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Research Article

Innovation of Paving Stones for the Control of Surface Runoff for a Sustainable Environment: A Case Study of AIT to Block Factory Junction

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Abstract

Urbanization in the Greater Accra region of Ghana has intensified surface runoff, flooding, and water pollution due to the proliferation of impermeable surfaces that disrupt natural drainage and reduce groundwater recharge. To address this challenge, this study investigates the development of sustainable permeable paving stones as an alternative to conventional pavers, aiming to mitigate runoff impacts around the AIT Hill Top Junction area and maximize the efficiency of existing drainage infrastructure. An experimental methodology was adopted to evaluate the mechanical and hydraulic properties of permeable paving stone mixtures. A total of forty-eight samples were cast using two cement brands Dangote 42.5R and Ghacem 42.5R with fine aggregates (quarry dust), coarse aggregates (granite), and silica fume (SF) as an additive. Comprehensive tests were conducted to determine compressive strength, moisture content, workability, and permeability, while secondary data on chemical composition were analyzed to explain performance variations. The results show that the paving stones exhibit moderate permeability, with an infiltration rate of 0.625 ml/s, while also revealing that cement composition significantly affects compressive strength. Specifically, Dangote 42.5R cement, with its higher CaO and lower SiO_2 content, produced the strongest samples, achieving an average compressive strength of 26.55 N/mm^2 and a water absorption rate of 10.38%., the inclusion of silica fume was found to enhance strength through pozzolanic reactions. These findings provide valuable insights into the design and optimization of permeable paving stones for sustainable urban drainage systems and establish a foundational framework for improved design and construction practices. Ultimately, this research offers practical evidence for the feasibility of permeable pavements in tropical environments, contributing to more resilient stormwater management and sustainable infrastructure development.

Keywords

Permeable Paving Stones, Concrete Mix Design, Cement Composition, Compressive Strength, Moisture Content, Permeability, Ordinary Portland Cement

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1. Introduction

Urbanization and rapid infrastructure development have significantly altered natural hydrological cycles, particularly through the widespread use of impervious surfaces such as asphalt and conventional concrete pavements. According to Mariana, these surfaces inhibit infiltration, leading to increased surface runoff, higher peak discharge, urban flooding, erosion, and degradation of receiving water bodies [1].

Marchioni and Becciu observe that in many developing urban regions, including parts of West Africa, the limitations of conventional drainage systems are increasingly evident, as they primarily emphasize rapid conveyance of stormwater rather than addressing runoff generation at the source [2]. Mariana, Graham and colleagues, also notes that traditional urban stormwater management approaches relieve heavily on underground drainage infrastructure designed to transport runoff from high-elevation areas to low-lying zones. While effective in the short term, such systems are often economically unsustainable and environmentally inefficient under conditions of continued urban expansion [1, 3].

Smith and Johnson explain that the increase in impervious surfaces associated with urban growth intensifies runoff volumes and pollutant transport, contributing to flooding, sedimentation, and water quality deterioration [4]. Consequently, there is growing need for sustainable, decentralized stormwater control measures that reduce runoff at its source and restore natural hydrological functions. Zhiji and colleagues point out that Permeable pavements have emerged as a viable solution for sustainable stormwater management by allowing precipitation to infiltrate through pavements surfaces into underlying layers, thereby reducing runoff volume and peak flow rates [2, 5].

Marchioini and Becciu further describe these systems' function through a combination of infiltration, storage, and gradual release of stormwater, effectively mimicking pre-development drainage conditions. In addition to hydrological benefits, Zhuge notes that permeable pavements (PP) have been shown to improve runoff quality by filtering suspended solids, heavy metals and hydrocarbons through sedimentation and adsorption process within the pavement structure [2, 6].

Despite their advantages, the structural performance and durability of permeable paving systems remain key concerns, particularly in systems remain key concerns, particularly in regions where climatic conditions, material availability, and construction practices differ from those in which most existing studies have been conducted. Cetin, as well as Miklas Scholz, have found that permeable pavements are typically limited to low-traffic applications due to reduced compressive strength compared to conventional pavements [7, 8].

Furthermore, Rafiat highlights that a notable gap exists in the literature regarding standardized concrete mix ratios for permeable paving stones that adequately balance permeable paving stones that adequately permeability, strength, and durability. This lack of standardized guidance constrains the widespread adoption of permeable pavements in practical engineering applications [9].

Material composition, particularly cement chemistry and the incorporation of supplementary cementitious materials, plays a critical role in determining the mechanical and hydraulic performance of PPS. Rafiat and Prabhat and colleagues explain that Silica Fume (SF), a highly reactive pozzolanic by-product of silicon and ferrosilicon production, has been widely reported to enhance concrete strength, durability, and microstructural refinement when used in optimized proportions [9, 10]. However, limited research has examined the combined influence of cement chemical composition and SF addition on permeable paving stones within tropical environments, where high rainfall intensity and temperature variations impose additional performance demands.

This study addresses these gaps by investigating the innovation of permeable paving stones for surface runoff control using the AIT Hill Top junction to Block Factory junction as a case study. The research experimentally evaluates permeable paving stones produced with two commonly used brands of Ordinary Portland Cement (OPC) (Dangote 42.5R and Ghacem 42.5R) and varying proportions of SF.

The results indicate that permeable paving stones can achieve adequate structural performance while maintaining effective hydraulic functionality when appropriate materials and mix proportions are employed. The findings show that cement chemical composition significantly influences compressive strength, with Dangote 42.5R exhibiting superior performance due to its higher calcium oxide content.

Overall, the study confirms that properly designed permeable paving stones represent a technically feasible and sustainable alternative to traditional pavements for urban stormwater management.

2. Definition and Background of Permeable Pavement

Mariana defines permeable pavements as structures with open spaces that allow water and air to pass through and are suitable for various applications such as roads, parking lots, and courtyards [1]. These pavements must support traffic loads while enabling swift water infiltration into the pavement voids. Various surface options are available, including precast concrete blocks, porous concrete, and porous asphalt, amongst others. These designs are known to provide vehicular support, while the pavement base or subbase is like conventional ones but with higher aggregate void content to function as a water reservoir. Due to reduced strength, permeable pavements are typically used in low-traffic areas with limited heavy vehicle loading [1].

The research on permeable pavements began in the 1970s, primarily through laboratory simulations, with full scale tests starting in 1980s. These studies demonstrated the effectiveness of permeable pavements in reducing runoff volume and removing pollutants, confirming their potential as Sustainable Urban Developments (SUDs) and their local feasibility.

Johnson and colleagues further investigate various sustainable paving materials, including permeable concrete, pervious asphalt, and interlocking permeable pavers [11]. Their study evaluates the effectiveness of these materials in controlling surface runoff and reducing pollutants, providing insights into their environmental benefits and limitations. The research emphasizes that the selection of appropriate paving material depends on site-specific conditions, traffic loads, and stormwater management objectives [11].

Chen and colleagues examine the design principles and performance evaluation of permeable pavements in managing stormwater runoff [12]. Their research discusses factors such as pavement structure, infiltration rates, and pollutant removal efficiency, offering recommendations for optimizing the effectiveness of permeable pavement systems. The study highlights that proper design considerations, including aggregate gradation, void content, and subbase thickness, are critical to achieving long-term performance and durability [12].

Brown and colleagues assess the environmental impacts and benefits of innovative paving solutions, including their contribution to reducing urban heat island effect, enhancing water quality, and promoting groundwater recharge [13]. Their research emphasizes the importance of considering life cycle assessments and long-term sustainability in pavement design and implementation. The findings suggest that permeable pavements offer significant environmental advantages over traditional impervious surfaces, particularly in terms of stormwater management and thermal performance [13].

Lee and colleagues conduct an economic analysis of permeable pavement systems for sustainable stormwater management, evaluating their cost-effectiveness compared to traditional impervious surfaces [14]. Their research considers factors such as installation costs, maintenance expenses, and societal benefits, providing insights for decision-makers and urban planners. The study concludes that while initial costs of permeable pavements may be higher than conventional pavements, the long-term benefits, including reduced stormwater infrastructure requirements and environmental advantages, often justify the investment [14].

2.1. Background to Silica Fume

SF, which is also known as 'Micro silica,' is an amorphous (non-crystalline) polymorph of silicon dioxide, silica. In addition, it is an ultrafine powder collected as a byproduct of silicon and ferrosilicon alloy production, and it consists of spherical particles with an average particle diameter of 150nm. Its field of application is pozzolanic material for high performance concrete and offering a sustainable solution for the construction industry. That is, it reacts with calcium hydroxide to form cement. As environmental concerns escalate, identifying alternative applications for industrial byproducts has become a pressing priority to mitigate harmful impacts. Silica fume (SF), a byproduct of silicon and ferrosilicon production, presents a promising solution, [9]. This industrial waste material has been repurposed in various construction and materials science applications, offering potential benefits for sustainability and waste reduction. Furthermore, it can be considered environmentally friendly by reducing pollution, conserving natural resources and low CO_2 emissions. That is, it reduces the permeability of concrete to chloride ions which protects the reinforcements steel of concrete from corrosion. Hence, it can reduce pollution from corrosion and the environmental impact of repairing and replacing damaged concrete structures. The usage of SF can be used to produce geopolymer concrete, which has lower CO_2 emissions compared to traditional concrete.

Miklas Scholz recommends that silica fume and superplasticizer can be added to permeable concrete ingredients, and this brings about an improved compressive strength of permeable pavements to allow for higher load capacity which also depends on the application [7].

Noor and colleagues investigate the use of natural Zeolite and synthetic zeolite to create zeolite-enhanced blended cement for enhancing the properties of concrete paver blocks and paving stones [15]. Their research demonstrates that the use of natural zeolite as an admixture in concrete enables paver blocks and paving stones to attain greater durability and compressive strength, thereby increasing the sustainability of paving stones.

2.2. Physical Properties of Silica Fume and Ordinary Portland Cement

Prabhat and colleagues explain that the amount of silicon dioxide in the silica fume is greater than 90% and 85% when fabricated from silicon metal and ferrosilicon alloys, respectively [10]. SF consists of extremely fine, spherical particles which are typically smaller than 1 μm in diameter. With a specific gravity of 2.2, it has a remarkably high specific surface area, ranging from 15,000 to 30,000 m^2/kg as seen in (Table 1), which is significantly greater than cement's specific surface area of approximately 1,500 m^2/kg. In addition, the exceptional fineness of silica fume (SF) contributes to its filler effect, creating an ideal environment for the nucleation of calcium hydroxide crystals. Furthermore, Abdulrahman notes that the chemical composition of silica fume usually consists of more than 90% SiO_2 (85-99%) with other oxides such as: Fe_2O_3, Al_2O_3, CaO, MgO, Na_2O, and K_2O which is less than 1%, As seen in Table 2 [16].

Table 1. *Physical properties of Ordinary Portland Cement (OPC) and Silica Fume (SF).*

Item	Physical Properties	OPC	SF
1	Specific gravity	3.1	2.2
2	Mean grain size (μm)	22.5	0.15
3	Specific area (m^2/kg)	3,250	15,000-30,000
4	Colour	Dark Grey	Light Grey or Dark Grey

2.3. Chemical Composition of Silica Fume and Ordinary Portland Cement

Akyen and Kankam, as well as Mohamed, provide the chemical compositions of the two cements (Dangote 42.5R and Ghacem 42.5R) and silica fumes used in this study [17, 18]. The extracted chemical compositions are presented in (Table 2), and it is utilized in this research work.

Table 2. *Chemical Composition of Ordinary Portland Cement and Silica Fume.*

Item	Chemical Composition	Ghacem 42.5R (%)	Dangote 42.5R (%)	Silica Fume (%)
1	Silicon dioxide (Si02)	22.1	15.7	97
2	Aluminum oxide (Al2O3)	5.20	3.78	0.2
3	Iron oxide (Fe203)	4.04	3.49	0.5
4	Calcium oxide (CaO)	61.1	70.1	0.2
5	Magnesium oxide (MgO)	3.25	1.08	0.5
6	Sodium oxide (Na2O)	0.00	0.00	0.2
7	Potassium oxide (K2O)	0.680	0.773	0.5

3. Materials and Methods

This chapter outlines the research methodology used to achieve the research objectives. The methodology involves procurement of materials (fine aggregate or quarry dust, coarse aggregates/granite, silica fume (additive), cement, etc.) for the construction of traditional pavement (T) and permeable pavement (P) /paving stones. Furthermore, compressive strength test and moisture content test will be carried out on both paving stones, and slump test will be carried out to determine the workability of the concrete mix. In addition, the permeability of the permeable paving stone will also be tested.

In addition, this chapter further provides a detailed explanation of the methods used to collect data on compressive strength, permeability, and moisture content. This information is crucial in understanding the properties of the paving stone samples used in the study.

To gain a deeper understanding of the compressive strength of the paving stone samples, secondary data was used to acquire the chemical compositions of the two cements (Dangote 42.5R 'C_1' and Ghacem 42.5R 'C_2' as well as silica fumes used in the research. The tests conducted in this study aim to provide valuable insights into the strength, durability, and workability of each cast sample. These results will be further analyzed and discussed in subsequent chapters, providing a comprehensive understanding of the properties of the paving stone samples.

3.1. Materials

Fine Aggregates/Quarry Dust: These materials served as the primary filler and binding agents in the paving stone mixture, enhancing its strength and durability. In addition, materials raging between 0.075mm to <3mm will be used in constructing the paving stones/pavement samples.

Coarse Aggregates (3-8mm diameter): These provide structural integrity and porosity to the paving stones, allowing for efficient water permeability.

Silica Fume (SF): As an additive, SF improved the mechanical properties and durability of the permeable paving stones. Its pozzolanic properties reacted with calcium hydroxide to form calcium silicate hydrate, enhancing strength and resistance to degradation. See Figure 1.

Cement: Different cement brands were used to assess their impact on the performance of permeable paving stones.

The selection of these materials is guided by the need to optimize the strength, durability, and permeability of the paving stones. By combining fine and coarse aggregates, the mixture achieves a balance between binding and porosity. The addition of SF to the permeable paving stone concrete mix enhances its mechanical properties and resistance to environmental stressors. Utilizing different cement brands allows for a comprehensive evaluation of their effects on paving stone performance. This thoughtful material selection ensures the development of sustainable and durable permeable paving stones that meet the demands of urban drainage systems.

3.2. Methodology

This research adopted an experimental approach to investigate the effects of Silica fumes as a substitute for cement on the properties of permeable paving stones. The methodology involves constructing 48 paving stone samples using two different cement brands and testing them at 7-day intervals. Compressive strength tests are carried out on the samples to assess their durability. Permeability tests are carried out on the permeable paving stones (PPS) to evaluate their ability to filter stormwater and to determine their infiltration rate. Moisture content tests are also carried out to determine the paving stone's water absorption percentages.

The adoption of Silica fumes as an additive is expected to enhance the PPS's performance, and the comparison between the two cement brands (Ghacem 42.5R 'C2' and Dangote 42.5R 'C1') will provide insights into their suitability for permeable paving applications. In addition, by utilizing two different cement brands in conducting tests on the paving stones/pavements, it offers several benefits. By comparing the performance, strength, and durability of paving stones made with distinct cement brands, researchers can evaluate the consistency of results across different cement types and assess their compatibility with other materials.

This setup also allows for the investigation of variability in test results due to differences in cement properties, providing a more comprehensive understanding of how cement selection impacts paving stone quality. Furthermore, testing multiple cement brands reflects real-world construction scenarios where different brands may be used, enabling the identification of optimal cement choices for specific applications. For instance, researchers can explore how Cement brand 'A' and Cement brand 'B' influence compressive strength, durability, and environmental resistance, shedding light on the physical and chemical properties that drive these differences. By controlling other variables and selecting cement brands with distinct characteristics, researchers can isolate the effects of cement brand on paving stone performance, ultimately informing evidence-based decisions in construction and materials science.

The adopted methodology is justified due to its comprehensive approach, which addresses the mechanical, hydraulic, and durability aspects of permeable paving stones. Unlike previous studies which focused on a single aspect or used simulated experiments, this study's experimental design ensures realistic results that can be applied to practical scenarios. Furthermore, the use of two cement brands and the incorporation of SF, an additive provides a nuanced understanding of the interactions between materials and their impact on the paving stones' performance.

In conclusion, this study's methodology is more robust and reliable than previous methods, which relied heavily on theoretical models or limited experimental data. By testing the samples at regular intervals, this study captures the temporal effects of the materials' interactions, providing a more accurate representation of the paving stones' behavior in real-world conditions.

3.3. Data collection

To gather accurate and reliable data for innovating permeable paving stones, we adopted the following methods:

Compressive Strength Tests: We evaluated the compressive strength of all concrete samples at intervals of 7, 14, 21, and 28 days. We conducted these tests in the laboratory using a 2000KN Universal Testing Machine (UTM). We tested traditional pavement samples without additives ('T'- 0% silica fume, 100% cement) and permeable paving stones (PPS) both with additives 'P10' to 'P40' and without 'P0".

Porosity and Void Ratio Measurements: We determined the porosity of the permeable paving stones by performing permeability tests on the concrete samples. We poured 500ml of water onto each stone and measured the resulting infiltration rate. See Figure 2.

3.4. Experimental Plans

This research required an assessment of the compressive strength of both traditional and permeable paving stones to ensure their safety, durability, and reliability. We executed the research process as follows:

Sieve Analysis: we conducted a sieve analysis on the procured quarry dust samples to separate the required aggregates from the bulk material. We utilized a set of standard sieves. To ensure thorough drying and accurate results for the large quantity of material, we air-dried the samples for 48 hours rather than the standard 24-hour period. Table 3 presents the results of this analysis, while Figure 3 illustrates the particle size distribution curve for the 5kg (5000g) material sample used.

Sample Construction and Mix Ratios: we constructed a total of 48 paving stone samples: 24 using Ghana Cement (Ghacem) 42.5R and 24 using Dangote 42.5R. We followed BS EN 13877-2:2013 for traditional paving stones and IRC: 44-2017 for permeable pavements. We applied a mix ratio of 1:1.3:1.6 for traditional stones and 1:1.1:1.6 for permeable stones; these variations created the necessary voids in the permeable samples. We also performed concrete slump tests on the mixes to ensure sufficient workability for filling the molds (see Figure 3.6 and Chapter 4).

Additives and Curing: we integrated silica fume additives into the PPS mixes at increments of 10% to 40%. The specific cement-to-silica fume ratios were:

100% / 0% (Control)
90% / 10%
80% / 20%
70% / 30%
60% / 40%

We cured the samples for 7, 14, 21, and 28 days. For every curing age, we tested 48 samples (24 of Brand A-Dangote 42.5R and 24 of Brand B-Ghacem42.5R) for compressive strength, permeability (this test was only carried out on PPS samples), and moisture content.

Identification and Testing Procedures: for dentification, we marked Dangote 42.5R as 'C_1' and Ghacem 42.5R as 'C_2'. We labeled traditional and permeable samples as 'T' and 'P,' respectively.

Moisture Content: We conducted moisture content tests on samples before compressive testing (refer to Table 4).

Infiltration: We monitored how the stones absorbed and released water over the curing intervals to observe the infiltration process.

Compressive Strength: We tested all samples at 7-day intervals. Compressive strength of each sample was calculated.

Figure 1. *Coarse & Fine (Quarry Dust) Aggregates, Dust, Cement, and SF.*

Figure 2. *Permeability test on PPS.*

Table 3. *Particle Size Distribution of Aggregates.*

IS Sieve Size (mm)	Weight Retained (g)	Percentage Weight Retained (%)	Cumulative Weight Retained (%)	Cumulative Passing (%)
13.2	217	4.34	4.34	95.66
9.5	682	13.64	17.98	82.02
4.75	1225	24.5	42.48	57.52
2.56	736	14.72	57.2	42.8
0.15	2005	40.1	97.3	2.7
0.075	134	2.68	99.98	0.02
Pan	0	0	0	0
sum	4999	99.98		

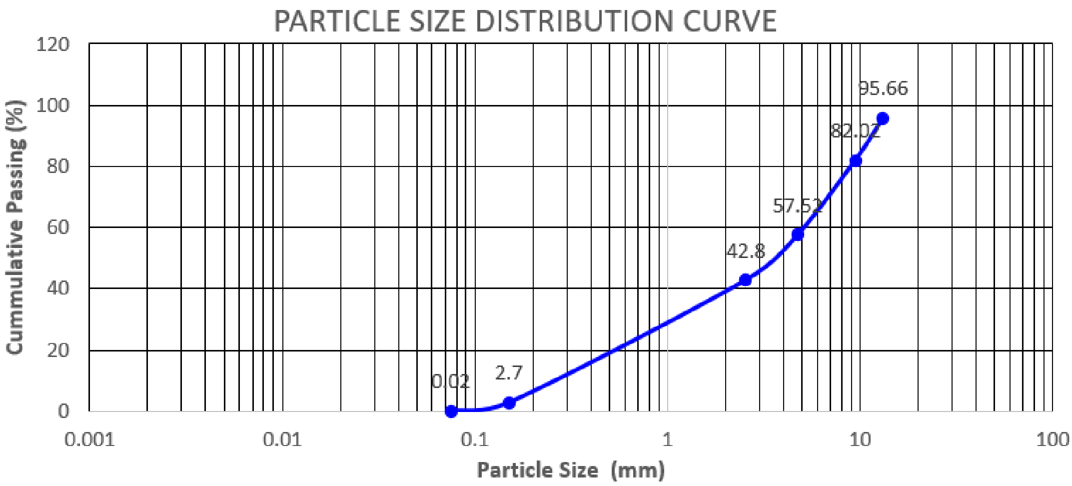

***Figure 3**. Particle Size Distribution Graph.*

4. Experimental Results and Analysis

This chapter provides a detailed breakdown of each section of the project methodology. Following the design and testing of traditional (T) and permeable (P) paving stones, their compressive strength, moisture content, workability (slump test), and permeability were evaluated. The chemical compositions of the binders (cements and silica fumes) were also assessed, along with their influence on the characteristic strength and water absorption patterns of the samples. The primary objective of this study is to develop paving systems that enhance water absorption and retention, thereby reducing runoff-related issues.

4.1. Sieve Analysis Results

The graphical representation (Figure 3) of results in (Table 3) shows that the soil has a relatively uniform distribution of particle sizes, with a gradual decrease in the percentage of particles passing each sieve. Hence, this suggests that the soil is well graded.

4.2. Slump Test

A slump test was conducted on both the traditional paving stone and permeable paving stone mixes to determine their workability. The results showed a zero (0) slump, which is a standard requirement for paving stones. This indicates that the mixes possessed adequate workability and were suitable for constructing the paving stone samples.

4.3. Permeability Test Result

500ml of water gradually poured onto the paving stones.

The paving stones absorbed approximately 200ml of the water and released 300ml in 8 minutes (480s), indicating a moderate level of permeability. This observation was consistent across all paving stone samples. Visual description of The test can be seen in the appendix section.

$$Infiltration\ \ rate(mL/min) = \frac{Waterinfiltrated(mL)}{Time(min)} \quad (1)$$

$$= \frac{300mL}{480s} = 0.625mL/s$$

Hence, the water infiltrated the paving stone at a rate of 0.625ml/s. That is, 37.5 ml of water will infiltrate the paving stone in 1 minute.

4.4. Moisture Content Test

This study examines the water absorption and compressive strength behavior of paving stones constructed using two different cement types, Dangote 42.5R and Ghacem 42.5R, under varying design conditions. Traditional impervious paving stones and permeable paving stones were produced, with the latter fabricated both without additives and with the inclusion of silica fume. The experimental design was intended to evaluate how cement brand and additive incorporation influence the chemical composition, hydration reactions, and curing process, thereby affecting porosity and strength development. To assess moisture absorption, a moisture content test was conducted by recording the weight of each sample at specific curing ages (7, 14, 21, and 28 days), relative to the initial weight measured after 24 hours of casting (see Table 1). This systematic monitoring of water absorption patterns provides insight into the microstructural evolution of each mix and explains the performance differences, particularly identifying the sample with the highest compressive strength as a function of its chemical constituents and curing dynamics.

The results in Table 4 are calculated using Equation (2), and the average MC is calculated using Equation (3). The equations are then repeated to calculate the MC and average MC for all the paving samples.

$$\text{Moisture Content (MC)} = (\text{Wet Weight} - \text{Initial weight}) X 100\% \quad (2)$$

$$C1T = (3.73 - 3.64)\ X\ 100\% = 9.0\%$$

$$C2T = (3.70 - 3.63)\ X\ 100\% = 7.0\%$$

$$(AverageMC) = \frac{Day\ 7\ \text{MC} + Day\ 14\ \text{MC} + Day\ 21\ \text{MC} + Day\ 28\ \text{MC}}{4} \quad (3)$$

$$C1T\ (Average\ MC): \frac{9 + 9+9+9}{4} = 9.0\%$$

$$C2T\ (Average\ MC): \frac{7 + 11.5+8+9.5}{4} = 9.0\%$$

The average MC was calculated and plotted on a graph to better understand the differences in water absorption pattern which also influenced the compressive strength of each paving stone. On average, P_0 which is permeable paving stone constructed with 0% additive (SF) and 100% cement (Dangote 42.5R 'C_1') had the highest water absorption rate of 10.38%, followed by 'P_{20}' which is permeable paving stone constructed with 20% additive (SF) and 80% cement (Ghacem 42.5R 'C_1'). See Table 4.

4.5. Compressive Strength Test

The compressive strength of each paving-stone sample was determined at curing ages of 7, 14, 21, and 28 days using Equation (4). Tables 5-8 present the strength values determined for each specimen at various ages, while Figures 5-8 illustrate the corresponding trends. Figure 4 shows how the mixtures absorb water on average during the curing period.

At 7 days, C_1T (traditional paving stone produced with Dangote 42.5R) recorded the highest compressive strength, followed by C_2P_0 (permeable paving stone produced with 100% Ghacem 42.5R and 0% silica fume). At this age, C_2P_{40} (a permeable paving stone made with 60% Ghacem 42.5R and 40% silica fume) showed the lowest strength. Both C_1T and C_2T traditional specimens met the BS minimum strength, but several permeable mixtures failed to satisfy the IRC requirement at 7 days (Figure 5).

After curing for 14 days, C_2P_{10} (a permeable paving stone made with 90% Ghacem 42.5R and 10% silica fume) showed the highest compressive strength. The next strongest was C_1P_0 (produced using 100% Dangote 42.5R and no silica fume). C_2P_{40} remained the lowest-strength mixture at this age (Figure 6). On 14 days, both traditional mixtures met the required strength, and all permeable paving stones satisfied the IS strength criteria referenced in the IRC guidelines.

By 21 days, compressive strength increased for all mixtures (Figure 7). C_2P_0 (with 100% Ghacem 42.5R and no silica fume) showed the highest value, while C_1P_0 (containing 100% Dangote 42.5R and no silica fume) and C_1T had values that were only slightly lower. The lowest strength continued to be associated with C_2P_{40}. At this curing age, all paving-stone mixtures met the specified strength requirements.

At 28 days, the strength development exhibited mixed behavior, with marginal increases in some mixtures and slight reductions in others (Figure 8). C_1P_{10}, which consists of 90% Dangote 42.5R and 10% silica fume, reached the highest strength after 28 days, with C_1P_0 and C_1T coming next. On the other hand, C_2P_{40} had the lowest strength once again. Notwithstanding these differences, all mixtures satisfied the required strength at 28 days.

To compare various curing ages thoroughly, the average compressive strength for each mixture was measured during the 7–28-day period (refer to Figure 9). The results indicate that C_1P_0 exhibited the highest mean compressive strength (26.55 N/mm^2), alongside its corresponding moisture-absorption behaviors (Figure 4), followed by C_2P_0 (26.05 N/mm^2) and C_2P_{10} (25.99 N/mm^2). Overall, the permeable paving stones achieved higher compressive strengths than the traditional paving stones and exceeded the IRC guideline values. Based on the average-strength performance, Dangote 42.5R produced the most favorable outcome, with C_1P_0 (100% Dangote 42.5R; 0% silica fume) yielding the highest average compressive strength.

$$\text{Concrete Strength} = \frac{\text{Compressive Strength } (N/mm2)}{\text{Area } (mm2)} \quad (4)$$

Table 4. Moisture Content (MC) of the paving samples.

Mark	Day (7) Initial weight (kg)	Day (7) Wet weight (kg)	Day (7) MC. (%)	Day (14) Initial weight (kg)	Day (14) Wet weight (kg)	Day (14) MC. (%)	Day (21) Initial weight (kg)	Day (21) Wet weight (kg)	Day (21) MC. (%)	Day (28) Initial weight (kg)	Day (28) Wet weight (kg)	Day (28) MC. (%)
C_1 T	3.64	3.73	9.0	3.87	3.96	9.0	3.62	3.71	9.0	3.72	3.81	9.0
C_2 T	3.63	3.70	7.0	3.64	3.75	11.5	3.65	3.73	8.0	3.59	3.68	9.5
$C_1 P_0$	3.55	3.64	9.0	3.53	3.65	12.0	3.48	3.57	9.5	3.39	3.50	11.0
$C_2 P_0$	3.64	3.72	8.5	3.50	3.60	10.0	3.63	3.73	10.5	3.71	3.78	7.5
$C_1 P_{10}$	3.43	3.53	10.0	3.40	3.50	10.5	3.40	3.50	10.5	3.44	3.52	8.0
$C_2 P_{10}$	3.60	3.70	10.0	3.49	3.60	11.5	3.55	3.64	9.0	3.53	3.59	6.5
$C_1 P_{20}$	3.43	3.51	8.5	3.60	3.70	10.5	3.62	3.71	9.0	3.53	3.62	9.5
$C_2 P_{20}$	3.46	3.55	9.5	3.23	3.35	12.0	3.45	3.54	9.5	3.38	3.48	10.0
$C_1 P_{30}$	3.19	3.28	9.5	3.36	3.45	9.5	3.45	3.53	8.5	3.33	3.43	10.0
$C_2 P_{30}$	3.53	3.60	7.0	3.42	3.50	8.5	3.27	3.34	7.5	3.40	3.45	5.0
$C_1 P_{40}$	3.43	3.50	7.5	3.44	3.50	6.5	3.44	3.51	7.5	3.44	3.49	5.0
$C_2 P_{40}$	3.40	3.60	20.0	3.35	3.35	0.5	3.39	3.40	1.0	3.25	3.33	8.0

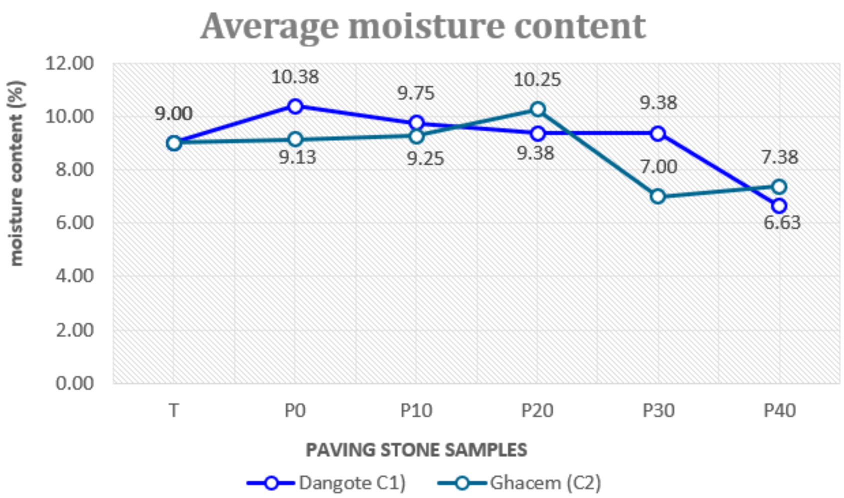

Figure 4. Average MC of Paving stone samples.

Table 5. Day 7 compressive strength of paving samples.

Mark or Ref No.	Dimension, (mm) l	b	h	Cross Sec. Area, (mm^2)	Age days	Load KN	Compressive Strength (N/mm^2)	Mix Proportion Strength	Mass (kg)	Density (kg/m^3)
C_1 T	200	100	80	20000	7	538.9	26.94	M17-M^{2}5	3.73	2331.3

Mark or Ref No.	Dimension, (mm)			Cross Sec. Area, (mm^2)	Age days	Load KN	Compressive Strength (N/mm^2)	Mix Proportion Strength	Mass (kg)	Density (kg/m^3)
	l	b	h							
C_2 T	"	"	"	"	"	407.7	20.38	""	3.70	2312.5
$C_1 P_0$	"	"	"	"	"	489.3	24.47	M5-M^{2}5	3.64	2275.0
$C_2 P_0$	"	"	"	"	"	522.1	26.10	""	3.72	2325.0
$C_1 P_{10}$	"	"	"	"	"	369.1	18.46	""	3.53	2206.3
$C_2 P_{10}$	"	"	"	"	"	456.6	22.83	""	3.70	2312.5
$C_1 P_{20}$	"	"	"	"	"	437.4	21.87	""	3.51	2193.8
$C_2 P_{20}$	"	"	"	"	"	346.5	17.32	""	3.55	2218.8
$C_1 P_{30}$	"	"	"	"	"	267.3	13.37	""	3.28	2050.0
$C_2 P_{30}$	"	"	"	"	"	349.3	17.46	""	3.60	2250.0
$C_1 P_{40}$	"	"	"	"	"	285.8	14.29	""	3.50	2187.5
$C_2 P_{40}$	"	"	"	"	"	169.8	8.49	""	3.60	2250.0

***Table 6**. Day 14 compressive strength of paving samples.*

Mark or Ref No.	Dimension (mm)			Cross Sec. Area, (mm^2)	Age days	Load KN	Compressive Strength (N/mm^2)	Mix Proportion Strength	Mass (kg)	Density (kg/m^3)
	l	b	h							
C_1 T	200	100	80	20000	7	356.6	17.83	M17-M^{2}5	3.95	2468.8
C_2 T	"	"	"	"	"	434.4	21.72	""	3.75	2343.8
$C_1 P_0$	"	"	"	"	"	463.6	23.18	M5-M^{2}5	3.65	2281.3
$C_2 P_0$	"	"	"	"	"	402.8	20.14	""	3.60	2250.0
$C_1 P_{10}$	"	"	"	"	"	407.9	20.40	""	3.50	2187.5
$C_2 P_{10}$	"	"	"	"	"	466.6	23.33	""	3.60	2250.0
$C_1 P_{20}$	"	"	"	"	"	419.4	20.97	""	3.70	2312.5
$C_2 P_{20}$	"	"	"	"	"	366.4	18.32	""	3.35	2093.8
$C_1 P_{30}$	"	"	"	"	"	378.0	18.90	""	3.45	2156.3
$C_2 P_{30}$	"	"	"	"	"	405.9	20.30	""	3.50	2187.5
$C_1 P_{40}$	"	"	"	"	"	311.8	15.59	""	3.50	2187.5
$C_2 P_{40}$	"	"	"	"	"	169.8	8.49	""	3.35	2093.8

Table 7. *Day 21 compressive strength of paving samples.*

Mark or Ref No.	Dimension (mm)			Cross Sec. Area, (mm^2)	Age days	Load KN	Compressive Strength (N/mm^2)	Mix Proportion Strength	Mass (kg)	Density (kg/m^3)
	l	b	h							
C_1 T	200	100	80	20000	7	582.7	29.13	M17-M²5	3.70	2312.5
C_2 T	"	"	"	"	"	410.1	20.50	""	3.73	2331.3
C_1 P 0	"	"	"	"	"	585.1	29.26	M5-M²5	3.57	2231.3
C_2 P 0	"	"	"	"	"	588.3	29.41	""	3.73	2331.3
C_1 P 10	"	"	"	"	"	528.6	26.43	""	3.50	2187.5
C_2 P 10	"	"	"	"	"	581.4	29.07	""	3.64	2275.0
C_1 P 20	"	"	"	"	"	576.8	28.84	""	3.71	2318.8
C_2 P 20	"	"	"	"	"	470.7	23.53	""	3.54	2212.5
C_1 P 30	"	"	"	"	"	403.6	20.18	""	3.53	2206.3
C_2 P 30	"	"	"	"	"	475.8	23.79	""	3.34	2087.5
C_1 P 40	"	"	"	"	"	346.7	17.33	""	3.51	2193.8
C_2 P 40	"	"	"	"	"	336.1	16.81	""	3.40	2125.0

Table 8. *Day 28 compressive strength of paving samples.*

Mark or Ref No.	Average Dimension (mm)			Cross Sec. Area, (mm^2)	Age days	Load KN	Compressive Strength (N/mm^2)	Mix Proportion Strength	Mass (kg)	Density (kg/m^3)
	l	b	h							
C_1 T	200	100	80	20000	7	585.0	29.25	M17-M²5	3.81	2381.3
C_2 T	"	"	"	"	"	556.1	27.80	""	3.68	2300.0
C_1 P 0	"	"	"	"	"	585.3	29.27	M5-M²5	3.50	2187.5
C_2 P 0	"	"	"	"	"	570.7	28.53	""	3.78	2362.5
C_1 P 10	"	"	"	"	"	596.3	29.82	""	3.52	2200.0
C_2 P 10	"	"	"	"	"	574.2	28.71	""	3.59	2243.8
C_1 P 20	"	"	"	"	"	579.3	28.96	""	3.62	2262.5
C_2 P 20	"	"	"	"	"	550.5	27.53	""	3.48	2175.0
C_1 P 30	"	"	"	"	"	573.6	28.68	""	3.43	2143.8
C_2 P 30	"	"	"	"	"	557.4	27.87	""	3.45	2156.3
C_1 P 40	"	"	"	"	"	331.6	16.58	""	3.49	2181.3
C_2 P 40	"	"	"	"	"	334.3	16.72	""	3.33	2081.3

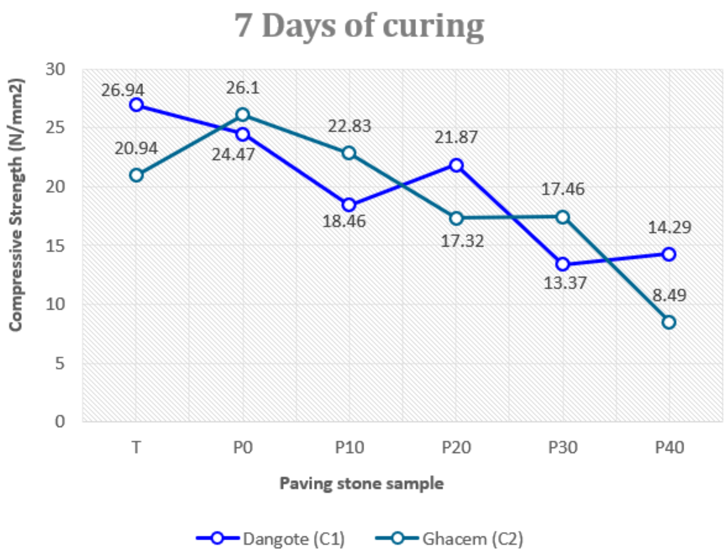

Figure 5. *Day 7 Compressive strength trend.*

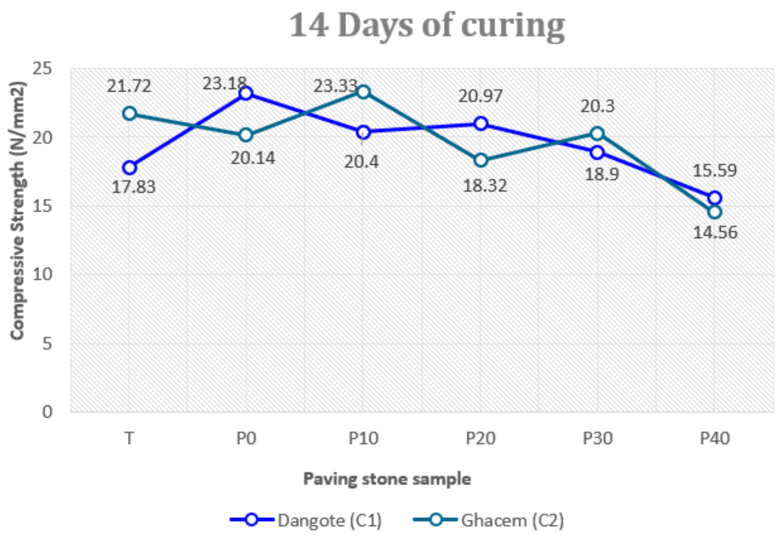

Figure 6. *Day 14 Compressive strength trend.*

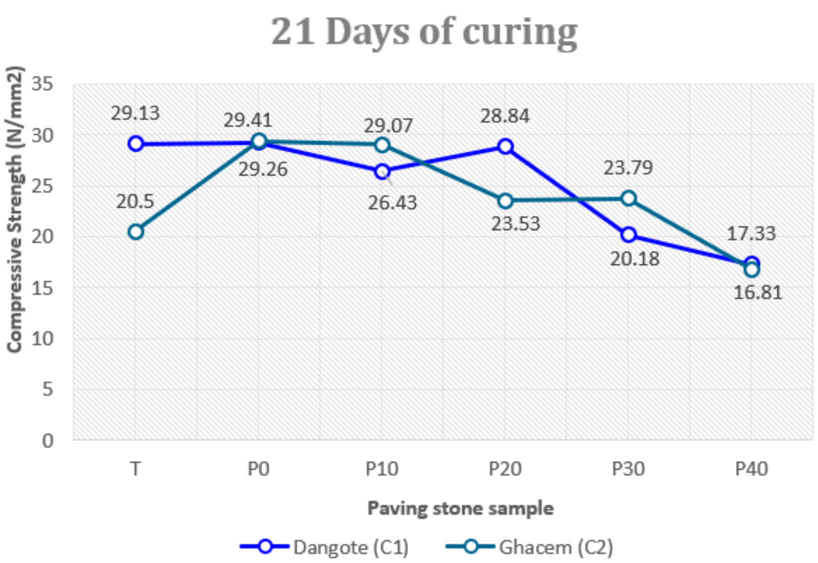

Figure 7. *Day 21 Compressive strength trend.*

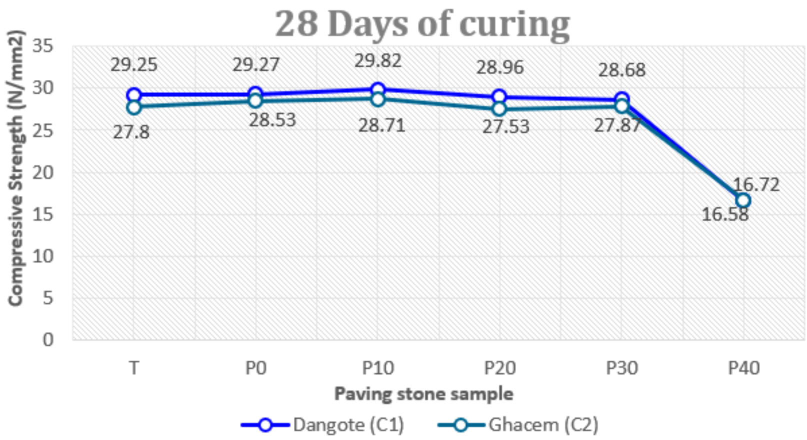

Figure 8*. Day 28 Compressive strength trend.*

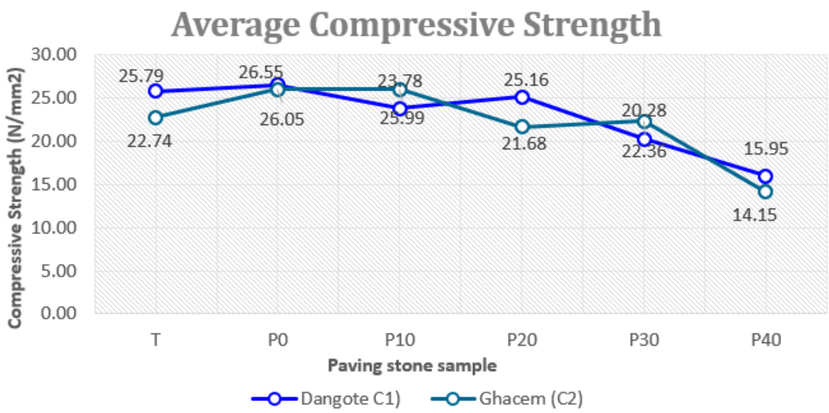

Figure 9*. Average Compressive Strength trend.*

Table 9*. Average compressive strength of paving samples.*

Mark or Ref. No.	Dangote (C_1) (N/mm^2)	Ghacem (C_2) (N/mm^2)
T	25.79	22.74
P0	26.55	26.05
P10	23.78	25.99
P20	25.16	21.68
P30	20.28	22.36
P40	15.95	14.15

5. Data Analysis and Discussion

All paving stone samples met the required strength after 28 days of curing. The average compressive strength of the samples over the curing period was calculated to determine the sample with the highest strength and the cement brand that would yield optimum results. The results are presented in Figure 9. The analysis revealed that C_1P_0 exhibited the highest average compressive strength of 26.55 N/mm^2 and moisture absorption rate which can be seen in Figure 4, closely followed by C_2P_0 with 26.05 N/mm^2, and C_2P_{10} with 25.99 N/mm^2. Notably, the permeable paving stones demonstrated higher compressive strength than the traditional paving stones, surpassing the guidelines stipulated in the IRC. According to the results, Dangote 42.5R yielded optimum results, as C_1P_0 (permeable paving stone cast with 100% Dangote 42.5R and 0% silica fume) exhibited the highest average compressive strength of 26.55 N/mm²."

Findings, conclusions, and recommendations were derived from the experimental observations and are intended to support the development and practical uptake of innovative paving stones/pavements in the construction industry. The results indicate that the performance differences between Dangote 42.5R and Ghacem 42.5R are associated with their chemical compositions: Dangote 42.5R exhibited a higher CaO content (70.1%) than Ghacem 42.5R (61.1%), which is expected to promote stronger hydration reactions and, consequently, higher compressive strength, while variations in other oxides (SiO_2, Al_2O_3, SO_3, and Fe_2O_3) may influence durability, setting behaviour, sulfate resistance, and appearance. Specifically, Ghacem 42.5R contained higher Al_2O_3 (5.2%) and Fe_2O_3 (4.04%), whereas Dangote 42.5R contained higher SiO_2 (22.1%) and lower SO_3 (2.1%). In line with these compositional trends, the highest mean compressive strength was obtained for C_1P_0 (26.55 N/mm^2), followed by C_2P_0 (26.05 N/mm^2), while partial cement replacement with silica fume improved the Ghacem-based mixture, with C_2P_{10} attaining 25.99 N/mm^2, likely due to improved particle packing and enhanced hydration/pozzolanic reactions. Water absorption and permeability tests, conducted by gradually applying 500 ml of water to each specimen, showed that approximately 200 ml was absorbed and 300 ml was released over 8 minutes (480 s), corresponding to an infiltration rate of 0.625 ml/s (37.5 ml/min) and indicating moderate permeability across all samples. The C_1P_0 mixture also recorded a relatively higher water absorption rate (10.38%), which coincided with its higher compressive strength and suggests a favourable pore structure and hydration development. Overall, permeable paving stones produced with both cement brands satisfied the required strength criteria and passed permeability evaluation, and the results further suggest that silica fume can be used to optimise mix designs for enhanced performance.

6. Conclusions and Recommendations

The average compressive strength of the paving stone samples over the curing period was evaluated to identify the mixture with the highest performance and to determine the cement brand capable of delivering optimum results. The analysis showed that the permeable paving stone mixture C_1P_0 achieved the highest average compressive strength of 26.55 N/mm², accompanied by a favourable moisture absorption behaviour, indicating an effective pore structure and hydration process. This was closely followed by C_2P_0 and C_2P_{10}, with average compressive strengths of 26.05 N/mm² and 25.99 N/mm², respectively. Overall, the permeable paving stones demonstrated superior compressive strength compared to the traditional paving stones and exceeded the strength requirements specified in relevant standards. Based on these outcomes, Dangote 42.5R cement was identified as the most effective binder, as its higher calcium oxide content contributed to improved hydration reactions and enhanced mechanical performance.

Beyond performance evaluation, this study contributes to existing knowledge by providing targeted insights into the behaviour of Dangote 42.5R and Ghacem 42.5R cements when used in permeable paving stone applications. The findings establish an optimal mix design framework for permeable pavements using these cement types and highlight the importance of binder chemistry in achieving a balance between strength and permeability. In addition, the application of this research to the AIT Hill Top junction in Ghana offers valuable contextual evidence for the feasibility of permeable pavements in tropical environments, where stormwater management and pavement durability are critical considerations.

To further enhance the performance of permeable pavements, it is recommended that silica fume be incorporated as an admixture rather than as a direct replacement for cement. Introducing silica fume at controlled proportions alongside the cement content would allow its pozzolanic properties to be fully exploited without reducing binder availability. This approach is expected to improve particle packing, strengthen the interfacial transition zone, and promote secondary hydration reactions, thereby improving compressive strength, durability, and hydraulic performance. Systematic testing across varying silica fume contents is recommended to identify optimal dosage levels.

In addition, modifications to the mix design should be explored to further improve permeability while maintaining adequate structural strength. Adjusting the aggregate-to-cement ratio, incorporating porous aggregates, and optimizing aggregate gradation can enhance interconnected void spaces and facilitate higher runoff infiltration rates. Any revised mix design should be carefully balanced to satisfy both strength and permeability requirements, ensuring functional and structural efficiency of the pavement system.

Future research should examine the effects of different silica fume sources and types on the mechanical and hydraulic performance of permeable paving stones, as material variability may influence pozzolanic reactivity. Field trials are also recommended to validate laboratory findings under real traffic and environmental conditions. Further studies may explore the use of alternative cement types and supplementary cementitious materials to improve sustainability and reduce environmental impact. In addition, research focused on scaling up permeable pavement implementation in African urban settings, including the development of region-specific standards and policies, would support broader adoption. Finally, life cycle assessment studies are recommended to evaluate the environmental performance of permeable pavements from material production to end-of-life management, thereby supporting sustainable infrastructure development.

Abbreviations

OPC	Ordinary Portland Cement
SF	Silica Fume
PPS	Permeable Paving Stone
MC	Moisture Content
SUDs	Sustainable Urban Developments
UTM	Universal Testing Machine

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Conflicts of Interest

The authors declare no conflicts of interest.

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