STRENGTH DEVELOPMENT OF GEOPOLYMER PAVING BLOCKS UTILIZING INDUSTRIAL WASTES

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ABSTRACT

Interest in geopolymer technology as a substitute for traditional Portland cement has increased due to the growing need for environmentally friendly construction materials. This study aims to focus solely on the strength development of geopolymer paving blocks made entirely from industrial waste materials—coal fly ash (CFA), sewage sludge ash (SSA), and waste glass powder (GP). This study investigates the effect of liquid-to-ash ratio (L/A), curing temperature, and alkaline activator concentration on the early-age compressive strength development of the geopolymer paving blocks. The mix design included a fixed ratio of Na_2SiO_3: NaOH ratio of 2.5, sodium hydroxide (NaOH) concentrations of 10 M, 12 M, and 14 M and sodium silicate (Na_2SiO_3). The L/A ratios (0.35 and 0.45) were used to investigate the effect of the percentage of mix and mix strength. All samples were oven cured at 80 °C and 110 °C, respectively, to understand the effect of curing temperature on strength. After oven drying at 110°C, the maximum compressive strength measured under heat oven curing was 36.95 MPa, at L/A = 0.45 and a concentration of 14 M NaOH. This strength satisfies the 35 MPa compressive strength requirement of the Local Government Engineering Department (LGED), Bangladesh for paving block. According to these results, waste based geopolymer paving blocks are a viable and environmentally friendly substitute for traditional paving materials promoting sustainable waste recycling process.

Keywords: *Geopolymer paving blocks, industrial wastes, compressive strength, alkali activators, curing temperatures.*

1. INTRODUCTION

Nowadays, using paving blocks to build road infrastructure is regarded as a feasible substitute that is gaining traction because of its many benefits, including increased robustness and longevity along with lower maintenance costs (Nurwidayati et al., 2024). Paving blocks are commonly seen in a variety of locations including roads, and city streets. Currently, concrete paving blocks are being used demanding a significant amount of factory-made cement (Chairunnisa et al., 2024). Global warming is seriously affected by the CO_2 release during the cement manufacturing process. In particular, 1 ton of CO_2 emissions are released during the manufacturing of 1 ton of Cement (Davidovits, 2013). In order to replace cement as an environmentally acceptable material, civil engineers are constantly investigating alternative paving block mixes with low carbon emissions and sustainability (Hassan et al., 2019).

Geopolymers are amorphous to semi crystalline three-dimensional bulk materials which can be synthesized by the reaction between aluminosilicate powders in various alkaline solutions at ambient or slightly elevated temperatures (Debnath et al., 2022a). The chemical process of turning inorganic materials into natural cement is known as geo-polymerization (Susilowati et al., 2016; Sofyan et al., 2023; Rizki Abdila et al., 2025). Recently, geopolymer has become a practical substitute for cement when creating paving block mixes Geopolymers demonstrate increased strength and better adhesion (Abdila et al., 2021). Alumina and silica are needed to produce this geopolymer substance (Kavipriya et al., 2022).

Coal fly ash (CFA) is a fine, powdery by-product generated from the combustion of pulverized coal in thermal power plants. The tiny particles are carried by flue gases and collected from the exhaust system. Due to its pozzolanic properties, CFA reacts with calcium hydroxide in the presence of moisture to form additional cementitious compounds, thereby improving the strength, durability, and workability of Portland cement concrete (Thang Nguyen Ho Chi et al., 2016).

A high concentration of heavy metals found in wastewater have a tendency to build up in sewage sludge (SS). Sewage Sludge Ash (SSA) is produced as a by-product during the incineration process of wastewater sludge (Pathirana et al., 2019). SS was mostly dumped into oceans and landfills in previous decades.

The quantity of reactive silica in waste glass powder (GP) suggests that it may be employed as an additional binder ingredient in cementitious systems, according to current research trends. Waste glasses are typically crushed to create geopolymer (Khan et al., 2021).

In Bangladesh, thermal power plants generate a considerable amount of CFA, estimated at over 1.5 million tons annually, most of which is either landfilled or remains unutilized due to a lack of proper disposal and reuse strategies. Similarly, SSA is produced as a by-product of wastewater treatment, and its disposal presents growing environmental and public health concerns, particularly in urban areas like Dhaka and Chattogram. Furthermore, glass waste is rapidly accumulating in Bangladesh due to increased consumption of packaged beverages and inadequate recycling infrastructure. Glass powder, when finely ground, has been found to possess pozzolanic properties suitable for geo-polymerization.

In geopolymer concrete, an alkali-activated aluminosilicate substance is used in place of the conventional cement-based binder. Fly ash turns to natural cement through geo-polymerization in presence of NaOH and Na_2SiO_3 solutions (Karimul et al., n.d.).

The growing demand for infrastructure and urban development in Bangladesh has led to a significant rise in cement consumption, contributing to extensive environmental degradation. Traditional Ordinary Portland Cement (OPC) production is energy-intensive and emits a substantial amount of carbon dioxide (CO_2), accounting for around 8% of global anthropogenic CO_2 emissions (Andrew, 2018). In Bangladesh, where infrastructure growth is accelerating, cement consumption increased by more than 10% annually between 2010 and 2020 (Karimul et al., 2018).

This study examines the effectiveness of using GP, SSA and CFA as a complete substitute for cement in paver blocks. The objective is to assess how alkali activators, liquid /solid ratios, and curing temperatures affect the growth of paving blocks' compressive strength shedding important light on the viability of using CFA, SSA, and GP as sustainable cement substitutes in the manufacturing of concrete paving blocks.

2. METHODOLOGY

To assess the compressive strength of geopolymer-based paving block, a systemic selection of raw materials, optimized mix design and controlled curing conditions have been conducted grounded on prior research. As a principal precursor, CFA has been employed, which has been used in different percentages in the production of geopolymer concrete. Because they have been used independently to replace CFA in previous research, GP and SSA are combined to partially replace CFA. To start the geo-polymerization and maintain the ideal modular ratio, sodium hydroxide (NaOH) flakes and sodium silicate (Na_2SiO_3) liquid solution are utilized as alkaline activators. Using optimum mix design, the compressive strength was evaluated in two different curing conditions, heat curing (HC) and microwave curing (MC) to investigate the effect of temperature.

2.1 Raw Materials

2.1.1 Precursors

In this study, a mixture of CFA collected from Barapukuria Coal Based Thermal Power Plant, SSA collected from Dasherkandi Sewage Treatment Plant and GP from local market located in Shakhari Bazar, Dhaka were used as the precursors. All the precursors were ball milled properly before being used. According to ASTM C618 (ASTM C618-23, 2023) all the precursors in this study were F type ash which makes it clear that SiO_2, Al_2O_3, and Fe_2O_3 are the significant components in the CFA. The main components in SSA are SiO_2, Al_2O_3 and CaO. The major components in GP are SiO_2, Na_2O and CaO. In addition, all the precursors contain small amount of Ba, Mg, Ti, Zr, Cr, Mn, Zn, Ni and other heavy metal ions specially in the GP. Although particle size analysis was not conducted experimentally due to laboratory limitations, the selected fineness aligns with previous studies indicating that precursor particles below 75 μm enhance dissolution and reaction activity in alkaline media(Assi et al., 2018).Precursors that pass through #200 standard sieve have been used in the experiment.

2.1.2 Alkaline Activator

Alkaline activator for this study was prepared by mixing Na_2SiO_3 solution and NaOH. Na_2SiO_3 is provided in aqueous form for the dissolution of solid aluminosilicate-based precursors (Dimas et al., 2009) molarities NaOH have been used (e.g 10M, 12M and 14M) mixing NaOH flakes containing 98% caustic soda of its weight dissolving in distilled water (Bachtiar et al., 2020; Debnath et al., 2022b; Pathirana et al., n.d.) until the NaOH pellets were completely dissolved. For proper reactivity of precursors, a ratio of Na_2SiO_3 and NaOH of 2.5 was maintained, studying from previous results (Abdila et al., 2021; Shaikh & Vimonsatit, 2015; Widayanti et al., 2018). The NaOH solution was prepared 30 minutes before mixing it with the Na_2SiO_3 solution for letting it cool to ambient temperature to prevent thermal disruption in geopolymerization process (Karimul et al., n.d.). The chemical compositions of the Na_2SiO_3 are 29.04% SiO_2, 14.10% Na_2O, and 56.86% H_2O by mass collected from Super Silica Bangladesh.

2.2 Mix Design

In Table 1, a single composition of solid ash materials combining 50% CFA, 30% SSA and 20% GP by weight of total solid precursor with a constant modular ratio of Na_2SiO_3 and NaOH that is 2.5 is used for making a composition of 3 different molarities of NaOH ranging from 10M to 14M. Two different liquid-by-ash (L/A) ratios of 0.35 and 0.45 were used to examine the effect of the activator on the properties and consistency of geopolymer paste. The mixture ID are demonstrated in a format of "CxSyGz" indicating x% of CFA, y% of SSA and z% of GP. All the parameters are kept constant except L/A and the molarity of NaOH across the batch to observe the outcomes based on their influence.

Table 1: Various combinations used in the study

Combination	Composition			NaOH Molarity (M)	NaOH	Na_2SiO_3	L/A
	CFA	SSA	GP				
C50S30G20	50	30	20	10	0.816	2.04	0.35
	50	30	20	12	0.816	2.04	
	50	30	20	14	0.816	2.04	
	50	30	20	10	0.635	1.587	0.45
	50	30	20	12	0.635	1.587	
	50	30	20	14	0.635	1.587	

2.2.1 Mixing

Ball-milled and oven-dried CFA, SSA and GP were mixed for 5 minutes to make a homogeneous mixture. The Na_2SiO_3 solution mixed with 10M, 12M and 14M NaOH solutions and cooled to room temperature about 30 minutes before was mixed with solid precursors manually for an additional 10 minutes to ensure uniform distribution of alkaline activators.

2.3 Casting

The mixed paste was cast into a mould with internal dimensions of 50mm x 50mm x 50mm according to (ASTM C109/C109M − 21, 2021) standard guidelines. For each mix and curing condition three samples were tested. To stop the evaporation of the water, the moulds were sealed with food-grade wrapping paper. The fresh matrix in the moulds was placed for 48 hours in the laboratory. After they were strong enough to withstand handling stress, they were collected and arranged for different curing setups.

2.4 Curing

The produced geopolymer cube specimens were cured under two different curing methods. In both methods, demoulded samples were heat cured in an oven at temperatures of 80°C and 110°C for 24 hours. Before heat curing, each sample was wrapped with food-grade wrapping paper covered with transparent tape to reduce moisture loss due to heat curing.

2.4.1 Heat Curing

After heat curing, the samples were removed and kept at ambient room temperature for an additional 7 days to allow further curing before the compressive test was conducted.

2.4.2 Microwave-oven (MO) Curing

After heat curing, the samples were subjected to microwave curing by placing them in a microwave oven operating at 180 watts for 10 minutes and a compressive test was conducted the next day after microwave-oven curing.

2.5 Compressive Strength Test

After following two different curing methods, prepared cube matrices were placed in a compressive strength machine under a vertical loading rate of 1.2 kN/s to investigate the effect of the change of

molarity of NaOH and elevated heat curing temperatures as per ASTM C109/C109M (ASTM C109/C109M − 21, 2021). The cubes were placed in an alignment so that the tamping surface will be perpendicular to the vertical loading surface. The compressive strength of each combination was determined after examining the compressive strength of three specimens and taking the mean values.

3. RESULTS AND DISCUSSION

The research was conducted to analyse the strength of geopolymer-based paving block with different NaOH molarities under various heat curing temperatures using two curing methods. The experimental results and their significance are also illustrated graphically in the following sections. The average value along with the standard deviation was reported to represent data variability.

3.1 Effect of Liquid-to-Ash Ratio at Two Heat Curing Temperatures

The values of compressive strength demonstrated in table 2 represent the propensity of improvement of compressive strength with the increasing concentration of NaOH where samples were kept under ambient condition for 7 days after heat curing at 80°C when L/A are 0.35 and 0.45.

Table 2: Effect of two L/A ratio on compressive strength at 80°C heat curing

Molarity Of NaOH	Average Compressive Strength (MPa) at L/A: 0.35	Average Compressive Strength (MPa) at L/A: 0.45
10M	16.43	16.36
12M	17.89	18.25
14M	21.57	29.12

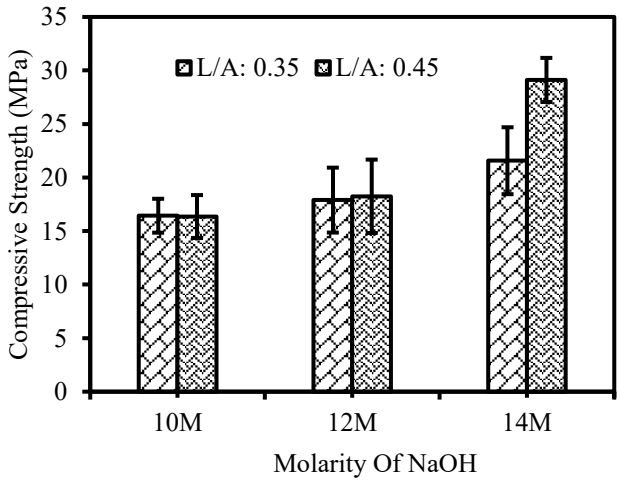

Figure 1: Effect of L/A at 80°C heat curing

Figure 1 presents the incremental development of compressive strength, where samples were kept under ambient condition for 7 days after heat curing at 80°C, for L/A ratios of 0.35 and 0.45, evaluated across three different sodium hydroxide (NaOH) molarities (e.g.10 M, 12 M, and 14 M). The figure also demonstrates uniform increase of strength with higher molarity illustrated in column charts. Standard deviation is indicated by error bar in each of the graphical presentation. Maximum strength has been

obtained at L/A ratio 0.45 which is 29.12 MPa. The value is 34.99% higher than the compressive strength experienced at L/A ratio 0.35 with NaOH concentration 14M.

Table 3: Effect of two L/A ratio on compressive strength at 110℃ heat curing

Molarity Of NaOH	Average Compressive Strength (MPa) at L/A: 0.35	Average Compressive Strength (MPa) at L/A: 0.45
10	18.62	20.32
12	22.17	21.66
14	28.84	36.95

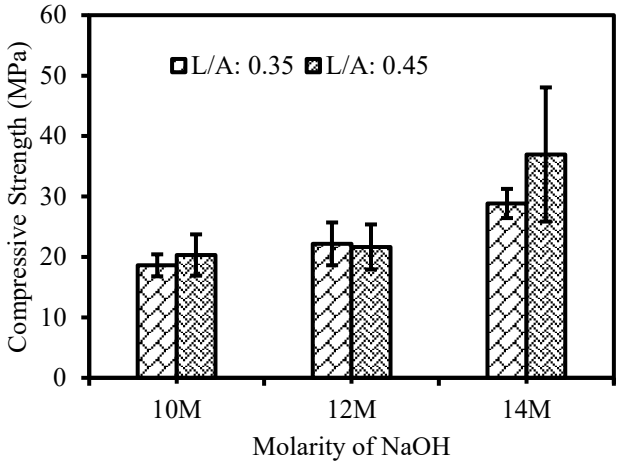

Figure 2: Effect of L/A for 110°C heat curing

According to table 3, the compressive strength increased incrementally as the NaOH concentration increased in similar curing process at 110°C heat curing. Figures 2 shows the relevant results in column charts, with error bars denoting standard deviations for each mix configuration, in this case for the C50S30G20 blend. Presence of excess amounts of solid precursors and reduction in activator content hinder the workability of the mixture of geopolymer paste by inducing water retention property and introducing friction within the dry particles (Adam, 2019; Sathonsaowaphak et al., 2009; Sun et al., 2022), shows that activator to binder ratio up-to 0.55 shows significant improvement in compressive strength where degradation occurs when the ratio becomes 0.6. Optimum fraction of activator to binder promotes matrix densification in structure through pore blocking within the structures acting as a network modifier. Excessive presence of activators can risk unreacted activator promoting efflorescence and reduction in matrix integrity.

3.2 Effect of Heat Curing Temperature at Two Liquid-to-Ash Ratio

When heat curing temperatures are 80°C and 110°C at an L/A of 0.35, the compressive strength values shown in table 4 indicate the tendency for compressive strength to increase with increasing NaOH concentration when samples were kept under ambient conditions for 7 days after heat curing.

Table 4: Effect of two heat curing temperature on compressive strength at L/A: 0.35

Molarity Of NaOH	Average Compressive Strength (MPa) at 80°C	Average Compressive Strength (MPa) at 110°C
10	16.43	18.62
12	17.89	22.17
14	21.57	28.84

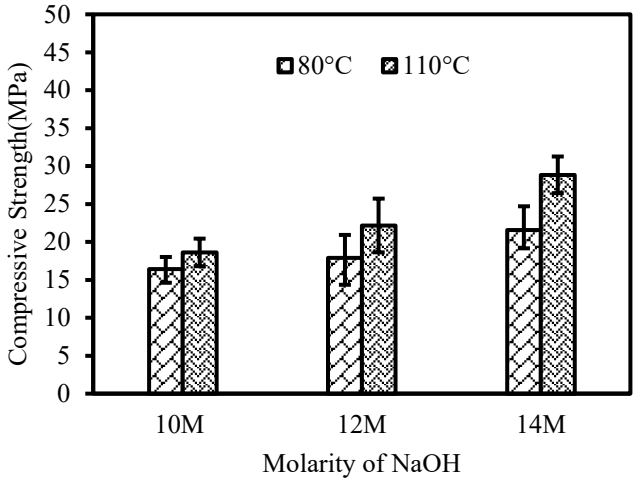

Figure 3: Effect of heat curing temperature at L/A: 0.35

Figure 3 presents the incremental development of compressive strength following similar curing process at L/A ratio 0.35 evaluated across three different sodium hydroxide (NaOH) molarities (e.g.10 M, 12 M, and 14 M) for heat curing temperature 80°C and 110°C. A uniform increase of strength with higher molarity is illustrated in column charts. Standard deviation is indicated by error bars in each of the graphical presentation. Maximum strength was obtained at 110°C heat curing temperature that is 28.84 MPa at a concentration of NaOH 14 M. The value is 33.72% higher than the compressive strength experienced at 80°C heat curing temperature with NaOH concentration 14M.

Table 5: Effect of two heat curing temperature on compressive strength at L/A: 0.45

Molarity Of NaOH	Average Compressive Strength (MPa) at 80°C	Average Compressive Strength (MPa) at 110°C
10	16.36	20.32
12	18.25	21.66
14	29.12	36.95

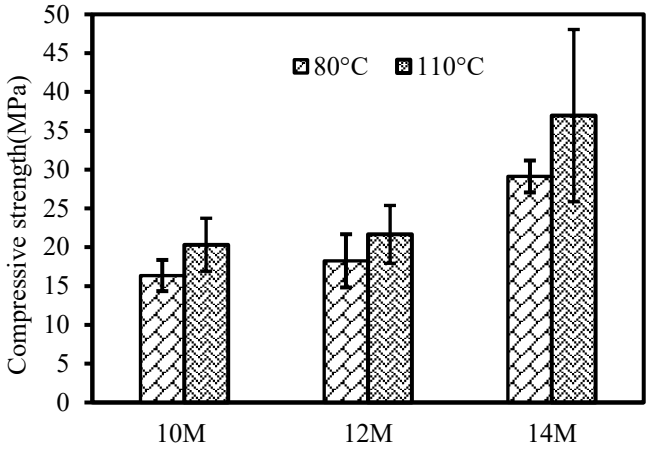

Figure 4: Effect of heat curing temperature at L/A: 0.45

Incremental development of compressive strength with rising of concentration of NaOH adopting similar curing process as mentioned earlier at heat curing temperature of 80°C and 110°C stated at table 4 and 5, respectively. The corresponding results are displayed in column charts in figures 3 and 4, where standard deviations are indicated by error bars. The maximum compressive strength is 36.95 MPa acquired at liquid to ash ratio 0.45 for heat curing temperature of 110°C highlighting the positive influence of higher curing temperature on strength development, while also satisfying the 35 MPa compressive strength requirement specified by the Local Government Engineering Department (LGED) (Final Report Preparation and Incorporation of Alternative Pavement Section (Interlocking Concrete Block Pavement) into Road Design Manual, 2021). A positive correlation is observed between temperature and compressive strength with the progress of temperature increment. This enhancement can be attributed to the continuation of geo-polymerization process with the removal of physical bound water that leads to the formation of denser and cohesive matrix of geopolymer. The observed positive relationship aligns with the existing behavior of geopolymer where mild heat expansion can accelerate kinetics reaction improving mechanical performance. Current investigation confines to 110°C temperature without inducing thermal stress or microstructural damage as previous studies have shown degradation of strength exceeding temperature 200°C considering the beneficial use of geopolymer (Shaikh and Vimonsatit, 2015).

3.3 Effect of NaOH in Development of Compressive Strength

Figure 4 illustrates the consistent increase of compressive strength with increase of molarity of NaOH (e.g. 10, 12 and 14). The fresh mortars became more rigid as the concentration of NaOH rose. Due primarily to the leaching of silica and alumina with high concentrations of NaOH and high ratios of Na_2O to Al_2O_3, the strength rose as the concentration of NaOH increased (Sathonsaowaphak et al., 2009). Because Na ions were needed to balance the charges and construct the alumino-silicate networks, the higher concentration of NaOH in the solution led to an increase in Na ions, which was crucial for the geopolymerization process (Sathonsaowaphak et al., 2009).

3.4 Effect of Two Curing Methods

In table 6, at a liquid-to-ash (L/A) ratio of 0.45, NaOH concentration of 14M, and heat curing temperature of 110°C, the compressive strength results indicate a notable difference in strength development between the two curing methods indicating that heat curing is more effective in enhancing compressive strength than microwave-oven curing.

Table 6: Effect of two different curing methods at 14M, L/A=0.45 & 110°C heat curing

Average Compressive Strength for Heat Curing (MPa)	Average Compressive Strength for Microwave-oven Curing (MPa)
36.95	33.82

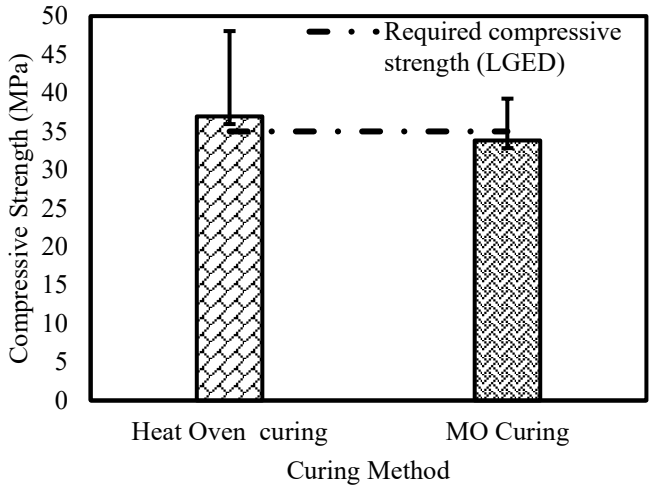

Figure 5: Effect of heat and micro-oven curing on compressive strength

Figure 5 depicted that the compressive strength of geopolymer blocks at heat curing is higher than that under microwave-oven curing, indicating that samples kept for 7 days ambient conditions after heat curing yield a higher average compressive strength compared to microwave-oven curing. Furthermore, the standard deviations shown as the error bars suggest greater variability in strength under heat curing than under MO curing. This implies that heat curing may facilitate more favourable or stable geopolymerization reactions over the tested duration, resulting in improved compressive strength.

4. CONCLUSIONS

This study aimed to investigate the effectiveness of industrial and municipal wastes for producing geopolymer paving blocks. Compressive Strength tests are performed to determine the influence of several variables including L/A ratio, curing temperature, curing method and molarity of NaOH. This study concludes with the following findings:

1. This experimental study reveals that both sodium hydroxide (NaOH) molarity and curing temperature significantly influence the strength development of geopolymer paving blocks. Results indicate a consistent increase in compressive strength with higher molarity levels (10 M, 12 M & 14 M) and elevated curing temperatures (80 °C and 110 °C), across different liquid-to-ash (L/A) ratios (e.g. 0.35 and 0.45).
2. The highest compressive strength was obtained at heat curing temperature of 110 °C with an L/A ratio of 0.45, highlighting the crucial part that heat activation plays in promoting geo-polymerization processes.
3. A comparison of heat curing and microwave-oven (MO) curing settings shows that the average compressive strength of heat curing is higher than that of MO curing.
4. Greater variability in samples kept in ambient condition after heat curing suggests that, ambient conditions may support complete geopolymerization, however they are sensitive to ambient condtions.

This study could not evaluate the durability, absorption, abrasion and leachability of heavy metals of the paving block. It is expected that future study would investigate these factors before a practical application.

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Declaration of Use of AI:

The authors declare that this manuscript was prepared entirely by the authors without the use of artificial intelligence (AI) tools in the writing, editing, analysis, or preparation of this manuscript.

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