SCG, microstructural and hydration analyses, a skeletal density measurement, a comparison with SCG from plain coffee, and the pretreatment of the SCG.

CONCLUSION

Spent coffee grounds from Touba coffee in Senegal are a light, uniformly graded, sand-size lignocellulosic residue with a bulk density of 438 kg/m³, an absolute density of 650 kg/m³, a natural water content of 15.2 % and a water absorption of 91.7 %. Replacing cement by these grounds at 5 to 35 % reduced the specimen mass and the strength steeply, with no measurable flexural strength from 15 % and no compressive strength at 35 %, whereas the thermal conductivity fell from 0.94 to about 0.14 W/m·K. The loss of strength exceeded the reduction of the cement mass, which points to effects other than binder dilution. Raw spent coffee grounds are therefore better suited to non-structural insulating uses at low replacement levels than to load-bearing elements, and their pretreatment is a promising direction.

Declaration by Authors

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