International Information and Engineering Technology Association
Advancing the World of Information and Engineering

Revue des Composites et des Matériaux Avancés-Journal of Composite and Advanced Materials
Vol. 36, No. 2, April, 2026, pp. 385-394
Journal homepage: http://iieta.org/journals/rcma

Sustainable Pervious Concrete: Enhancing Performance with Recycled Waste Materials

Swati Sonawane, Mugdha Kshirsagar*, Muskaan Kushwaha, Aroushi Bhagwat, Sonal Waghmare

Department of Civil Engineering, Symbiosis Institute of Technology, Symbiosis International University, Pune 412115, India

Corresponding Author Email: mugdhak@sitpune.edu.in

https://doi.org/10.18280/rcma.360214

Received: 20 January 2026
Revised: 20 March 2026
Accepted: 31 March 2026
Available online: 30 April 2026

Keywords:
pervious concrete, waste materials, sustainable construction, recycled aggregates, ceramic waste

ABSTRACT

This study examines the use of ceramic waste tiles as a partial substitute for natural coarse aggregates in pervious concrete to enhance sustainability without compromising functional performance. A series of experiments was conducted to use Portland cement and various proportions of processed ceramic waste aggregates. The compressive strength, density, water absorption and porosity of the mixes were evaluated to determine mechanical and physical properties. Seven mix designs were designed in order to study how the percentage of replacement affected structural and hydraulic behavior. The findings suggest that there is enough compressive strength with the controlled introduction of ceramic waste without losing the interconnecting pore structure necessary to the performance of drainage. The optimum mix exhibited a balance between mechanical stability and hydraulic activity, demonstrating the technical viability of waste-incorporated pervious concrete for light-duty pavement applications. Hydraulic performance was measured using the standard infiltration test procedure. Although the mechanical and physical short-term properties were thoroughly tested, long-term durability factors like freeze-thaw and clogging susceptibility were not experimentally tested and are identified as opportunities for future research. Overall, the results show that waste-based pervious concrete with ceramic form could be applied as a sustainable substitute for stormwater management to protect the resources, minimize construction waste and take a responsible approach to the development of cities.

1. INTRODUCTION

Fast urbanization has significantly covered the impervious surfaces, which interfere with the natural hydrological cycles and reduce the groundwater recharge. This has increased the urban flooding, the surface temperatures and made the urban heat island effect worse. At the same time, solid waste production in the world will be 3.4 billion tonnes in 2050 and the content of ceramic waste makes an important portion of this quantity since it includes high levels of rejection during manufacturing, transportation and construction processes [1, 2]. The ceramic industry alone contributes to almost 30% of waste production that is not biodegradable and can be disrupted in the environment, as it is a tough one that is not easily disposed of over the long run [3, 4]. Simultaneously, the traditional concrete manufacturing method is one of the primary sources of CO_2 emission in the world, about 7 to 8% [5], which once again confirms the necessity of developing sustainable construction materials that will involve waste valorisation and provide the function [6-8]. Pervious concrete could be a good alternative for storm water control in highly urbanized areas like Pune, India, where the waterlogging is a major problem due to the heavy rainfall and inefficient drainage systems [9-11]. It also has an interlocking pore structure, usually 15 to 30% pores, which allows quick passage and a high rate of runoff absorption, recharge of groundwater, and partial filtration of whatever pollutants are present [12, 13]. The applicability of pervious concrete to structural applications is however limited by the natural strength to permeability trade-off that greater porosity increases hydraulic conductivity but decreases compressive strength because porous pervious concrete has lower paste and aggregate bonding and lower density [14-16]. The recent investigations have considered the recycled materials such as waste glass, plastics, fly ash and ceramic aggregates pervious concrete systems [17-21].

Although the ceramic wastes have shown good performance in conventional concrete, a methodical analysis of their graded integration and their effects on the strength-permeability interaction of pervious concrete has not been done extensively [22-25]. In that regard, the study examines the percentage of aggregate replacement in ceramic tiles of 10 to 40 % and their impact on compressive strength, hydraulic performance, density, and porosity of pervious concrete. The point of aim is to clarify the impacts of intrinsic characteristics of ceramic aggregates, such as decreased specific gravity and increased water absorption, on the effective ratio of water to cement, interconnectedness of pores, and the synergy of strength to permeability. Through the measurement of the change in performance with respect to replacement gradients, the study determines the ideal level of replacement at which the structure is adequately built without sacrificing the capacity to infiltrate. The novelty of this work is:

(i) Systematic Replacement Gradient: The use of an organized replacement gradient (10%, 20%, 30%, 35% and 40%) to identify threshold behaviour as opposed to an individual substitution level.
(ii) Quantified Strength–Permeability Trade-Off: Quantitative understanding of strength to permeability interaction in order to specify an optimal performance range.
(iii) Mechanistic Interpretation: The mechanistic impact of ceramic aggregate characteristics on volumetric and microstructural properties.
(iv) Regional Adaptation: Changing the experimental structure to suit Pune's climatic and other infrastructural settings. This study, therefore, hypothesizes an optimization framework of ceramic waste incorporated in pervious concrete that promotes pavement design and development of urban structures that are sustainable and climate resistant.

2. LITERATURE REVIEW

Pervious concrete has become a leading research topic in sustainable pavement engineering because it has the ability to be applied in managing storm water concurrently, reducing urban heat islands, and conserving resources. Its mechanical, hydraulic, and environmental performance properties have been well researched, especially this is in the context of optimization of pore structure and use of recycled materials or waste materials. The current literature review is used to synthesize the research on the pervious concrete and waste material integration conducted in the past to establish the findings, limitations and gaps in research that guide the aim of the existing study.

2.1 Pervious concrete

Pervious concrete is a very porous cementitious composite, which is meant to permit water to bypass into its interlocked cellular structure [1, 26, 27]. Its behavior can be controlled by a series of properties of pore structure such as porosity, connectivity, tortuosity and pore size distribution, which depend on aggregate grading, compaction energy, water-cement ratio and addition of other supplementary materials [28-31]. Pervious concrete is usually there with 15 to 30% interconnected voids as a result of low or undeveloped fine aggregates, resulting in high permeability that can be used in groundwater recharge and attenuation of runoff [1, 32-35]. Nevertheless, porosity also means compressive strength, and thus structural use is usually limited only to low-traffic pavements.

In addition to hydraulic performance, pervious concrete has the benefits of lower surface temperature, caused by evaporation cooling, better skid resistance caused by surface texture and potential use of industrial by-products and recycled materials [36-41]. However, the porosity to compressive strength relationship is always a critical design issue where the mix proportioning strategies must be optimized in such a way that structural and hydraulic performance are balanced [42-45].

2.2 The waste material in construction

One of the most common ways to improve the concept of sustainability has been the introduction of waste products, meaning recycled glass, plastics, fly ash and slag in pervious concrete to promote the utilization of natural aggregates [17, 19, 46-51]. These materials are capable of enhancing the desired performance qualities such as durability, workability and toughness when applied in the optimum combination. Additionally, the alternative solutions decrease landfill wastes, decrease environmental impact and promote principles of the circular economy [29, 52-57]. The overall life cycle assessment framework of ceramic waste utilization in pervious concrete is illustrated in Figure 1.

Though the studies have proved the viability of the incorporation of waste, most of them seem to study the isolated mechanical parameters or durability of the structure, but not to compare the synergy of the strength and hydraulic performance. As a result, future studies are needed to measure the tradeoffs in terms of performance in conditions of controlled replacement gradients and develop performance-driven optimization frameworks of sustainable pervious concrete deployment.

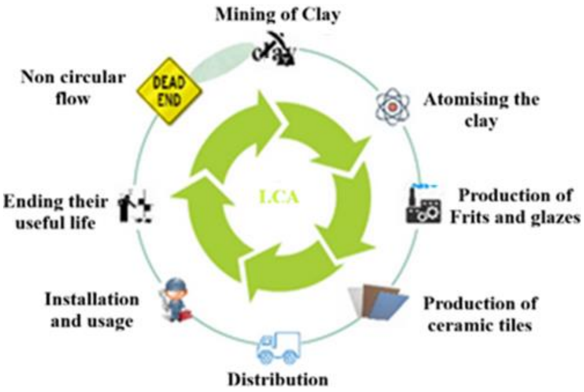

Figure 1. Circular life cycle assessment of ceramic waste-based pervious concrete

3. MATERIALS AND METHODS

The experimental study is aimed at testing pervious concrete with the replacement of natural coarse aggregates with ceramic waste aggregates 10 to 40%. The foundations of the methodology are systematic characterization of the raw materials, proportioning of the mixes in control, standardized specimen preparation and mechanical, physical and hydraulic performances. The overall process adopted for mixing pervious concrete is illustrated in Figure 2.

3.1 Raw materials

3.1.1 Cement

An ordinary Portland cement (OPC 53 grade) that met the requirements of IS 12269 was deployed as the binding material. The tests of standard consistency and preliminary and terminal setting time were done in accordance with IS 4031 to confirm adherence to specifications. The cement has been purchased locally in Pune, India.

3.1.2 Natural coarse aggregate

Crushed granite aggregate with angular particles and a particle size ranging from 8 to 12.5 mm was used. All tests were conducted in accordance with IS 2386. The measured properties are as follows: specific gravity of 2.70, water absorption of 0.5%, aggregate crushing value of 12.86%, and aggregate impact value of 20.2%.

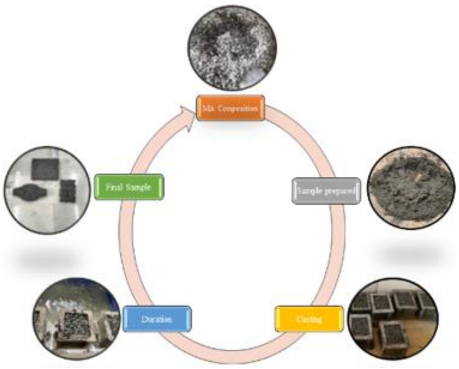

Figure 2. Experimental procedure for mixing and preparation of pervious concrete specimens

3.1.3 Ceramic waste aggregate

Discarded glazed ceramic floor tiles were sourced from tile manufacturing industries and construction waste sites in Pune. The tiles were manually crushed using a mechanical hammer and subsequently sieved to obtain particle sizes ranging from 4 to 12 mm, ensuring compatibility with the gradation of the natural aggregates. The ceramic aggregates revealed the following properties: specific gravity of 2.11, water absorption of 2%, aggregate crushing value of 14.33%, and aggregate impact value of 24.2%.

The physical and mechanical properties of the natural coarse aggregate and crushed ceramic tile aggregate are summarized in Table 1.

Due to the lower specific gravity and higher water absorption of the ceramic aggregates, an influence on the effective water-to-cement ratio and pore connectivity of the pervious concrete matrix was to be expected.

Gradation Analysis:

The sieve analysis results for ceramic tile aggregates are presented in Figure 3.

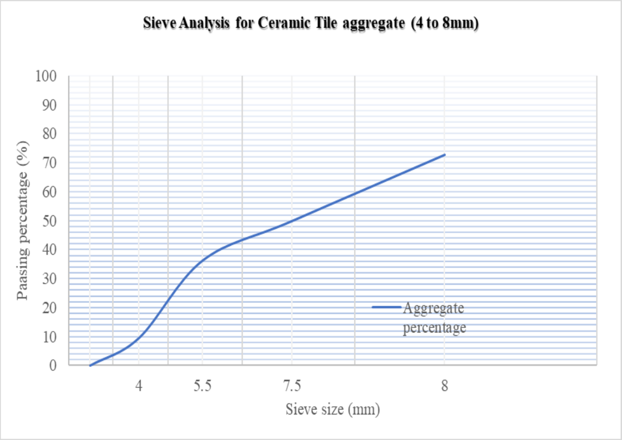

Figure 3. Ceramic tile aggregate sieve analysis (4 mm to 8 mm size range)

The gradation characteristics of ceramic tile aggregates in the 8 mm to 12 mm size range are shown in Figure 4.

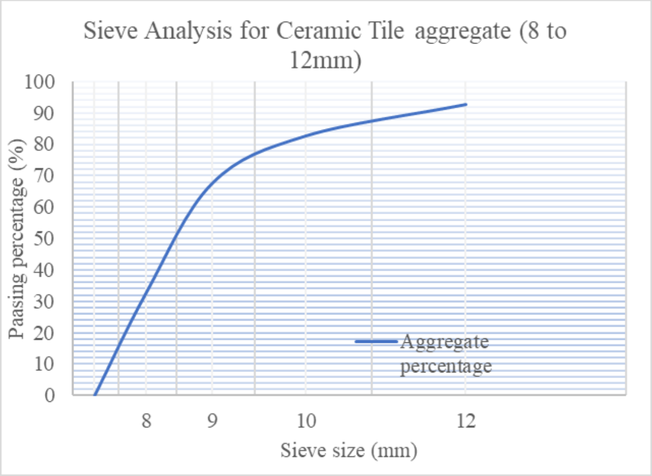

Figure 4. Ceramic tile aggregate sieve analysis (8 mm to 12 mm size range)

The sieve analysis confirmed that the majority of particles fell within the 4 mm to 12 mm range, ensuring a uniform particle size distribution as required by the selected mix design.

3.2 Raw material characterization

The characterization of raw materials using their normal intensity will also be performed. Characterization of raw materials in the form of normal intensity will be conducted as well.

Before the mix preparation, a test of quality control was made on all materials:

- Specific gravity and absorption of water: IS 2386.
- Crushing and impact value: IS 2386.
- Consistency and time of setting cement: IS 4031.
- Gradation verification Sieve analysis.

These tests were used in ensuring uniformity, reliability and standard specifications prior to mix proportioning.

The variation in the quantity of natural aggregates and ceramic tile replacement used in different concrete mixes is illustrated in Figure 5.

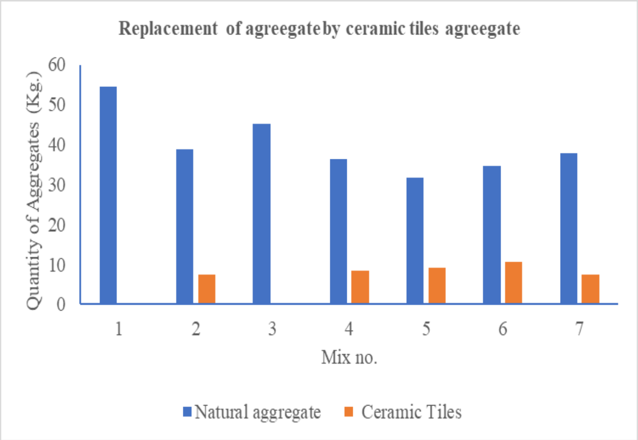

Figure 5. Quantity of aggregates vs. ceramic tiles replacement in concrete mixes

Table 1. Aggregate test results

Material	Specific Gravity	Water Absorption (%)	Surface Moisture	Crushing Value (%)	Impact Value (%)
Coarse aggregate	2.7	0.5	Nil	12.86	20.2
Crushed waste ceramic tiles	2.11	2	Nil	14.33	24.2

Table 2. Mix design

Mix Design No.	No. of Cubes	Total Concrete Volume	Cement-Aggregate Ratio	Cementitious Materials		Aggregates			Water-to-Cement Ratio	Water Content
				OPC 53	Fly Ash	Coarse Aggregate (10-12 mm)	Coarse Aggregate (8-12 mm)	Ceramic Tiles (8-12 mm)		
1	9	0.003 m^3	18/82	28.3 kg	NA	54.5 kg	NA	NA	0.45	2.710 kg
2	9	0.003 m^3	18/82	8.025 kg	NA	45.3 kg	NA	NA	0.35	2.808 kg
3	9	0.003 m^3	18/82	7.623 kg	0.401 kg (5%)	45.3 kg	NA	NA	0.35	2.668 kg
4	9	0.003 m^3	18/82	8.025 kg	NA	NA	45.3 kg	NA	0.35	2.808 kg
5	9	0.003 m^3	18/82	8.025 kg	NA	31.71 kg	NA	9.060 kg (30%)	0.45	3.611 kg
6	9	0.003 m^3	18/82	8.025 kg	NA	34.73 kg	NA	10.57 kg (35%)	0.55	4.413 kg
7	9	0.003 m^3	18/82	8.025 kg	NA	37.75 kg	NA	7.55 kg (25%)	0.43	3.611 kg

3.3 Mix proportioning

Mix design was established in pursuance of IS 10262 as well as IS 456. Seven mix designs were made depending on the different combinations of ceramic aggregate replacement (10%, 20%, 25%, 30%, 35% and 40%). Aggregate-to-cement ratios were between 18:82 and 30:70 and water-cement ratios were between 0.35 and 0.55 in order to adjust to the greater absorption of the ceramic aggregates. The mix proportions and material quantities adopted for the different concrete mixes are presented in Table 2.

All mixes were separated into cubes of specimens, 3 cube specimens, which were tested after 7, 14, and 28 days. All the figures were converted to a normalized level on a per cubic meter basis.

3.4 Specimen preparation

The following standard procedure was applied to the specimen:

Step 1: Dry mixing

Cement, natural aggregates, and ceramic aggregates were dry mixed for 2 min. The selected size range of coarse aggregates and crushed ceramic waste aggregates used in the experimental study are shown in Figure 6.

Figure 6. The size of coarse aggregate and ceramic waste aggregate chosen

The in-house mixing process of cement and aggregates during specimen preparation is illustrated in Figure 7.

Figure 7. In-house picture of mixing of cement

Step 2: Addition of water

Water was added gradually in small increments to achieve a homogeneous consistency.

Step 3: Casting

The fresh concrete was cast into greased 150 mm cube moulds in two layers. Light hand compaction was applied to preserve an interconnected porous structure while ensuring adequate bonding. The prepared pervious concrete cube specimen used for experimental testing is shown in Figure 8.

Figure 8. Pervious concrete cube

The in-house prepared pervious concrete cube specimens after casting and curing are presented in Figure 9.

Figure 9. In-house pictures of a pervious concrete cube

Step 4: Demoulding

Demoulding of the specimen took place after 24 hours.

Step 5: Curing

The water curing was performed on 7, 14, and 28 days at temperatures of 27+ or -2 °C.

3.5 Testing protocol

Standards of testing adhered to in the present study are as follows:

The Indian Standards (IS), ASTM standards, and ISO codes followed in the present experimental investigation are summarized in Table 3.

After curing, the specimens were subjected to both mechanical and physical tests, which included:

- Compressive strength measured on 150 mm cubes.
- Dry density (hardened mass-to-volume ratio).
- Total porosity determined in accordance with ASTM C1688.
- Surface permeability (hydraulic conductivity) measured using the constant-head method in accordance with ASTM C1701/C1701M.

It should be noted that this study did not investigate long-term durability aspects, such as freeze-thaw resistance and clogging behavior. These are identified as objectives for future research.

The overall process and methodology adopted in the present research work are illustrated in Figure 10.

Table 3. Standards followed in the experimental study

Sr. No.	IS Code	ASTM Code	Description
1.	IS 1727:1967	NA	Indian standard for casting of pervious concrete.
2.	IS 383:1970	NA	Indian standard for specification of aggregates for concrete.
3.	NA	ASTM C1688/C1688M	Method of test for porosity and density of freshly mixed porous concrete.
4.	ISO 17785-1:2016	NA	Procedure for determining the permeability of hardened pervious concrete.
5.	NA	ASTM C1747/C1747M-13	Method of test for evaluating resistance to degradation of porous concrete via impact and abrasion.
6.	NA	ASTM C1701/C1701M-09	Standard method for measuring the permeability of in-place porous concrete.

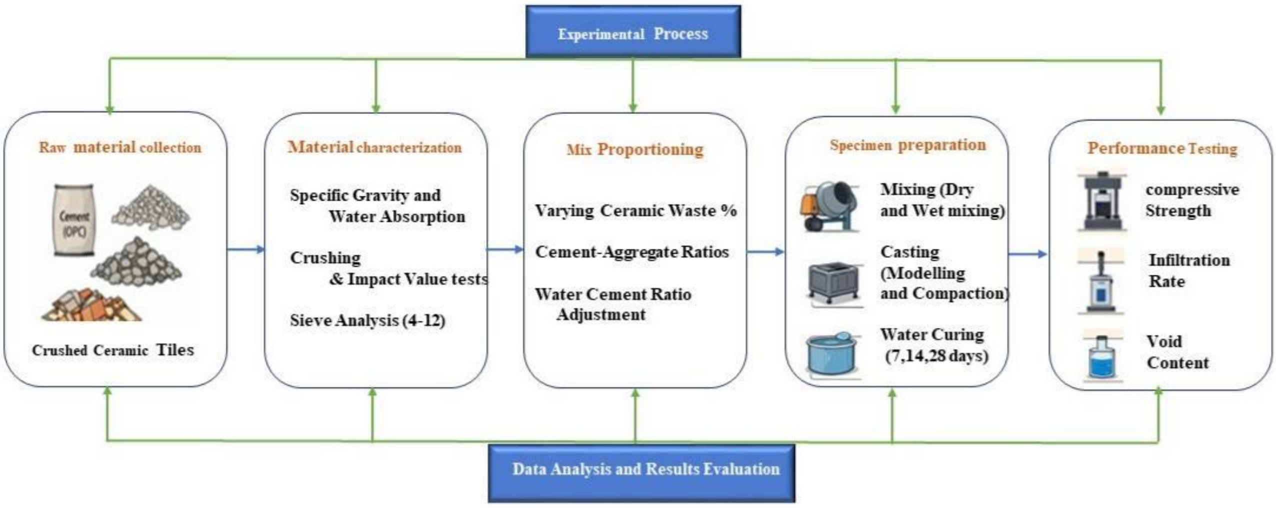

Figure 10. Process diagram of research work

4. RESULTS AND DISCUSSIONS

4.1 Hardened dry density

The hardened dry density of the pervious concrete was on a decreasing tendency as the replacement of the ceramic aggregate increased. It is mostly explained by the fact that the specific gravity of ceramic aggregates (2.11) is much less in comparison to natural granite aggregates (2.70). The higher the content of the ceramic, the lower would be the unit weight of the composite, which showed growth in the amount of void organization within the composite.

The change of the density prior to and after casting is shown in Figure 11. They are seen to reduce in density following casting and this can be explained by the entrapping of air, the stabilization of pores as the compaction happens and also the redistribution of moisture as the casting process goes through drying. The difference between theoretical and hardened densities can affirm the existence of the interconnected voids, which is vital towards functioning in the hydraulic way, but has a bearing on structural capability. Density cast values exhibited a range of 1848 to 1893 kg/m^3 of mixes on a volume of ceramic tiles and thus with features of lightweight compared to the traditional concrete, although with the fundamental and viable properties of structural strength in pervious concrete systems.

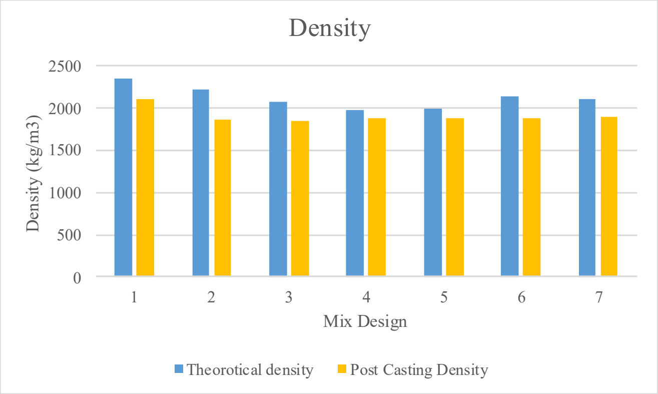

Figure 11. Concrete density before and after casting

4.2 Compressive strength

The compressive strength in 28 days ranged from 10.56 MPa (Mix 1: control) and 4.25 MPa (Mix 6: increased replacement level). The greatest strength was observed with a 30% replacement (Mix 5) of ceramic tiles containing a mix that produced a strength of 8.25 MPa.

The variation in compressive strength of different pervious concrete mixes is illustrated in Figure 12.

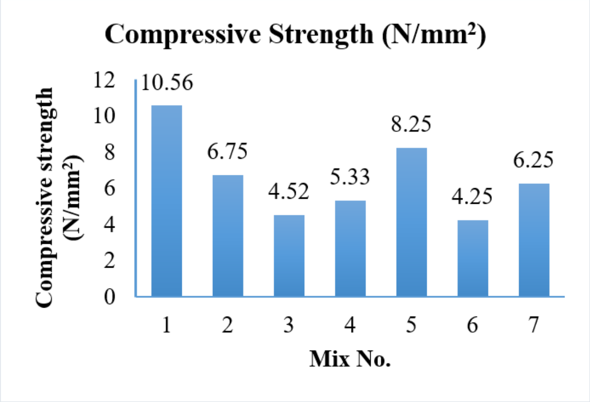

Figure 12. Compressive strength of concrete mixes

Compressive strength was seen to constantly decrease above 30% replacement. The above behaviour indicates the progression of the power of internal porosity, as well as the decreased tendency of load transfer among the aggregate particles with growing ceramic content. Strength Trend Analysis: Compressive strength was at an acceptable level of low traffic pavement at up to 30% replacement. Above 30%, a major drop in the strength was registered, up to 4.25 MPa, with higher replacement levels. This is because the enhanced performance at 30% replacement was due to moderate absorption of ceramic aggregates (2%) of water that minimized effective free water and locally sharpened the structure of the paste. Morphology of the particles which improve mechanical interlocking at area of transition at the interface. Even connectivity of pores without unnecessary disconnectivity of load bearing aggregate skeleton. Beyond a replacement level of more than 30%, too much ceramic addition enhances vacuity and aggregate lack of interlocking, which leads to strength wearing out.

The compressive strength and density results obtained for different concrete mixes are summarized in Table 4.

Table 4. Summary of strength and density results

Mix Design No.	No. of Cubes	Total Concrete Volume (m^3)	Compressive Strength (N/mm^2)	Density Before Casting (kg/m^3) (Theoretical)	Density After Casting (kg/m^3) (Post Casting)
1	9	0.003	10.56	2350.14	2100.92
2	9	0.003	6.75	2214.23	1864.44
3	9	0.003	4.52	2070.00	1848.89
4	9	0.003	5.33	1977.45	1872.95
5	9	0.003	8.25	1985.87	1872.96
6	9	0.003	4.25	2135.00	1876.66
7	9	0.003	6.25	2106.70	1893.33

4.3 Hydraulic surface permeability

The hydraulic performance also increased as the content of ceramic aggregates increased because the interconnected pore structure was better and because the density of the composite had decreased. A higher capacity to infiltrate was made easier by greater porosity. The replacement mix 30% obtained an 1800 mm/hr infiltration, which is higher than the suggested replacement pavement systems more than >1000 mm/hr of concrete sidewalks and parking lots. The replacement of more than 35% led to only a small increment of infiltration and a significant decrease in compressive strength. This implies declining hydraulic gains with reference to the structural losses at increased replacement levels.

4.4 Strength permeability trade-off

The obtained outcomes indicate that there is an obvious negative correlation between compressive strength and permeability, Ceramic content, porosity, and infiltration. Ceramic content, Density, Compressive strength. The correlation is, however, nonlinear. The 30% replacement level is an ideal performance range whereby: Compressive strength is 8.25 MPa and Permeability 1800 mm/hr, Stable density 1873 kg/m^3. This balance thinks that the incorporation of ceramic waste should be optimal instead of being maximal. Over replacement does not represent the hydraulic benefit of the skeleton proportionally.

4.5 Application feasibility

A performance-based evaluation was conducted by correlating the experimental results with practical pavement requirements. Mix 1 (10.56 MPa) meets the requirements for pedestrian pavements and low-volume vehicle applications. Mix 5, with a compressive strength of 8.25 MPa at 30% replacement, falls below the lower-bound requirements for light-duty parking areas and internal roads. Mixes with compressive strengths below 5 MPa are suitable only for non-load-bearing drainage layers or landscaping applications. Considering both mechanical strength and high infiltration capacity, the 30% ceramic replacement mix exhibits the most favorable balance for permeable pavement applications under light-traffic conditions.

4.6 Mechanistic interpretation of optimal replacement

This theory explains the success and failure of the replacement methodology. The optimal performance observed at the 30% replacement level is attributed to the following factors:

- A widened downward shift in the effective water-to-cement ratio (2%);
- Improved interfacial bonding due to the rough and angular surface texture of the ceramic aggregates;
- Maintenance of stability and a load-bearing skeleton, while avoiding excessive skeletal densification through controlled pore connectivity.

Beyond the 30% replacement threshold, excessive porosity within the ceramic aggregates undermines aggregate interlocking, resulting in a reduction of compressive strength to 4.25 MPa. The findings support the fact that the strength permeability interaction is nonlinear and is governed by aggregate absorption properties, pore structure development and volumetric stability.

5. CONCLUSIONS

This study demonstrates that waste ceramic tiles can be successfully used as a partial replacement for natural coarse aggregates in pervious concrete, with an optimal replacement level of 30%. The experimental findings confirm that, at this replacement level, the structural capacity is maintained with minimal adverse effects on the functional and mechanical performance of the pervious concrete.

The 30% replacement mix attained a compressive strength of 8.25 MPa, but also a high hydraulic performance of 1800 mm/hr. infiltration capacity, which means that there is a balanced interaction between strength and permeability. Replacement above 30%, the strong compressive strength was found to be much lower, as low as 4.25 MPa, which proves that with a high level of ceramic incorporation, the interlocking and load transfer process between the aggregates is weakened by high internal porosity.

The given findings make it clear that the incorporation of the ceramic waste should be optimized, not maximized. At the estimated performance window, without overstepping the performance limits that are deemed acceptable, it is possible to achieve environmental advantages such as waste diversion and improved management of stormwater. The findings promote the use of the performance-based optimization framework for sustainable pervious concrete design.

5.1 Summary of findings

- Compressive strength remained generally satisfactory when up to 30% of natural coarse aggregates were replaced with ceramic waste.
- A higher ceramic content increased porosity and hydraulic conductivity due to enhanced pore connectivity.
- The strength-permeability relationship was non-linear, governed by aggregate absorption characteristics and pore structure development.
- The 30% replacement level offered the best compromise between structural adequacy and drainage performance.

5.2 Practical implications

The use of ceramic waste in the pervious concrete also leads to sustainable construction, and this aspect of the construction scenario has made sure to shift the industrial waste off the landfills and has reduced reliance on virgin natural aggregates. The method would assist in the circular economy principles of pavement engineering.

The optimized mix can be used in low-volume roads with low-level infiltration capacity and high mechanical strength, which would be suitable for the application of sidewalks, pedestrian pavements, parking, and low-volume roads. It could be noted that the implementation of such systems of permeable pavements can enhance urban resilience by improving the mitigation of stormwater runoff, localized flooding, and providing a contribution towards moderating surface temperatures.

Pervious concrete has been widely used all around the world in countries such as the United States, Japan, and other European countries in the completion of works like parking lots, sidewalks, and low-traffic pavements. The results of the current research can justify analogous applications in the booming cities where drainage systems do not yet follow the needed standards.

5.3 Scope and limitations

This experiment is restricted to the short-term mechanical and hydraulic performance testing under laboratory-controlled conditions as laboratory controlled. Resistance to long-lasting strength factors, such as freeze-thaw resistance, clogging attribute, abrasiveness, and results of exposure to the environment, was not experimented.

Differences in the composition of waste material, compaction energy and gradation can have a considerable effect on pore connectivity and mechanical behavior. Further studies should thus concentrate on:

- Durability evaluation over a period of time under cyclic environmental conditions.
- Hydraulic performance field validation.
- Interfacial transition zones microstructural examination.
- Clogging and maintenance assessment.

The subsequent research on the hybrid waste mixtures and optimization of the gradation can be considered a potential performance improvement without compromising the structural performance.

REFERENCES

[1] Maalouf, A., Mavropoulos, A. (2023). Re-assessing global municipal solid waste generation. Waste Management & Research, 41(4): 936-947. https://doi.org/10.1177/0734242X221074116

[2] Jebaranjitham, J.N., Christyraj, J.D.S., Prasannan, A., Rajagopalan, K., Chelladurai, K.S., Gnanaraja, J.K.J.S.(2022). Current scenario of solid waste management techniques and challenges in Covid-19 – A review. Heliyon, 8(7): e09855. https://doi.org/10.1016/j.heliyon.2022.e09855

[3] Murali, G., Hassas, N., Abdelgader, H.S. (2025). Ceramic waste as a sustainable cementitious resource: Pathways to cleaner and high-performance concrete. Cleaner Materials, 18: 100352. https://doi.org/10.1016/j.clema.2025.100352

[4] Özkılıç, Y.O., Althaqafi, E., Bahrami, A., Aksoylu, C., et al. (2024). Influence of ceramic waste powder on shear performance of environmentally friendly reinforced concrete beams. Scientific Reports, 14(1): 10401. https://doi.org/10.1038/s41598-024-59825-7

[5] Wu, S., Shao, Z., Andrew, R.M., Bing, L., et al. (2024). Global CO_2 uptake by cement materials accounts 1930–2023. Scientific Data, 11(1): 1409. https://doi.org/10.1038/s41597-024-04234-8

[6] Wu, Y., López-Cereno, R.D., Aidarov, S., Álvarez, P.P. (2025). Pervious concrete pavements for climate change adaptation and mitigation: A systematic review of performance, sustainability, and future perspectives. In Road Materials and Pavement Design, pp. 1-36. https://doi.org/10.1080/14680629.2025.2544244

[7] Li, Y. (2025). A comprehensive review of recycled materials in eco-friendly pavement construction. Građevinar, 77(10): 981-993. https://doi.org/10.14256/JCE.4274.2025

[8] Prakash, A., Deshmukh, M.R. (2025). Advancements and future directions in sustainable construction materials for eco-efficient and resilient built environments. Journal of Research in Civil and Architectural Engineering, 10(2): 79-88.

[9] Sudarsan, J.S., Reddy, K.J.P., Biyabani, H.A., Kumari, P., Sinha, S. (2021). Impact of fragile water management strategies and mitigation-A case study of Pune City, India. IOP Conference Series: Materials Science and Engineering, 1026(1): 012001. https://doi.org/10.1088/1757-899X/1026/1/012001

[10] Sathiparan, N., Dassanayake, D.H.H.P., Subramaniam, D.N. (2024). Utilization of supplementary cementitious materials in pervious concrete: A review. International Journal of Environmental Science and Technology, 21(6): 5883-5918. https://doi.org/10.1007/s13762-023-05440-4

[11] Yu, F., Guo, J., Liu, J., Cai, H., Huang, Y. (2023). A review of the pore structure of pervious concrete: Analyzing method, characterization parameters and the effect on performance. Construction and Building Materials, 365: 129971. https://doi.org/10.1016/j.conbuildmat.2022.129971

[12] Adresi, M., Yamani, A., Tabarestani, M.K., Rooholamini, H. (2023). A comprehensive review on pervious concrete. Construction and Building Materials, 407: 133308. https://doi.org/10.1016/j.conbuildmat.2023.133308

[13] Seifeddine, K., Amziane, S., Toussaint, E. (2022). State of the art on the mechanical properties of pervious concrete. European Journal of Environmental and Civil Engineering, 26(15): 7727-7755. https://doi.org/10.1080/19648189.2021.2008511

[14] Bai, X., Zhou, H., Bian, X., Chen, X., Ren, C. (2024). Compressive strength, permeability, and abrasion resistance of pervious concrete incorporating recycled aggregate. Sustainability, 16(10): 4063. https://doi.org/10.3390/su16104063

[15] Joshi, T., Dave, U. (2022). Construction of pervious concrete pavement stretch, Ahmedabad, India–Case study. Case Studies in Construction Materials, 16: e00622. https://doi.org/10.1016/j.cscm.2021.e00622

[16] Sandoval, G.F., Jussiani, E.I., de Moura, A.C., Andrello, A.C., Toralles, B.M. (2022). Hydraulic and morphological characterization of clogged pervious concrete (PC). Construction and Building Materials, 322: 126464. https://doi.org/10.1016/j.conbuildmat.2022.126464

[17] Khankhaje, E., Kim, T., Jang, H., Kim, C.S., Kim, J., Rafieizonooz, M. (2024). A review of utilization of industrial waste materials as cement replacement in pervious concrete: An alternative approach to sustainable pervious concrete production. Heliyon, 10(4): e26188. https://doi.org/10.1016/j.heliyon.2024.e26188

[18] Ahmad, S.A., Saeed, B.H., Hussein, S.N., Ahmed, H.U., Rafiq, S.K., Ahmad, D.A., Fqi, K.O. (2024). Impact of substituting coarse aggregate with waste glass granules on the fresh and mechanical properties of pervious concrete: An experimental study. Journal of Building Pathology and Rehabilitation, 9(1): 29. https://doi.org/10.1007/s41024-024-00390-x

[19] Singh, S.B., Murugan, M., Chellapandian, M., Dixit, S., et al. (2023). Effect of fly ash addition on the mechanical properties of pervious concrete. Materials Today: Proceedings. https://doi.org/10.1016/j.matpr.2023.09.165

[20] Singh, N., Singh, A., Ankur, N., Kumar, P., Kumar, M., Singh, T. (2022). Reviewing the properties of recycled concrete aggregates and iron slag in concrete. Journal of Building Engineering, 60: 105150. https://doi.org/10.1016/j.jobe.2022.105150

[21] Li, Y., Zhang, J., Ding, J., Chen, F.Z., Liu, M.Z., Liu, J., Hou, Z. (2025). Performance evaluation and microstructure study of pervious concrete prepared from various solid waste admixtures. International Journal of Concrete Structures and Materials, 19(1): 7. https://doi.org/10.1186/s40069-024-00738-0

[22] Li, C., Zhang, X., Cao, X., Yu, Y. (2025). Sustainable performance and interfacial characteristics of fully recycled concrete with combined recycled concrete,

brick, and ceramic aggregates. Sustainability, 17(23): 10503. https://doi.org/10.3390/su172310503

[23] Gao, S., Huang, K., Chu, W., Wang, W. (2023). Feasibility study of pervious concrete with ceramsite as aggregate considering mechanical properties, permeability, and durability. Materials, 16(14): 5127. https://doi.org/10.3390/ma16145127

[24] Zhang, P., Zhang, P., Wu, J., Guo, Z., Zhang, Y., Zheng, Y. (2023). Mechanical properties and durability of sustainable concrete manufactured using ceramic waste: A review. Journal of Renewable Materials, 11(2): 937-974. https://doi.org/10.32604/jrm.2022.023290

[25] Oinam, Y., Kim, H.K., Pyo, S. (2025). A novel approach to understanding the compaction energy effect on the pore network and fatigue resistance of pervious concrete. International Journal of Pavement Engineering, 26(1): 2521099. https://doi.org/10.1080/10298436.2025.2521099

[26] Barbhuiya, S., Qureshi, T., Das, B.B. (2025). Advancing sustainable pavements: A review of low-carbon construction materials and practices. Discover Concrete and Cement, 1(1): 19. https://doi.org/10.1007/s44416-025-00020-w

[27] Khoshnaw, G.J., Younis, K.H., Hamad, W.A., Ismail, A.J., et al. (2024). Experimental investigation on pervious recycled aggregate concrete made of waste porcelain. Civil Engineering Journal, 10(9): 2888-2901. https://doi.org/10.28991/CEJ-2024-010-09-08

[28] Anburuvel, A., Subramaniam, D.N. (2023). Influence of aggregate gradation and compaction on compressive strength and porosity characteristics of pervious concrete. International Journal of Pavement Engineering, 24(2): 2055022. https://doi.org/10.1080/10298436.2022.2055022

[29] Ortiz-Marqués, A., Caldevilla, P., Goldmann, E., Safuta, M., Fernández-Raga, M., Górski, M. (2025). Porosity and permeability in construction materials as key parameters for their durability and performance: A review. Buildings, 15(18): 3422. https://doi.org/10.3390/buildings15183422

[30] Ferić, K., Sathish Kumar, V., Romić, A., Gotovac, H. (2023). Effect of aggregate size and compaction on the strength and hydraulic properties of pervious concrete. Sustainability, 15(2): 1146. https://doi.org/10.3390/su15021146

[31] Wu, S., Wu, Q., Shan, J., Cai, X., Su, X., Sun, X. (2023). Effect of morphological characteristics of aggregate on the performance of pervious concrete. Construction and Building Materials, 367: 130219. https://doi.org/10.1016/j.conbuildmat.2022.130219

[32] Zhang, J., Sun, H., Shui, X., Chen, W. (2023). Experimental investigation on the properties of sustainable pervious concrete with different aggregate gradation. International Journal of Concrete Structures and Materials, 17(1): 64. https://doi.org/10.1186/s40069-023-00625-0

[33] AlShareedah, O., Nassiri, S. (2021). Pervious concrete mixture optimization, physical, and mechanical properties and pavement design: A review. Journal of Cleaner Production, 288: 125095. https://doi.org/10.1016/j.jclepro.2020.125095

[34] Korat, A., Amin, M., Tahwia, A.M. (2025). A comprehensive assessment of ceramic wastes in ultra-high-performance concrete. Innovative Infrastructure Solutions, 10(1): 28. https://doi.org/10.1007/s41062-024-01806-w

[35] Sahdeo, S.K., Chandrappa, A., Biligiri, K.P. (2021). Effect of compaction type and compaction efforts on structural and functional properties of pervious concrete. Transportation in Developing Economies, 7(2): 19. https://doi.org/10.1007/s40890-021-00129-0

[36] Adresi, M., Yamani, A.R., Tabarestani, M.K. (2024). Evaluating the effectiveness of innovative pervious concrete pavement system for mitigating urban heat island effects, de-icing, and de-clogging. Construction and Building Materials, 449: 138361. https://doi.org/10.1016/j.conbuildmat.2024.138361

[37] Liu, X., Ye, Z., Lu, J.X., Xu, S., Hsu, S.C., Poon, C.S. (2024). Comparative LCA-MCDA of high-strength eco-pervious concrete by using recycled waste glass materials. Journal of Cleaner Production, 479: 144048. https://doi.org/10.1016/j.jclepro.2024.144048

[38] Mansour, M.A., Ismail, M.H.B., Imran Latif, Q.B.A., Alshalif, A.F., Milad, A., Bargi, W.A.A. (2023). A systematic review of the concrete durability incorporating recycled glass. Sustainability, 15(4): 3568. https://doi.org/10.3390/su15043568

[39] Li, A., Qiao, H., Li, Q., Hakuzweyezu, T., Chen, B. (2021). Study on the performance of pervious concrete mixed with waste glass powder. Construction and Building Materials, 300: 123997. https://doi.org/10.1016/j.conbuildmat.2021.123997

[40] Park, J.H., Kim, Y.U., Jeon, J., Wi, S., Chang, S.J., Kim, S. (2021). Effect of eco-friendly pervious concrete with amorphous metallic fiber on evaporative cooling performance. Journal of Environmental Management, 297: 113269. https://doi.org/10.1016/j.jenvman.2021.113269

[41] Huang, P., Zhang, K., Chui, T.F.M. (2025). Hydrologic performance of permeable pavements under extreme and regular rainfall conditions. Journal of Hydrology, 652: 132653. https://doi.org/10.1016/j.jhydrol.2024.132653

[42] Alemu, A.S., Yoon, J., Tafesse, M., Seo, Y.S., Kim, H.K., Pyo, S. (2021). Practical considerations of porosity, strength, and acoustic absorption of structural pervious concrete. Case Studies in Construction Materials, 15: e00764. https://doi.org/10.1016/j.cscm.2021.e00764

[43] Zhang, Y., Wang, H., Khair, A., Yang, J., Han, Y. (2025). Comprehensive evaluation of sound absorption performance in porous concrete pavement with crushed stone base course. Scientific Reports, 16: 2300. https://doi.org/10.1038/s41598-025-32128-1

[44] Shan, J., Zhang, Y., Wu, S., Lin, Z., Li, L., Wu, Q. (2022). Pore characteristics of pervious concrete and their influence on permeability attributes. Construction and Building Materials, 327: 126874. https://doi.org/10.1016/j.conbuildmat.2022.126874

[45] Anburuvel, A., Niruban Subramaniam, D. (2022). Investigation of the effects of compaction on compressive strength and porosity characteristics of pervious concrete. Transportation Research Record, 2676(9): 513-525. https://doi.org/10.1177/03611981221087236

[46] Sathvik, S., Rohithkumar, P., Shakor, P., Shahaji, Tantri, A., Kumar, V.P., Singh, A.K. (2024). Enhancing urban sustainability: A study on lightweight and pervious concrete incorporating recycled plastic. Discover

Sustainability, 5(1): 421. https://doi.org/10.1007/s43621-024-00644-1

[47] Manan, A., Zhang, P., Majdi, A., Alattyih, W., Ahmad, J. (2025). Utilizing waste materials in concrete: A review on mechanical and sustainable performance. Green Materials, pp. 1-18. https://doi.org/10.1680/jgrma.24.00122

[48] Arifi, E., Cahya, E.N., Waluyohadi, I., Abdullah, A., Rochman, T., Wicaksono, O.D. (2024). Experimental study on the performance of polymer pervious concrete using recycled concrete aggregate. IOP Conference Series: Earth and Environmental Science, 1311(1): 012022. https://doi.org/10.1088/1755-1315/1311/1/012022

[49] Huang, W., Wang, H. (2024). Comprehensive assessment of engineering and environmental attributes of geopolymer pervious concrete with natural and recycled aggregate. Journal of Cleaner Production, 468: 143138. https://doi.org/10.1016/j.jclepro.2024.143138

[50] Afsoosbiria, H., Machowska, A. (2025). Development of sustainable concrete using by-products as a green material, and potential solutions for sustainability in mass concrete construction—Comprehensive review. Sustainability, 17(22): 9983. https://doi.org/10.3390/su17229983

[51] Siddiqui, A.R., Khan, R., Akhtar, M.N. (2025). Sustainable concrete solutions for green infrastructure development: A review. Journal of Sustainable Construction Materials and Technologies, 10(1): 108-141. https://doi.org/10.47481/jscmt.1667793

[52] Tariq, Z., Bahadori-Jahromi, A. (2025). Incorporating ground granulated blast furnace slag & fly ash in concrete production for sustainable construction: A review. Engineering Future Sustainability, 2(1): 1-30. https://doi.org/10.36828/efs.318

[53] Ahmad, J., Kontoleon, K.J., Majdi, A., Naqash, M.T., et al. (2022). A comprehensive review on the ground granulated blast furnace slag (GGBS) in concrete production. Sustainability, 14(14): 8783. https://doi.org/10.3390/su14148783

[54] Marathe, S., Sheshadri, A., Nikolaiev, V. (2025). Life cycle assessment of sustainable air-cured alkali-activated concrete for permeable pavements using agro-industrial wastes. Scientific Reports, 15(1): 22012. https://doi.org/10.1038/s41598-025-04783-x

[55] Srikanth, K., Boddu, S.K., Bhamidipati, R.A. (2024). Life cycle assessment of supplementary cementitious materials in pervious concrete: A comparative approach. In International Conference on Novel Materials and Technologies for Energy and Environment, Hyderabad, India, pp. 185-202. https://doi.org/10.1007/978-981-96-6107-7_10

[56] Kumar, B.S., Srikanth, K. (2023). A study on properties of pervious concrete with high-volume usage of supplementary cementitious materials as substitutes for cement. Asian Journal of Civil Engineering, 24(7): 1997-2009. https://doi.org/10.1007/s42107-023-00619-z

[57] Samadi, M., Huseien, G.F., Mohammadhosseini, H., Lee, H.S., Lim, N.H.A.S., Tahir, M.M., Alyousef, R. (2020). Waste ceramic as low cost and eco-friendly materials in the production of sustainable mortars. Journal of Cleaner Production, 266: 121825. https://doi.org/10.1016/j.jclepro.2020.121825