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Recycling Spent Coffee Grounds on Permeable Interlocking Concrete Paving Blocks

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Abstract

Decomposition of spent coffee grounds (SCGs), a byproduct of brewing coffee, in disposed landfill sites releases significant amounts of potent greenhouse gases. This study aims to investigate the maximum recycling proportions of SCGs, a nonconventional filler material, for permeable interlocking concrete paving (PICP) blocks. These blocks have a porous structure that helps mitigate surface ponding while maintaining sound structural performance. Using Scanning Electron Microscope image analysis, the water absorbency of SCGs is inferred from the granular surface features of SCGs with voids of measured sizes. The flow table test was conducted to determine the water-to-SCG filler ratio, following a nonlinear trend, and then establish the water-to-cement ratio for constructing PICP specimens for this study. Among a range of PICP specimens with 9 different proportions of SCGs without replacing sand, those containing the 10% SCG filler as an inflection point exhibited the highest performance, achieving 18 MPa of compressive strength and 6 MPa of flexural strength, respectively. Conclusively, the PICP specimens with a maximum 10 % SCGs still maintained sufficient permeability at 0.47 mm/second, despite a 67% reduction compared to the control sample, attributed to the additional 1.69% weight of 10% SCGs. Based on the proven performance of tested PICP specimens, a maximum of 10% SCG filler has the potential to be applied in the concrete block market for recycling up to 27% of the annual Korean coffee consumption, reducing carbon emissions by more than 13,000 tons from incineration.

Keywords

Spent coffee ground; permeable interlocking concrete; paving; recycling; greenhouse gas emission

1. Introduction

Over 2.25 billion cups of coffee are consumed daily, resulting in a significant quantity of spent coffee grounds (SCGs) as a byproduct. If these SCGs are disposed of in landfills without proper management, they can produce methane. This greenhouse gas is 28 times more potent than carbon dioxide over 100 years, in addition to other harmful greenhouse gases. This contributes to atmospheric congestion and global warming. To put things into perspective, if all the estimated 18 million metric tons of wet SCGs were left to decompose naturally, they would release over 2.3 billion cubic meters of methane annually [1].

The concept of adopting SCGs arises from the observation that the granular particles of SCGs bear a solid resemblance to sand, a fundamental material extensively used in civil engineering applications due to its high friction angles. However, SCGs exhibit low bearing strength even when their solid particles are optimally compacted. With a practical internal friction angle, SCGs can be adopted as fill materials to replace sand soils. Consequently, researchers have explored adding other materials or binders to SCGs for civil engineering applications [2].

SCGs contain mainly lignocellulosic compounds, which is forming cellulose (59.2-62.94 wt.%), hemicellulose (5-10 wt.%), and lignin (19.8-26.5 wt.%) [3]. The lignocellulosic components of SCG could serve as fillers in cement concrete. However, adjusting the water-to-cement weight ratio is necessary because of the water-absorbing nature of SCGs.

The pH of SCG may vary depending on the type of beans used or the intensity of roasting and is generally known to exhibit a weak acidity of about pH 5.3 [4]. The possibility of blending aggregate with Portland cement in an alkali environment can be considered. Coffee waste was used to reduce the pH level of recycled aggregate from Portland cement concrete, which initially measured around 11, irrespective of the aggregate size. Mixing the coffee waste with recycled aggregates resulted in the treated aggregates attaining a neutralized pH level of approximately 5. As a result, these treated aggregates demonstrated 3.3-6.2 % higher crushing values than non-treated ones [5]. Incorporating SCG into concrete mixtures could positively affect long-term compatibility by improving the pH levels.

Portland cement was mixed at an increased water-to-cement weight ratio of 0.44 for complete hydration with SCGs. However, a water-to-cement weight ratio greater than 0.38 is generally necessary for total hydration of typical concrete mixes. Compressive strength measurements were taken on cement mortar specimens fabricated with a fixed cement-to-water ratio and varying amounts of SCGs. The results showed that an optimal amount of SCGs could increase the compressive strength. However, tests with excessive or less SCG content revealed a deterioration in strength [6].

Porous concrete mixes such as PICP blocks deviate from traditional ones primarily because of differences in aggregate gradation stemming from the absence of fine aggregates. The porous structure of these mixes typically results in compressive and flexural strengths that are lower than those in conventional concrete. This material could be suitable for low-load pavements but ensures good structural, functional, and environmental performance. However, the pore structure of the surface material does affect the potential for clogging, but this can be mitigated through the optimal porous design of aggregate gradation and the implementation of on-site maintenance practices, which effectively manage stormwater flows [7]. Permeable interlocking concrete pavements can be constructed on an open-graded, crushed stone base. This base provides essential features like stormwater infiltration, storage, and partial treatment of pollutants. Permeable concrete units, consisting of pavers made with no-fines concrete, are installed similarly to other pavers. Nonetheless, experience has revealed that they are more prone to clogging than other alternatives [8].

This study aims to investigate the maximum recycling potential of SCGs in PICP blocks despite their nonconventional nature as fillers in cement concrete mixes. The porous structure of the blocks helps manage stormwater flows while ensuring that the physical properties of the PICP blocks exceed the required structural performance standards outlined in KS F 4419 [9]. In conclusion, this research determines the potential reduction in greenhouse carbon emissions from disposing of spent coffee grounds within the Korean concrete block market context.

2. Materials and Specimen Preparation

2.1 Material Properties

Properties of Type 3 high early strength Portland cement, which was used in all mixes, are outlined in Table 1.

Table 1 Properties of Portland cement.

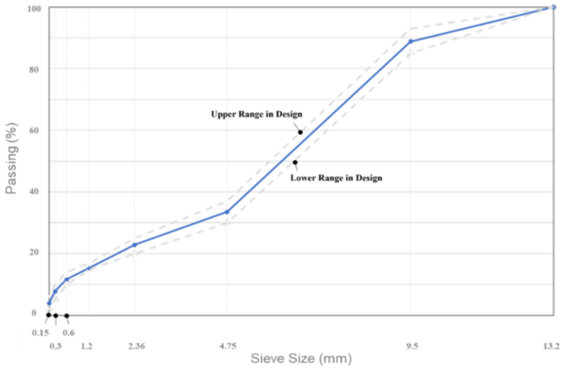
Key Chemical Components for Type 3 Cement[*]		Setting Time (hours)		Compressive Strength (MPa)		
MgO[**]	SO_3[***]	Initial	Final	3-day	7-day	28-day
3.01%	3.33%	3.0	4.0	23.0	36.7	54.2

[*] Type 3 Portland Cement should meet the maximum content limits for key chemicals (%)

[**] MgO: 5% maximum limit in composition

[***] SO_3: 4.5% maximum limit in composition.

Aggregate gradation consists of crushed gravel and sand, which pass from 9.5 mm through 0.15 mm IS sieves. Figure 1 (a) shows the composite gradation curve between the upper and lower range in the PICP aggregate design, which has been internally specified.



(a) Aggregate Gradation Chart

Sieve Size (mm)	Passing (%)
0.6	100
0.3	4.17
0.15	5.0
0.075	0

(b) SCGs Size Distribution

Figure 1 Composite aggregate gradation and crushed SCG size distribution.

Coffee wastes were gathered from a local coffee shop in Korea. Following a 24-hour drying process at 100°C, the coffee wastes were then crushed using a 45 W electrical grinder for 15 minutes. The resulting pulverized SCGs exhibit the following gradation distribution in Figure 1 (b). The SCGs were used without any chemical treatment, nor were their sizes sieved after the grinding process.

An admixture of the naphthalene-based liquid superplasticizer, with a density ranging from 1.1 to 1.3, was added to the PICP mixture at a 0.5% weight of the cement. It enhances fluidity while reducing the water content of the cement by 12% or more. This is achieved through its dispersing effect, utilizing electrostatic repulsive forces between cement particles.

2.2 Permeable Interlocking Concrete Paving (PICP) Mix Design

PICP specimens were designed with 9 different amounts of SCGs. Knowing the water-permeable structure of PICP blocks, samples were fabricated by simply adding SCG filler without replacing any portion of sand. The final water content was determined by adding the amount absorbed by the SCG filler, as assessed through its intrinsic water absorption capability and the flow table test, to the original water-cement content (Table 2).

Table 2 Mix Design for PICP Specimens.

SCGs (%)	Weight (10,000 g)			Water-to-Cement Ratio (w/c)
	Cement	Gravel	Sand	
0				0.35
1				0.39
3				0.40
5	1,667	5,883	2,500	0.41
7				0.42
10				0.43
13				0.44

15	0.45
20	0.47

The study investigated the maximum SCG content that would maintain the performance of PICP specimens compared to the control sample without any SCGs.

2.3 Testing Methods

Following a strategic framework depicted in Figure 2, testing methods are detailed with equations to evaluate the structural performances of PICP specimens with varying SCG inclusions.

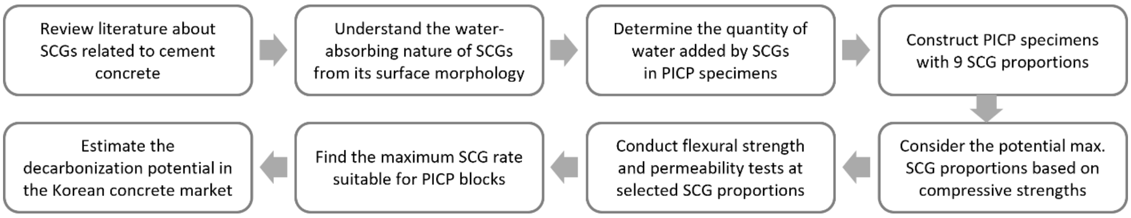


Figure 2 Study Framework to Assess Decarbonizing Potential in Korean Concrete Market.

The water absorbing capacity test used conditioned SCGs after drying the SCGs samples in a 100°C oven for 24 hours. For the test, three filter paper bags containing 10 grams of dried SCGs and 10 grams of dried SCGs were prepared and soaked in distilled water at room temperature for 15 minutes [10]. When the water absorption relative to its own weight was then measured over time until no further change was observed, the water-absorbing capacity was calculated using Equation (1):

$$Water\ Absorbing\ Capacity = \frac{W_{wet} - W_{dry}}{W_{dry}} \tag{1}$$

Compressive strengths were first assessed following ASTM C 109 standards. Cubic specimens of 50 × 50 × 50 (mm) in size were prepared in a 14-day curing process using early high-strength cement and were conditioned at room temperature until testing. The compressive tests were conducted consistently using the loading machine, and the strength values were reported as the average of three samples.

The flexural strength test applied a load (P) to the center point of the 140 mm support span on the brick-shaped specimens, which were fabricated in 200 × 100 × 60 (mm) dimensions in the same way as the compressive strength specimens, utilizing a loading machine with a compressive capacity of 100 kN under the experimental conditions depicted in Figure 3. The test was conducted at a constant speed of 50 mm/min until reaching the maximum load to determine the flexural strength based on Equation (2):

$$Flexural\ Strength\ (MPa) = \frac{3Pl}{2bd^2} \tag{2}$$

where,

P = Ultimate load at break (N)

l = Support span (140 mm)
b = Width of rectangular block (mm)
d = Thickness of rectangular block (mm)

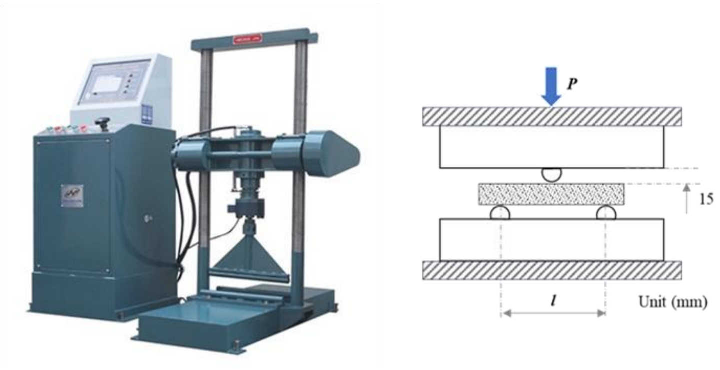


Figure 3 Flexural strength test illustration (KS F 4419).

Measurements of permeability were conducted, consecutively, followed by the flexural strength tests on dried permeability-tested specimens. The permeability (K) test procedure, illustrated in Figure 4, involves measuring the amount of distilled water poured into the upper reservoir of the PICP specimen block through the inlet and subsequently discharged through the outlet over 30 seconds using Equation (3). To understand the effect of the SCG filler content on permeability, the density of the SCG samples was further determined to be 1 (ml/gram) by measuring the weight of SCGs mixed with 50 ml of distilled water in a measuring cup at 25°C. Using this density coefficient, the volume ratio occupied by the SCGs in the brick-shaped PICP specimen with a volume of 1,200 ml was converted, and the relationship between the weight affected by the included SCGs and the measured permeability value was studied.

$$K = \frac{d}{h} \times \frac{Q}{A \times s} \tag{3}$$

where,

K = Permeability (mm/s)
Q = Outflow of drained water (mm^3)
d = Thickness of rectangular block (mm)
h = Difference in water level (mm)
A = Surface area of rectangular block (mm^2)
s = 30 seconds

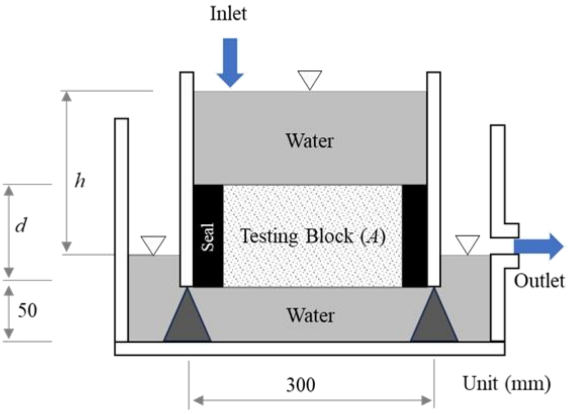
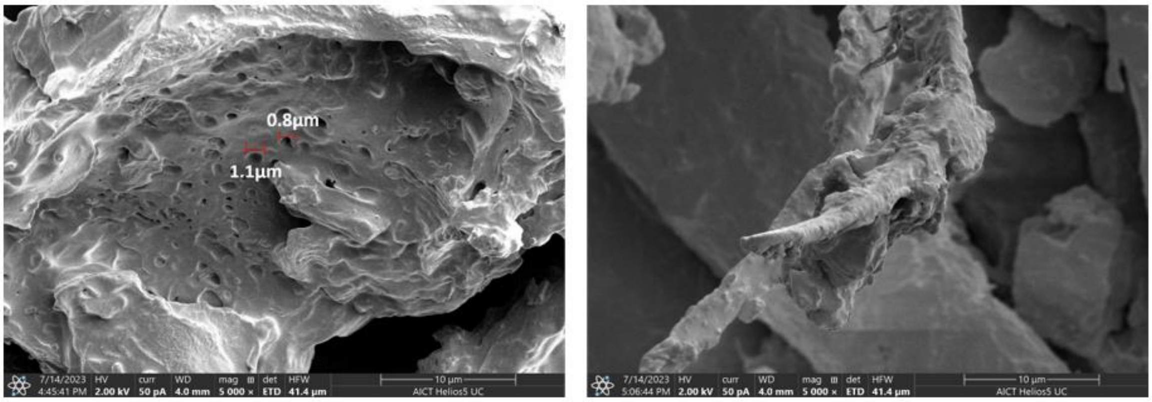


Figure 4 Permeability (K) test setup and calculation (KS F 4419).

3. Results and Discussion

3.1 Analysis of Scanning Electron Microscope (SEM) Images for SCG Surface Morphology

The Focused Ion Beam Scanning Electron Microscope (Helios 5 UC at Seoul National University) was used to examine the surface morphology and structure of the microstructured SCG in comparison with a typical cellulosic fiber pellet commonly used in paving mixes. The surface features of the samples were well observed through SEM images at a magnification of 10 µm. In Figure 5 (a), the surface of granular SCG contains voids, mostly ranging from 0.8 to 1.1 µm in diameter, which are larger than the water molecular size of about 0.3 nm. Meanwhile, the linear fibrous surface structure observed in natural cellulose pellets in Figure 5 (b). These voids are believed to affect moisture absorption on the surface of SCG. This discovery necessitates measurements of the added water amount to fabricate PICP specimens with varying proportions of SCG fillers correctly.



(a) SCG (b) Natural Cellulose Fiber

Figure 5 Comparative Microsurface Morphology in 10 µm Scale.

3.2 Assessing Added Water Content along SCG Filler Inclusion

The combination of water and cement significantly influences the strength and durability of PICP blocks. An excessive amount of water weakens the strength of the cured PICP blocks, while insufficient water causes poor workability of the concrete mixture. The amount of added water with the increase in SCG filler content was carefully investigated to determine.

Firstly, a water absorbency experiment was conducted to ascertain whether the amount of added water can be predicted based on the intrinsic moisture absorbing capacity of SCGs. The water absorption of SCGs was determined to have an average of 85% wt. Ratio relative to the weight (gram) of SCGs, shown in Figure 6 (a), using Equation (1).

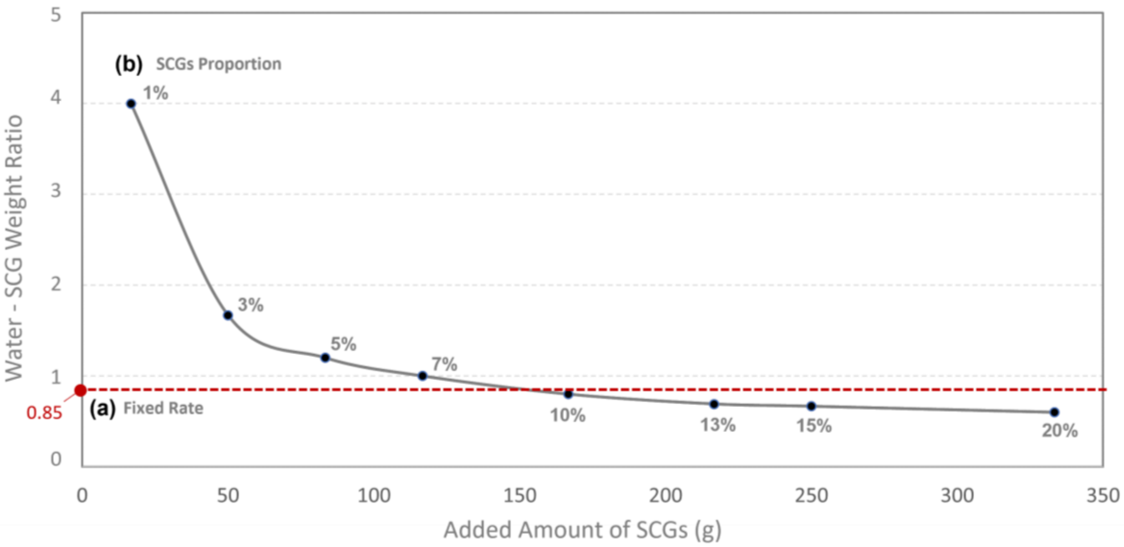


Figure 6 Added-Water Ratio along SCGs: (a) Water Absorbing Capacity, (b) Flow Table Test.

The water contents with the inclusion of SCGs were also measured through the flow table test (ASTM C 230). Initially, the flow table test was conducted on the PICP control mixture (w/c = 0.35) without adding SCGs beforehand, resulting in a flow diameter of 165 mm. Afterward, the flow table tests were carried out using progressively increasing amounts of added SCGs, as specified in the mix design (Table 2).

The findings from Figure 6 (b) reveal that the water added to the PICP mixture nonlinearly increases as the amount of SCG filler increases, as determined by the flow table Test. This is attributed to a combination of factors, including the interaction between the components of the cement mixture and the water absorption capacity of SCGs themselves. Except the 10% SCG inclusion, the adoption of the fixed 85% wt. Water ratio was limited in determining additional water required for other SCG proportions. Therefore, the water-to-cement ratios, as shown in Table 2, for different SCG proportions, were selected for PICP specimen fabrication using the flow table test.

3.3 Finding the Maximum SCG Inclusion Amount in PICP Blocks

3.3.1 Compressive Strength Assessment

Figure 7 shows the compressive strength values of the cubic PICP test specimens at 9 different rates of added SCGs, following the PICP Mix Design in Table 2. Upon examination, it was observed that the compressive strength of PICP specimens demonstrated a slightly increasing pattern until the addition of 10% SCG filler, reaching 18.7 MPa. Subsequently, they did not meet the compressive strength criteria of 16 MPa from 13% SCGs, according to the standard specifications for PICP blocks used in sidewalks in Seoul City in Korea [11]. The cellulose component of SCG fillers, up to 10%, can resist initial cement cracking in the porous structure of PICP specimens, which inherently have a low load-bearing capacity [4]. However, with SCG inclusions higher than 10%, cracking could initiate prematurely within the SCG fillers in low strength [2].

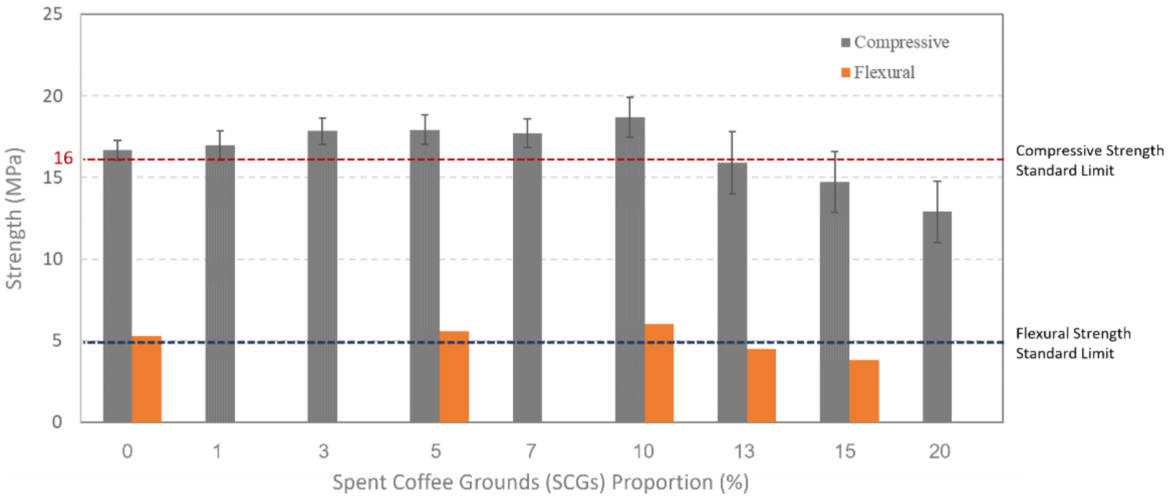


Figure 7 Compressive and Flexural Strengths of PICP Specimens with SCG contents.

3.3.2 Flexural Strength Assessment

As shown in Figure 7, the average flexural strength of the control specimens at 0% SCGs exceeds the standard criteria at 5 MPa, reaching 6 MPa for a 10% SCG filler content with only a slight variation. However, beyond this point, a noticeable decreasing trend was observed, falling below the standard limit. Understanding the correlation between compressive and flexural strengths, this trend, with an inflection point at 10% SCG inclusion, aligns with findings in compressive strength measurements. The cellulose property in SCG, up to 10%, could contribute to an improvement in the modulus of rupture under the tensile stress condition at the bottom of PICP specimens.

3.3.3 Permeability Assessment

The results shown in Figure 8 highlight the immediate impact of SCG addition on permeability right from the initial stage. By incorporating a maximum of 10% SCG filler, structural voids in PICP specimens could be filled, accounting for 13.9% of the volume, corresponding to 1.67% of the total weight as per the SCG weight ratio in Figure 8. Permeability then decreased significantly to 0.47 mm/s, a reduction of 67% compared to the control specimen value, while still satisfying the standard limit of 0.1 mm/s. Nevertheless, challenges arose in establishing a simple relationship between the rate of SCG volume increase and the corresponding decrease in permeability measures.

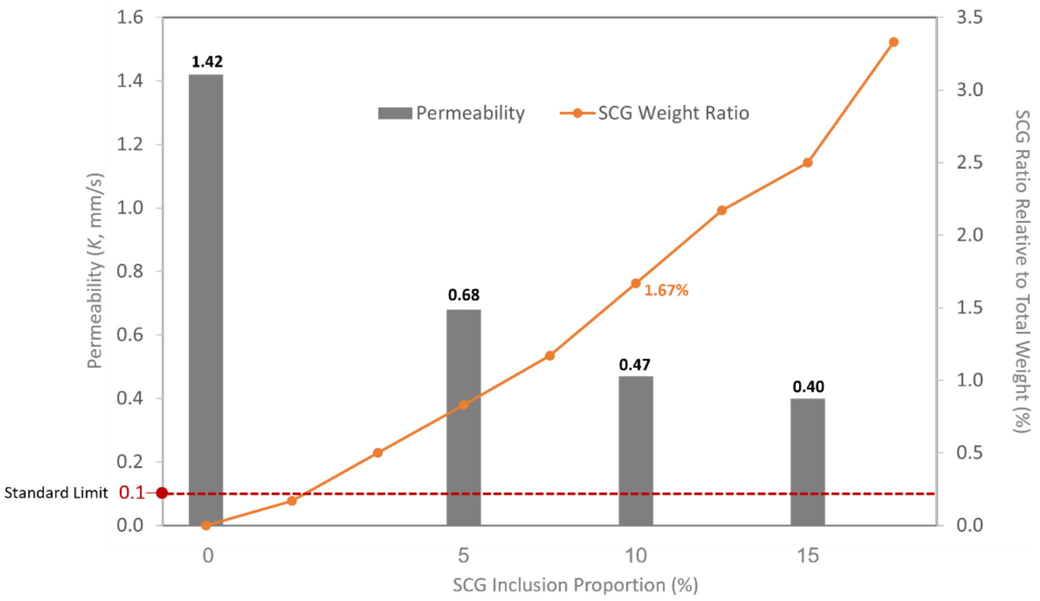


Figure 8 Permeability Measurements and Analysis.

This study aims to maximize the recycling of SCGs that meet the required performance for PICP blocks. Up to the maximum 10% SCG filler inclusion, there was a slight increase in compressive and flexural strengths compared to the control. However, a noticeable reduction in permeability was observed, even though its requirement was satisfied. This was made possible because there was enough space to include 10% SCG filler within the sufficient internal porosity without replacing sand from the elemental composition of the non-SCG PICP block.

Nonetheless, during the permeability experiment, traces of organic byproducts from SCG were noticeable on the surface of the permeated distilled water. This occurrence might be attributed to the insufficient surface coating of SCG by cement. Further research on optimizing the cement ratio should be pursued. Moreover, the inclusion of SCGs can enhance the pH of the PICP mixture and exploit the beneficial interfacial properties of lignocellulose in conjunction with recycled gravel and sand, resulting in blocks with sufficient strength.

3.3.4 Estimating Decarbonization Potential in the Korean Concrete Block Market

In Korea, coffee consumption amounts to approximately 150,000 tons per year, and almost all of it, 99.8%, is discarded as household waste, creating a significant byproduct. The country's yearly production of interlocking concrete blocks is estimated to be around 24 million m^2. According to the data presented in Table 3, each squared meter of the utilized PICP blocks weighs 100 kg. By incorporating SCGs up to 10% of the weight of cement, there is strong potential to recycle up to 40,320 tons of coffee waste annually. This recycling amount is equivalent to 27% of the total coffee consumption. Additionally, it is estimated that by employing the technology in this study, greenhouse carbon emissions can be reduced by a maximum of 13,628 tons. This reduction is calculated based on the emission rate of approximately 0.338 tons of carbon emissions per metric ton of coffee waste when incinerated.

Table 3 Potential Carbon Emission Reduction from Coffee Wastes in Korea.

PICP Block Wt.[1] (kg/m^2)	**SCGs in Blocks**[2] (kg/m^2)	**KR Interlocking Block Market** (Yearly, m^2)	**SCGs Wt.** (tons)	**Yearly Coffee Consumption** (tons)	**SCG Recycling Rate** (%)	**Carbon Reduction**[3] (tons)
100	**1.68**	**24 Million**	**40,320**	**149,083**	**27**	**13,628**

[1] Total weight of PICP blocks per m^2. [2] 10% SCGs Content. [3] carbon emissions by incineration of coffee (338 kg/ton)

4. Conclusions

This study was initiated to mitigate the growing greenhouse gas emissions associated with coffee waste, a consequence of the global popularity of coffee consumption. An engineering approach was employed to construct PICP specimens with SCG fillers, evaluate their performance, and identify the maximum recycling content of SCGs. This research yields the following findings and provides recommendations for future studies.

Analysis of the micro surface morphology of SCGs discovered larger voids with diameters ranging from 0.8 to 1.1 µm, exceeding the size of water molecules. This observation suggests that SCGs have a water-absorbing nature, justifying the need to add extra water in proportion to the number of SCGs present to fabricate PICP mixes. The flow table test confirmed that additional water is required as the SCG filler portion in the PICP mixes increases. The fixed 85% weight ratio, relative to the weight of SCGs as measured in the water-absorbing capacity test, showed limited similarity in the 10% SCG-added specimens.

The compressive strengths of cubic PICP specimens reached 18.7 MPa at 10% SCG filler as the inflection point. The cellulose component of SCGs could initially contribute to stability by resisting cracking. However, beyond this point, their low bearing capacity predominantly impacts the specimens, resulting in premature deterioration.

The flexural strength pattern, with SCG content ranging up to 10%, aligns well with the findings from the compressive strength analysis, maintaining 6 MPa. The improved tensile property of PICP specimens with a 10% SCG proportion can likely be attributed to the positive effect of SCG filler under flexural loading conditions.

The inclusion of SCGs has an instantaneous impact on permeability. Permeability of 0.47 mm/s on PICP blocks with 10% SCG filler is acceptable for practical use. However, achieving a significant 67% reduction in permeability compared to 0% SCG specimens presents a challenge. In future research, it is worth investigating the composition of partially substituting sand with an equivalent weight of SCG filler, as this could potentially improve permeability while preserving good compressive and flexural strengths.

By implementing the technology from this study in the interlocking concrete block market in Korea, it is estimated that around 27% of the total coffee consumed annually in the country could be effectively recycled. This recycling effort is expected to reduce more than 13,000 tons of carbon emissions, which would otherwise be generated if all the coffee waste were incinerated.

To mitigate greenhouse gas emissions, further research is needed to optimize the composition design, particularly the cement content, to ensure adequate surface coating of SCG. Additionally, incorporating SCGs can improve the pH of the PICP mixture and capitalize on the beneficial interfacial properties of lignocellulose, alongside recycled gravel and sand. This synergy results in PICP blocks with enhanced strength and contributes to decarbonization efforts.

Author Contributions

The authors confirm their contributions to the paper as follows: study conception and design by Joel Lee and S. Lee; data collection and analysis by H. Song and J. Park; analysis and interpretation of results by Joel Lee and S. Lee; literature review and drafting of the manuscript by Joel Lee. 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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