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Study of Recycled Spent Coffee Grounds as Aggregates in Cementitious Materials

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Abstract

Most spent coffee grounds (SCGs), a byproduct of brewing coffee, are buried in landfill sites, and their decomposition produces significant greenhouse gases. As the recent warming of the Earth's climate has made it imperative that industries reduce greenhouse gas emissions, the present study investigates the viability of recycling SCGs for use as a partial replacement of aggregates in concrete materials. Cement mortar samples with a fixed cement-to-water ratio and varying amounts of SCGs were fabricated and tested. Mechanical strength tests revealed that an appropriate amount of SCGs can improve compressive strength. However, since strength deterioration was also observed in samples with too much or too little SCG content, finding the optimal amount is necessary for implementation. The samples' thermal conductivity decreased as the amount of SCGs increased, capturing the effective insulating substance of air within the SCGs' porous structure. The increased insulating capacity of concrete materials resulting from the addition of SCGs could be beneficial in terms of a building's lifecycle cost and carbon emissions. Thus, the SCGs once disposed of in landfills to emit greenhouse gases can be transformed into an appealing and eco-friendly building material if the proper concrete mix ratio is used.

Keywords

Spent coffee grounds (SCGs); coffee waste; eco-friendly concrete material; building material; mechanical and thermal properties

1. Introduction

Coffee is one of the most common and widely consumed beverages in the world, and its consumption is continuing to increase. Spent coffee grounds (SCGs) are organic waste produced by the coffee brewing process [1]. In general, a single cup of coffee yields almost double the amount of wet SCGs. As a result, approximately 7.4 million tons of SCGs are generated annually worldwide [2]. The rapid increase in the amount of SCGs is unsurprising, given the fast-growing coffee business around the world. SCGs are organic compounds that require a substantial volume of oxygen to decompose their organic structure. Due to this organic composition, SCGs produce excessive amounts of greenhouse gases such as carbon dioxide (CO_2) and methane (CH_4) during the decomposition process. Also, caffeine, tannins, and poly-phenols in SCGs are highly toxic to the environment [3-5]. Therefore, the disposal of SCGs has become a globally recognized environmental and economic issue.

The conventional discharge of SCGs in landfills is accompanied by several environmental issues such as the acidification of soil and the emission of greenhouse gases into the atmosphere. In the last several decades, a number of studies have investigated more eco-friendly ways of disposing of SCGs. McNutt and He [6] conducted a comprehensive literature review regarding the potential utilization of SCGs in various industries. According to their findings, SCGs can be used as energy sources [7-9], phenolic compounds and antioxidants [10, 11], fertilizer [12, 13], subgrade filler material [14], composite materials [15], and adsorptive filters [16]. Of those potential utilizations, several studies proposed ways of recycling SCGs in construction materials such as ceramics, concrete, and mortar. Such notions are appealing since SCGs encapsulated in construction materials become inactive and neutralized, resolving the related environmental issues.

Eliche-Quesada et al. [17] studied the viability of using SCGs in clay brick production. In that study, clay bricks were fabricated with various SCGs ratios ranging from 0 to 5 wt-% through dry (110°C for 48 hours) and heated (950°C for 24 hours) processes. The authors investigated changes in compressive strength and insulation capacity based on the amount of SCGs in the clay brick samples. Scanning electron microscopy (SEM) image analyses revealed that open-cell porosities formed in the samples with 1 to 2 wt-% SCGs, resulting in low thermal conductivity. Conversely, increased insulation capacity was observed in bricks with higher SCG ratios (i.e., 3 to 5 wt-%), where closed-cell porosities were found. Although bricks with 3 wt-% SCGs showed the highest compressive strength, no consistent trend was observed as a function of the amount of SCGs, since more SCGs in the bricks sometimes either increased or decreased the compressive strength. Based on the experimental results, the authors concluded that clay bricks with 3 wt-% SCGs offered optimal results in terms of mechanical, physical, and thermal properties.

Another experimental study on ceramic materials with SCGs was conducted [3] in which the authors investigated the mechanical and physical properties of clay mixtures with 0, 5, 10, 15, and 20 wt-% of SCGs, as well as the resulting plastic behaviors (both workability and extrudability). Additionally, three different temperatures (i.e., 900°C, 1,000°C, and 1,100°C) were taken into account to evaluate the effect of firing temperature. Mechanical strength tests showed linearly decreasing trends in compressive strength and modulus of rupture in ceramic samples with increasing amounts of SCGs. This trend was not quite the same as what was observed by Eliche-Quesada et al. [17] because the SCG ranges in this test were not designed to capture differences in samples with 0 and 5 wt-% of SCGs. Note that in Eliche-Quesada et al. [17], samples with 3 wt-% of SCGs showed the highest mechanical properties, and more SCGs led to strength deterioration. With no exception, higher firing temperatures led to stronger mechanical strengths but lower thermal insulating properties, due to the reduced apparent porosity. The high absorption capacity of SCGs resulted in improved mixture extrudability but worsened workability. Thermal insulation properties were significantly improved by increasing the amount of SCGs. Based on the test results, it was concluded SCGs could be incorporated into ceramic brick production, providing acceptable mechanical and physical properties and improved thermal insulation performance. The authors suggested that 5 to 10 wt-% of SCGs would be an ideal ceramic-SCG mixture offering the best compromise between physical and mechanical properties.

Guendouz and Boukhelkhal [18] explored the possibility of incorporating SCGs into dune sand concrete. In that study, SCGs were used as a fine aggregate to replace sand in dune sand concrete mixes. The SCGs were mixed with sand, cement, fillers, water, and plasticizer to manufacture dune sand concrete at several volumetric ratios to the sand (i.e., 0%, 5%, 10%, 15%, and 20%). The authors evaluated the effects of the amount of SCGs on the physical, mechanical, and thermal properties of the dune sand concrete. Their experiments demonstrated decreases in workability, bulk density, and compressive strength by increasing the SCGs. However, substantial improvement in thermal insulation performance was also observed. Based on this observation, the authors concluded that dune sand concrete with SCGs could be used as a cost-effective and eco-friendly insulating material. Although this study suggested the possibility of using SCGs in concrete material, further research is necessary to investigate the effects of small amounts of SCGs (between 0% and 5% volumetric ratio to aggregates) on concrete’s mechanical properties.

Na et al. [19] explored the feasibility of using spent coffee grounds in cement mortars. The authors performed an experiment with different weight ratios of SCGs to cement (0%, 1.0%, 1.5%, 5.0%, and 10.0%) to evaluate the effect on the compressive strength of cement mortars. In that study, SCGs were transformed into activated carbon through a physical carbonization process (heated at 600°C for one hour in a muffled furnace). The test showed that cement mortars with activated carbon less than 1.5 wt-% not only had higher early strength but also improved compressive strength as compared to a control specimen with no activated carbon. The authors presented the potential of using SCGs as an alternative filling material to sand in cementitious materials; however, this may not be an eco-friendly and cost-effective solution for disposing of SCGs, given that the physical carbonization process requires substantial energy to transform the SCGs into activated carbon.

Park et al. [20] investigated the recycling of SCGs as construction materials by maximally utilizing the acid characteristics of SCGs. The authors hardened SCGs using animal glue, starch, and red clay and conducted strength, durability, and pH tests. An unconfined compression test revealed that the strength of SCG samples can be significantly differed by binding materials; the animal-glued SCG samples showed unconfined compressive strength (UCS) of 2.5 MPa while the starch and red clay-treated SCG samples had around 0.2 MPa UCS. Similar trends were also obtained in the durability test. The animal glue-red clay-treated SCG samples showed the highest acid value (4.91) which could neutralize the cement whose pH value is 12.6. The authors concluded that the use of properly bound and treated SCGs for underground structures can prevent groundwater from alkalization found when they contact with cement-based structures.

Also, several studies have investigated the use of SCGs as nonstructural construction materials. For example, Suksiripattanapong et al. [21] studied the strength and microstructure properties of SCGs stabilized with rice husk ash and slag geopolymers to use for pavement construction materials. Moussa et al. [22] examined mechanical, thermal insulation, and sound absorption performance of SCGs bound with potato starch and concluded that this biocomposite can be an effective insulating and acoustical material with sufficient compressive strength to be used as non-bearing building materials.

The abovementioned works underscore the possibility of using SCGs in several types of construction material. However, the heating process when manufacturing clay bricks and activated carbon using SCGs inevitably produces greenhouse gases. Also, no clear agreement has been made regarding the effects of SCGs on mechanical strength. The present study focused on investigating the feasibility of incorporating SCGs into concrete materials without additional heating, producing a more eco-friendly recycling system. An experimental program was also designed to capture changes in concrete materials' physical properties as varied by SCG amounts within specific ranges. By supplementing the shortcomings and gaps seen in the aforementioned studies, SCGs can be more broadly recycled for use in construction materials, contributing to solving current global environmental issues and bringing economic benefits, as well.

2. Research Significance

The recent warming of the Earth's climate has brought global attention to reducing greenhouse gases. It is an inevitable worldwide trend that all kinds of industries should focus on environmental sustainability. Given that approximately 39% of the global carbon dioxide (CO_2) emissions is ascribed to the building construction industry (28% for building operations and 11% for building materials and construction, according to the 2019 Global Status Report for Buildings and Construction [23]), it is clear that the use of eco-friendly construction materials could contribute enormously to decreasing greenhouse gas emissions. This study investigated the feasibility of incorporating SCGs into concrete materials. SCGs are organic waste produced by the coffee brewing process and amount to as much as 7.4 million tons each year worldwide [2]. Although various studies have explored efficient ways of recycling such organic waste, most SCGs are still disposed of in landfills, increasing CO_2 emissions and soil acidification. Several experimental studies have shown that cementitious materials with SCGs improve thermal insulation capacity; however, the effect on mechanical properties is still questionable, as no consistent test results have been reported [3, 17, 18]. If SCGs added to cement mortar have mechanical properties equivalent to conventional mortar, they could be used as a construction material, with numerous benefits such as: 1) reducing CO_2 emitted from the disposition process of organic waste, 2) saving energy for cooling and heating, thanks to the improved thermal insulation capacity, 3) reducing the use of limited natural resources employed as fine aggregates (e.g., sand), and 4) bringing economic benefits by using abundant and nearly cost-free materials.

3. Experimental Test Program

A series of cement mortar compositions were prepared and tested at the Texas A&M Transportation Institute Center for Infrastructure Renewal Laboratory. The present study explored the effects of spent coffee grounds on the material properties of mortar samples, in terms of: a) compressive strength, b) thermal conductivity, c) formation of porosity (i.e., water absorption capacity), and d) concrete surface topography and composition. Thus, the experimental program included a compressive strength test, thermal conductivity test, porosity test, and SEM image analysis.

Cement mortar specimens were fabricated with various SCG ratios. Portland cement was mixed with water to a water-to-cement weight ratio (w/c) of 0.44, in order to achieve complete hydration (Note that $w/c > 0.38$ is generally needed for full hydration.). A commercially available washed coarse sand meeting ASTM C 33 [24] specifications was used as the aggregate. SCGs were collected from a Starbucks coffee shop near Texas A&M University's College Station campus. Based on ASTM C 109 [25], a cement-to-sand weight ratio of 2.75 was used for a control sample with no SCGs. For specimens with SCGs, some sand portions were replaced with SCGs while maintaining the same cement weight, resulting in different cement-to-sand weight ratios. When determining the amount of SCG filling reduced sand, the volume ratio to the sand was used instead of the weight ratio in order to consider significant differences in bulk density between the sand (1.522 g/cm^3) and SCGs (0.332 g/cm^3).

The weight ratios of the SCGs to cement for each specimen were determined based on previous experimental studies. Several tests showed that adding SCGs (or carbonated SCGs) to around 1.5% of ceramic or cement weight increased the maximum compressive strength. However, a significant strength drop was observed when SCGs (or carbonated SCGs) over 3.0 wt-% of ceramic or cement were added. Therefore, SCG ratios of 0.6, 0.9, 1.8, 3.0, and 6.0 wt-% of cement were used in this study to capture any changes in mechanical properties that might take place between 0.5% and 3.0% SCGs of cement weight. Also, cement mortar samples with no SCGs were used as control specimens. An excessive amount of SCGs (6 wt-% of cement weight) was selected to investigate stark contrasts in strength, thermal conductivity, and formation of porosity, even though significant strength deterioration was also expected. Note that SCG weight ratios to cement weights of 0.6%, 0.9%, 1.8%, 3.0%, and 6.0% corresponded to sand volumetric replacement ratios of 1.0%, 1.5%, 3.0%, 5.0%, and 10.0%, respectively. Table 1 presents the weight ratios of the mix design for each cement mortar sample.

Table 1 Weight ratios of cement mortar samples.

Material	Density (g/cm^3)	Weight Ratio (per cement)
Portland cement	1.494	1
Water	0.997	0.44
Sand	1.522	2.75, 2.72, 2.70, 2.66, 2.61, 2.47
SCG	0.332	0, 0.006, 0.009, 0.018, 0.030, 0.060 (= 0%, 1%, 1.5%, 3%, 5%, 10% substitution of aggregates volume)

Portland cement, sand, and SCGs were oven-heated at 100°C for 24 hours before mixing. Fifty-four cube specimens (50 × 50 × 50 mm) for the material properties test and six-cylinder specimens (ϕ30 mm × 10 mm) for SEM image analysis were cast on the same day (see Figure 1).

Figure 1 Preparation of cube and cylinder samples.

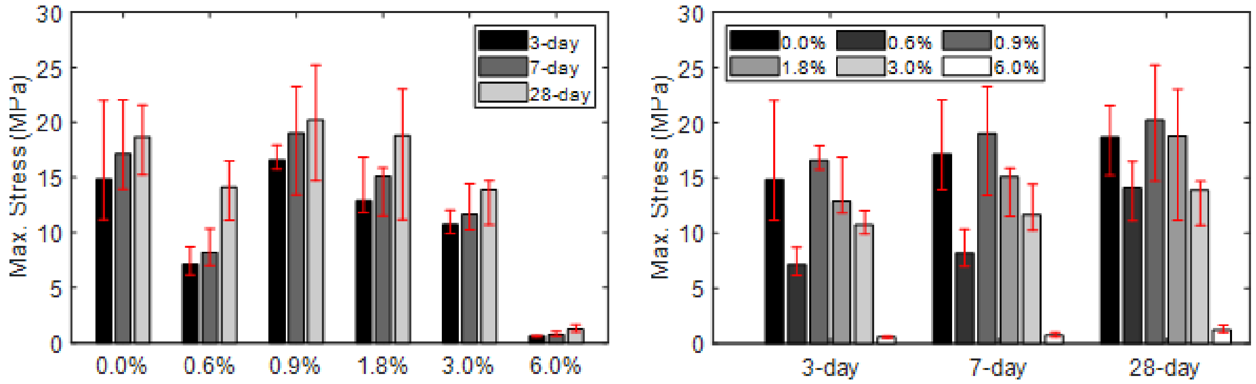
Although slumps were not recorded, cement mortar mixtures with 0% to 3.0% SCGs showed enough workability for molding. In the mixture with 6.0% SCGs, significantly reduced workability was noticeable, due to the high hygroscopic property of the SCGs. As soon as water was mixed with the sand, Portland cement, and SCGs, it was rapidly absorbed into the SCGs. The mixture then became very dry and stiff, leading to difficulties with molding. Other samples with less than 6% SCGs did not show such a rapid water absorption property and maintained sufficient workability. The present study considered cement mortar mixtures with a fixed cement-to-water ratio but different ratios of aggregates (both sand and SCGs). Given that SCGs can significantly influence the cement-to-water ratio, a further study varying the cement-to-water-to-sand ratio should be conducted to investigate cement-to-water ratios that can accommodate higher SCG ratios without compromising strength and workability.

All samples were cured in the curing room before testing at a constant temperature of 80°C with 50% relative humidity. Compressive strength was measured at 3, 7, and 28 days, and the other material properties such as thermal conductivity and water absorption capacity were measured at 28 days. The details regarding each test are provided in the following discussion.

4. Test Results and Discussion

4.1 Compressive Strength

Compressive strength tests were conducted using the universal testing machine for 3-, 7-, and 28-day aged mortar cube samples. All samples were cured in the same conditions before being tested. The applied load was gradually increased at 1,335 N/s in accordance with ASTM C 109 [25], which specifies the lower and upper load rates to a range of 900 to 1,800 N/s. Three samples for each SCG ratio were tested on the designated test date. Figure 2 presents the averages of three test values with error bars ordered by (a) SCG ratio and (b) curing days.



(a) by SCG ratio

(b) by curing day

Figure 2 Comparison of mortar sample compressive strengths.

As shown in Figure 2 (a), the compressive strengths of all specimens gradually increased by aging over time. Except for a few cases, early age strength trends observed in the 3- and 7-day tests were generally consistent with the 28-day strengths, which were 0.9%, 0.0%, 1.8%, 3.0%, 0.6%, and 6.0%, from highest to lowest. Surprisingly, samples with 0.6% SCGs (the least) showed a significant strength deterioration compared to the control samples (i.e., 0% SCGs). For all curing days, the 0.6% SCG samples displayed the weakest compressive strengths, except for the 6% SCG samples. However, adding more SCGs resulted in certain differences. 1) Samples with 0.9% SCGs showed the highest compressive strength of all specimens, regardless of curing days. 2) The 1.8% SCG samples showed maximum stresses almost identical to those of the control samples. More than 1.8% SCGs of cement weight in the mortar samples accelerated the deterioration of the compressive strength, as a) 3.0% SCG samples showed reduced compressive strength compared to control specimens and 1.8% SCG samples, and b) almost no resistance was found in the 6.0% SCG samples.

The improved or nearly equivalent compressive strengths of samples with 0.9% and 1.8% SCGs (despite the same cement-to-water ratio) could be due to the high water-absorption property of SCGs. An appropriate amount of SCGs reduced the amount of water but still allowed for a full hydration reaction between the cement and water, resulting in harder concrete. Conversely, due to the substantial reduction of water in the 6% SCGs, a chemical hydration reaction was not fully achieved, leading to significantly reduced strength. Reduced workability due to the water absorbed during the sample fabrication process has already been discussed above. This observation reveals that the use of high SCG ratios over 3.0% to cement weight should be avoided unless ways emerge to secure full hydration and sufficient workability.

The compressive strength test of the mortar cubes with various SCG ratios showed results similar to those of Eliche-Quesada et al. [17]; no clear trend was found between the strength and SCG amount. A direct comparison would not be appropriate because Eliche-Quesada et al. [17] tested clay materials rather than cement mortar; however, it is worth noting that both tests revealed that the amount of SCGs could increase the mechanical properties of cementitious materials.

4.2 Thermal Conductivity

Thermal conductivity, defined in terms of the heat flow across a temperature difference, indicates the magnitude of a material's ability to conduct heat. Thermal conductivity is closely related to energy efficiency in buildings, as cooling and heating comprise up to 40% of a building's energy consumption [23]. Building materials with low thermal conductivity are advantageous to maintaining indoor temperatures with less energy loss, whereas those with high conductivity are not effective at saving energy. In previous studies [17], cementitious materials mixed with SCGs showed improved insulation capacity, due to the open porosity of the material. It is worth investigating whether SCGs in concrete could offer the same benefit. Of the various methods and techniques, thermal conductivity can be experimentally determined using: 1) temperature differences between hot and cold surfaces of specimens, 2) thicknesses of specimens, and 3) the area of a specimen when a steady state is accomplished [26]. In the present study, a simplified equation [17] was adopted to measure the thermal conductivity of the mortar samples:

$$k = h_c b \left[\left(\frac{T_1 - T_{amb}}{T_1 - T_2} \right) - 1 \right] \tag{1}$$

where k = thermal conductivity, b = thickness of the mortar sample, T_1 = temperature of the mortar sample's hot surface (assumed to be equal to the steel plate temperature), T_{amb} = ambient temperature, T_2 = temperature of the mortar sample's cold surface, and h_c = air convection coefficient (10 WmK^{-1} herein).

All dried mortar samples were placed on a single heated steel plate. Temperatures were measured using a thermometer when the steel plate cooled to a specific level. Note that the concrete surface in direct contact with the steel plate was assumed to have the same temperature as the steel plate (i.e., the hot surface), and the opposite surface parallel to the contacting face was taken as a cold surface. The calculated thermal conductivity values using the measured temperature data for all mortar samples are plotted as the black line with a square symbol in Figure 3.

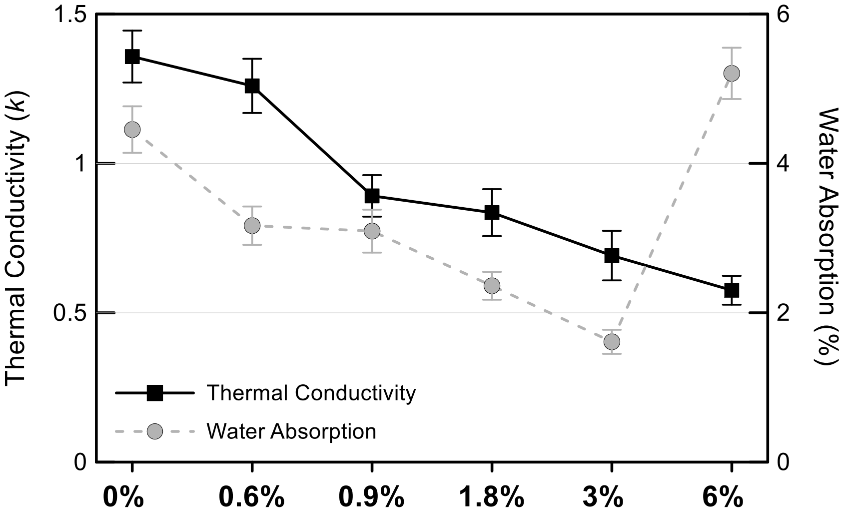
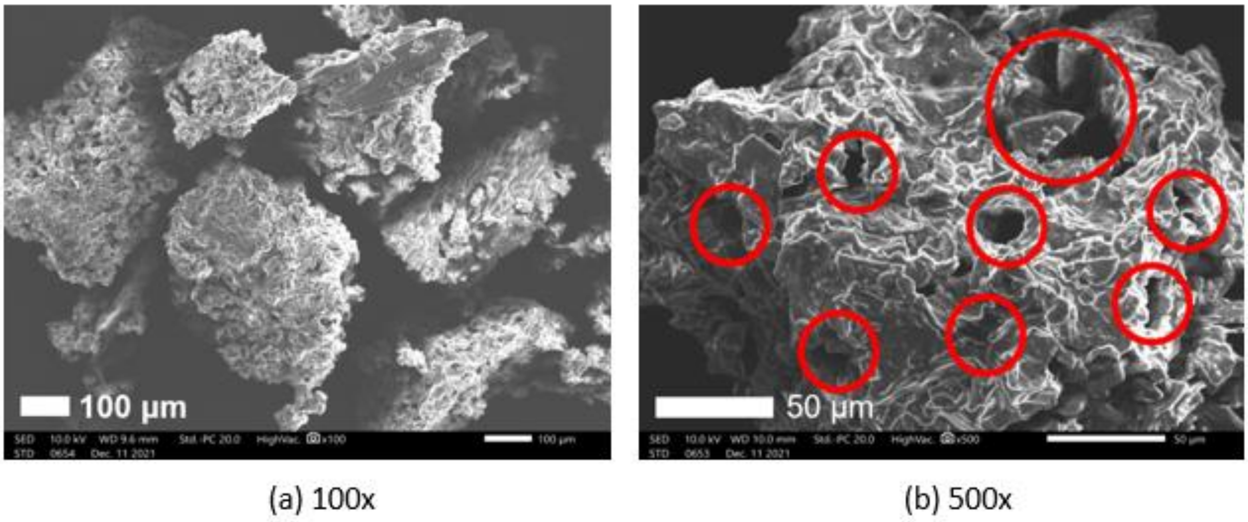


Figure 3 Thermal conductivity and water absorption.

As shown in the figure, without exception, thermal conductivity tended to decrease as the mortar samples' SCG content increased. Given that the inverse of thermal conductivity is thermal insulation capacity, concrete containing SCGs could be advantageous over regular concrete with regards to conserving building energy used for cooling and heating by acting as an effective insulator. The excellent performance of SCGs as an insulation material is also reported in [22]. The decreasing trend of thermal conductivity by SCG amount can be ascribed to the open-porosity structure of the microscopic particles comprising the mortar samples. SCGs are known to possess a porous structure [5], as shown in Figure 4 with pores highlighted in red. The pores in SCGs capture one of the most effective insulating substances, air, resulting in an increase in the insulation capacity. Also of note, the irregular relationship between the SCG amount and thermal conductivity that was found in previous studies [17, 18] was not seen in this research.



(a) 100x (b) 500x

Figure 4 SEM images of dried SCGs at different resolutions.

4.3 Water Absorption Capacity (Porosity Formation)

High water absorption capacity is a key feature found in SCGs and the reason why they are commonly used as an absorbent [16]. It is worth investigating if the high water absorption capacity is maintained in concrete with SCGs and if that would have any effect on the mechanical properties of the material. To compare the water absorption capacities by SCG ratio, the weights of the mortar samples were measured under dried (W_{dry}) and saturated surface dry (SSD) conditions (W_{ssd}). The samples were dried in an oven at 120°C for 24 hours to fulfill the dry condition, whereas they were immersed in water for 24 hours and surface-dried with a damp cloth for the SSD condition. The water absorption capacity was calculated by:

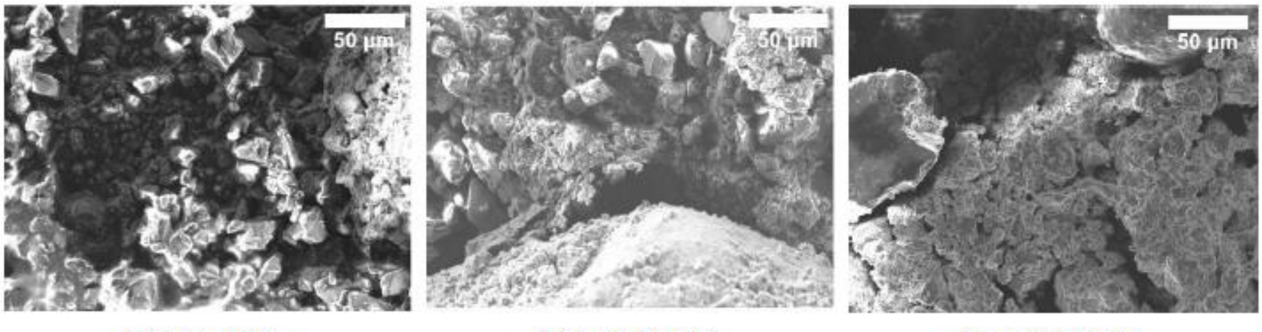
$$WA = \left(\frac{W_{ssd} - W_{dry}}{W_{dry}}\right) \times 100\% \tag{2}$$

where WA = water absorption, W_{ssd} = weight of the SSD sample, and W_{dry} = weight of the dried sample.

The water absorption capacities obtained for all samples are plotted in Figure 3 along the gray line with a circle symbol. The decreasing trend in water absorption capacity was prominent as the SCG ratio increased from 0 to 3.0%, and this observation agrees with the previous study that compared the water absorption rate of clay brick with SCGs less than 5 wt-% [17]. However, this trend was not maintained for the higher SCG ratio since a sudden leap in the water absorption rate was found at 6.0% SCGs. This higher water absorption rate by increasing SCG ratio was also found when only higher SCG ratios over 5 wt-% were tested [3]. This inconsistent observation based on the SCG ratio may be explained by the size of the material's particles. The samples were fabricated by fixing weights of cement and water and adjusting the volumes of sand and SCGs (fine aggregates). The particle size of SCGs is significantly smaller than that of sand, resulting in a more densely packed cementitious material for samples with higher SCG ratios. The denser microstructures in the material prevent the penetration of water, resulting in lower water absorption. The lower water absorption capacity of the higher SCGs ratios (0.6% to 3.0%) can be explained in this manner. Conversely, for the 6% SCG sample, the poor cohesiveness of the cement paste was clearly observed in the fabrication process. This was because the hydration reaction between cement and water was not fully activated, due to the highly water-absorbent SCGs. The poor adhesion of the cement paste led to larger pores, even visible to the naked eye after the samples were hardened. As a result, a high level of water absorption was found, unlike in the other SCG samples.

4.4 Scanning Electron Microscopy Image Analysis

The structural morphologies of the cement mortars with and without SCGs were investigated using SEM image analysis. The material's properties according to the amount of SCGs can be explained using the microstructure of the materials and the shape and size of the porosities obtained from the SEM images. Figure 5 presents the SEM images for each specimen. Note that the ϕ30 mm × 10 mm cylinder specimens were fully dried in an oven to prevent water vaporization, which could have obstructed the electron beam and reduced the clarity of the image.


(a) 0% SCG (b) 0.6% SCG (c) 0.9% SCG

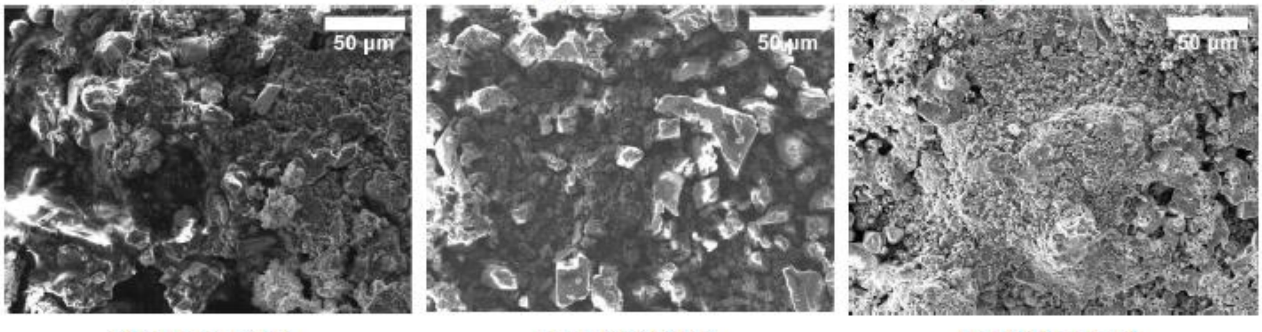

(d) 1.8% SCG (e) 3.0% SCG (f) 6.0% SCG

Figure 5 Scanning electron microscopy micrographs (500×).

As shown in the SEM micrographs, the mortar samples with 0.9% to 3.0% SCGs tended to be more densely structured because the interface between the cement paste and aggregates (coarse sand) was filled with fine SCG particles. While gaps in the interface were significantly reduced, the SCG pores still existed. This structural morphology explains observations regarding the thermal conductivity and water absorption capacity tests, as the porosity of the SCG particles allowed air to penetrate but was not large enough for water to do the same. Although the sample with 3.0% SCGs displayed more dense composites as shown in Figure 5 (e), its deterioration in compressive strength was inevitable, due to the increased amount of SCGs which have a low level of strength). Moreover, incomplete hydration was evident in the specimens with 6.0% SCGs (see Figure 5 (f)), as the separations with large pores between the materials were clear. Thus, the SEM analysis successfully demonstrated and supported the results from the material properties testing, along with the structural morphology of the tested samples.

5. Conclusions

The present study investigated the feasibility of incorporating SCGs into concrete materials to alleviate environmental issues arising from the significant increase in global coffee consumption. To eliminate the physical carbonization process that generates a substantial amount of greenhouse gases, the present research examined raw dried SCGs. Mortar samples were fabricated with different SCG ratios, and several material properties were measured. The following findings were revealed and recommendations for future research were derived.

- The compressive strength of the mortar samples was significantly influenced by the amount of SCGs. In particular, samples with 0.6% and 0.9% SCGs showed a completely different trend compared to the control specimens, as 24.5% decreased and 8.3% increased strengths were measured, respectively. For samples with over 3.0% SCGs, the high water absorption property of SCGs resulted in strength deterioration due to incomplete hydration. Thus, the amount of SCGs must be carefully selected when used as a construction material.
- Without exception, increasing the SCGs in the mortar samples increased the thermal insulation capacity. This trend was produced by the porous structure of SCGs, which captures the most effective insulation substance, air. Thus, concrete materials containing SCGs can serve as an effective insulator, saving energy used for cooling and heating.
- The water absorption capacity decreased as the SCG ratio increased whereas a sudden increase was found when the hydration reaction between water and cement was incomplete. The size of the material’s particles explains this irregular trend of water-absorption capacity.
- SCGs that are generally disposed of in landfills can bring numerous benefits to construction projects, serving as an effective insulator to save building energy and also acting as alternative filling material to substitute for more limited natural resources. To estimate the financial benefits and environmental impacts of using SCGs in concrete materials, lifecycle cost and carbon emissions analysis should be conducted in the future.
- Reduced workability and incomplete hydration were observed during the fabrication of samples with high SCG ratios due to the high water absorption property of SCGs. Further research is needed to find the ideal cement-to-water ratio that can accommodate higher SCGs ratios without compromising strength and workability.

Author Contributions

The authors confirm contribution to the paper as follows: study conception and design: Ju Dong Lee, and Jinho Kim; experimental test: Ju Dong Lee, Jinho Kim, and Seungjoo Lee; analysis and

interpretation of results: Ju Dong Lee, and Jinho Kim; draft manuscript preparation: Ju Dong Lee and Jinho Kim; All authors reviewed the results and approved the final version of the manuscript.

Competing Interests

The authors have declared that no competing interests exist.

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