International Journal of Engineering Research Excellence and Applied Science (IJEREAS)

Volume-IV (Issue 3) – July- Sept 2026 ISSN: 3048-5355

A REVIEW OF PERVIOUS CONCRETE PAVEMENT INCORPORATING ALTERNATIVE MATERIAL REPLACEMENTS

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Abstract: Pervious concrete pavement has received a lot of positive acceptance as a sustainable construction of storm water management and urban floods mitigation because it is very permeable and environmentally friendly. The review paper entails a critical evaluation of pervious concrete pavement, which entails replacement of the material by alternative materials that would enhance mechanical performance, durability and sustainability. Other forms of substitute materials are supplementary cementitious materials (metakaolin, fly ash, silica fume), industrial by-products (copper slag, recycled aggregates), and fibers that are taken under serious consideration in terms of their effects on compressive strength, permeability, abrasion resistance, and long term durability. The review brings out the trade off between a proper pore structure to support permeability and proper structural strength to support pavement application. The major conclusions suggest that optimum replacement level could be used to improve performance and minimize cement usage and environmental effects. The research gaps concerning durability, field performance, and standard mix design procedures are determined, which

gives guidance on how future studies on the use of eco-friendly pervious concrete pavements should be conducted.

Keywords: Pervious concrete pavement, Alternative materials, Metakaolin, Copper slag aggregate, Compressive strength, Sustainable construction, Eco-friendly pavements etc.

1. INTRODUCTION

The growth of urbanization and the fast construction of infrastructure has resulted in a substantial increase in impervious surfaces, which cause problems such as surface water run-off, urban flooding, groundwater depletion and poor water quality. Traditional concrete pavements are structurally effective, but they do not allow natural infiltration of rainwater and cause environmental imbalance. In this respect, pervious concrete pavement has been drawing a lot of interest as an environmentally friendly pavement material because of its interlocked pore structure that ensures that the storm water can be absorbed, runoff can be minimized, and groundwater can be replenished (Yang and Jiang, 2003; Akkaya and Çağatay, 2021).

The pervious concrete has several limitations to its usage that include the low mechanical strength and durability that are attributed to the high porosity and lower percentage of paste despite its environmental advantages. Therefore, recent studies have paid attention to the mix design parameters optimization being the water cement ratio, aggregate size, and target porosity to find the compromise between the performance and permeability (Lu et al., 2025; Liu et al., 2025; Lyu et al., 2024). Such researches emphasize that the key aspect of enhancing the performance of pervious concrete is the innovative choice of materials and their mix optimization.

Additional cementitious materials (SCMs) have been noted as a potential solution to improve the mechanical and sustainability of pervious concrete. Fly ash, GGBS, silica fume, and metakaolin have been observed to enhance the quality of the paste, interfacial transition zones, and long-term strength as well as decreasing cement use (Sathe and Dandin, 2025; Ganesh et al., 2018; Liu et al., 2018). Among these, metakaolin is of certain efficacy because of its high pozzolanic activity and its refining pore structure capability, which can possibly strengthen without unreasonably interfering with permeability.

Similar to the use of the cement replacement strategies, the use of industrial and construction wastes as aggregate substitutes has become a significant point of research in the area of sustainable pavement. It has successfully explored the use of recycled concrete aggregates, crushed clay bricks, waste glass and metallurgical slags in pervious concrete and has found a variable level of enhancement in mechanical properties and infiltration traits (Ahmed et al., 2025; Ahmad et al., 2024; Strieder et al., 2022; dos Santos Lima et al., 2022; Mirnezami et al., 2023). These researches support the viability of a natural aggregates substitute to save resources and decrease the ecological footprint.

Specifically, copper slag, a by-product of copper smelting has become the subject of an ever-growing research interest since it is characterized by high density, angular shape of particles and excellent mechanical strength. A number of researchers have found that copper slag has the potential to enhance compressive strength, abrasion resistance, and durability of conventional and pavement-grade concrete (Pushpakumara and Bandara, 2025; Chandra Pal et al., 2025). It has also demonstrated a promising outcome in pervious and alkali-activated pervious concrete with increased strength and reasonable permeability in case of optimal proportions (Seeni et al., 2025; Zheng et al., 2023). Also, the utilization of slag-based materials also conforms to the concept of the circular economy and sustainable waste management (Banerji et al., 2025; Mohanty et al.).

Even though the previous researches have conducted independent studies on the impacts of SCM and waste aggregates on pervious concrete, there is a dearth of research on the joint application of metakaolin and copper slag aggregate on pervious concrete pavement systems. Synergistic advantages could be achieved by the interaction of a very active pozzolanic binder and a dense aggregate of industrial by-products, which would increase structural capacity and hydraulic performance. Moreover, the literature is biased towards either mechanical or permeability, and fewer studies have been conducted to have a combination of the two in terms of optimization of pavement application under real life conditions.

Pervious Concrete in Pavement

Pervious concrete pavement is a new and green system of pavement, which is created to enable water to percolate through the top layer and the sub-layers instead of surface water run-offs. It is produced by either deliberate downsizing or removal of fine aggregates, which form a network of pore interconnections that are normally 15 to 30 percent in scale. By facilitating the ability of the pervious concrete pavements to handle storm water at its origin, this structure makes them a significant element of the sustainable urban drainage and low-impact development planning and strategy. Pervious concrete has frequent application in low- to medium-volume pavements like parking lots, sidewalks, pedestrian walkways, residential streets, shoulders and low-volume roads. The pavement system usually involves a pervious surface layer of concrete that is laid on open-graded granular base and sub-base that forms the structural support and temporary water storage. Such a stratified system diminishes the highest runoff rates, boosts the groundwater recharge rates and minimizes the necessity of the traditional storm water facilities.

Structurally, pervious concrete pavements have lower compressive and flexural strength than the traditional concrete pavements because they are highly porous. Thus, pavement design is aimed at the realization of a good balance between strength and permeability. The main parameters that determine the performance are the aggregate size and gradation, paste content, water cement ratio, compaction degree, and the curing conditions. Mix design and controlled placement should be done properly to achieve sufficient load-bearing capacity and durability. Other advantages of the pervious concrete pavements include less splash and spray of surface water, better skid resistance, less urban heat island effect and noise reduction, among others. Nevertheless, issues like pore clogging, Freeze/thaw, and abrasion during traffic loading, maintenance needs, and design detailed need to be met by proper selection of the material, design details, and periodical cleaning. The current development trends in the technology of pervious concrete pavements include addition of supplementary cementitious blends, fibers and recycled or industrial by-products aggregates to improve on mechanical performance and sustainability. When well designed, constructed and maintained, pervious concrete pavements offer an efficient and eco-friendly alternative to traditional pavements that can be used to enhance resilient and sustainable urban infrastructure.

Table: 1.1 Advantages of Pervious Concrete Pavements over Conventional Pavements

Aspect	Pervious Concrete Pavement	Conventional Pavement
Surface permeability	High	Nil
Storm water runoff	Very low	High
Groundwater recharge	Yes	No
Heat island effect	Low	High
Skid resistance	High	Moderate
Environmental impact	Low	High

2. LITERATURE REVIEW

Sathe and Dandin (2025) [1] performed an experimental research on permeable concrete using fly ash (FA) and ground granulated blast furnace slag (GGBS) as a partial replacement of cement. The experiment compared workability, compressive strength, split tensile strength, density, porosity and permeability, and replacement levels. It was found that mixes with FA and GGBS made at compressive strength values of the order of 1825 MPa at 28 days old, then later-age strength being greater than the control mix as a result of pozzolanic and latent hydraulic reactions, although early-age strength was slightly decreased. Split tensile had a similar trend and it improved gradually as the age of curing increased. Permeability coefficients were found in the acceptable range of 2-5 mm/s, and the porosity was in the range of 15-25% which proves that the interconnected pore structure is maintained, which is crucial in drainage. A replacement level of FA and GGBS was determined which gave an optimum result in performance both in strength and permeability.

Lu, Yang, and Jiang (2025) [2] researched the optimum mix design of pervious concrete with the focus on the knowledge of the relations between mix parameters and the key performance properties. The experimentally determined the influence of water cement ratio, aggregate cement ratio and target porosity on mechanical and hydraulic performance such as compressive strength, flexural strength, permeability coefficient and void ratio. The findings showed that compressive strength between 15 and 32 Mpa were attainable through optimum mix design and the higher the compressive strength, the lower was the target porosity and the target content of the paste. Coefficients of permeability were reported to be between 1.5 and 6.0 mm/s with a clear inverse correlation with strength. Examination of the correlation showed a negative correlation between, porosity and compressive strength with positive correlation between porosity and permeability. In the study, the best target porosity value was found to be around 1822, which offered a balance of structural strength and drainage efficiency.

Ahmed et al. (2025) [3] examined the possibility of using recycled crushed clay brick (CCB) waste as an aggregate in pervious concrete, particularly in terms of mechanical performance, hydraulic behavior, clogging behavior, and maintenance performance. The experiment assessed compressive strength, flexural strength, porosity, permeability, and long-term clogging resistance conditions at simulated load with the sediment. The findings also showed that the pervious concrete mix using crushed clay brick showed compressive strength between 12 and 22 Mpa that was lower than normal mixes but these were sufficient to support low-to medium-traffic pavement. The permeability coefficient was reported as 2.0-6.5 mm/s; this was due to the porous structure and rough surface of the aggregates of bricks. Values of porosity were kept at an average of 1828 percent, which is effective in the infiltration of storm water. Clogging tests showed that mixes with crushed clay brick were more susceptible to clogging because of higher fines retention but the permeability of up to 7085 percent could be obtained after regular maintenance procedures (vacuum sweeping and pressure washing).

Banerji et al. (2025) [4] examined the application of basic oxygen furnace (BOF) slag instead of natural aggregates in porous concrete pavements to achieve sustainability. The paper has also investigated how the addition of BOF slag impacts the pivotal performance parameters through compressive strength, density, porosity, and permeability and the durability-associated parameters applicable to the pavement applications. It was found that the porous concrete mixes with BOF slag attained compressive strength values of between 20 and 30 MPa and these were similar or even greater than the conventional porous concrete as a result of angular shape and greater stiffness of slag aggregates. Values of 1.8 to 5.0 mm/s were noticed in permeability coefficients, whereas the level of porosity was not exceeded in 1525 percent, which means that sufficient drainage capacity was ensured. There was also the use of BOF slag, which helped in enhancing the structural stability and abrasion resistance of the pavement.

Liu et al. (2025) [5] performed a combined experimental and numerical research to assess how the permeability and the strength of pervious concrete depends on target porosity and water to cement (w/c) ratio. The experiment used numerical modeling to interpret the transport and mechanical behavior by analyzing the compressive strength, permeability coefficient, porosity and pore structure using laboratory testing. The findings showed that compressive strength declined considerably with target porosity with reported compressive strength of 14 to 32 Mpa and permeability coefficients of 1.2 to 6.8mm/s as porosity went up. A w/c ratio above an optimum level resulted in decreased strength through weaker bonding of paste, and very low w/c ratios had an adverse impact on permeability through clogging channels in pores. Computer simulations were consistent with experiments, showing that strength and permeability have a strong inverse relationship. The optimum target porosity found out was 18-22% and w/c ratio of approximately 0.30-0.35 giving a compromise between mechanical strength and hydraulic efficiency.

Nguyen, Le, and Huynh (2025) [6] the authors tested the performance of high-volume coal combustion residual (CCR) concrete in pavement applications and focused on engineering, durability, microstructural, economic, and environmental issues. The experiment examined compressive strength, flexural strength, abrasion resistance, permeability, and durability attributes of concrete mixes that had large percentages of CCR as a cementitious substitute. The findings revealed that CCR-based concrete had a compressive strength of 25-40 Mpa and flexural strength with a range of 4.0-5.5 Mpa and this proved to be suitable to use in pavement. Durability tests revealed more resistance to sulfate attack and less shrinkage during drying than those of conventional concrete, which was attributed to the improved microstructure that had been formed by the reactions of pozzolans. The findings of permeability and pore refinement indicated increased long-term solubility and ingress of harmful factors. Economic and environmental audit showed that there was a significant cut on cost of material and the embodied carbon emissions as a result of reduction in consumption of cement.

Sain, Gaur, and Sarkar (2025) [7] evaluated the infiltration rate in modified block pavement systems with pervious concrete layers to increase the efficiency of storm water management. Experimentally the infiltration rate, reduction of surface runoff, clogging behavior and structural adequacy were experimentally tested under repeated conditions of loading. The findings showed that the modified block pavements obtained infiltration rates within 150450 mm/h, which is far better than the traditional impervious block pavements. By including pervious concrete layers, the subsurface water recharge was enhanced and also sufficient load bearing capacity was ensured to sustain light to moderate traffic conditions. With time there was progressive loss of capacity of infiltration proportional to the clogging of the surfaces, but periodical maintenance allowed to recover until 70-80 percent of the initial infiltration rate. **Pushpakumara and Bandara (2025) [8]** examined the use of copper slag waste as a partial substitute to natural fine aggregate in concrete, and the aim of the study was to enhance the performance of the material as well as ensure the efficient use of waste products. In the study, fresh properties, compressive strength, split tensile strength, flexural strength, density and the properties associated with durability were considered under various replacement levels of the fine aggregate containing copper slag. The findings revealed that the concrete mixes with slag of copper yielded higher compressive strength values of about 30 45 MPa and more so at the replacement levels of 40 60, which was due to dense and angular characteristics of the slag particles. It was found that workability increased as a result of the smooth surface texture of copper slag, whereas water absorption was less, which suggested a denser microstructure. Tests on durability indicated a higher level of resistance to chloride intrusion and lesser permeability as compared to the traditional concrete. Nonetheless, segregation and bleeding caused marginal strength loss as a result of excessive replacement levels.

Seeni, Maheswaran and Nakarajan (2025) [9] examined the effect of the addition of copper slag on the performance of ambient-cured alkali-activated pervious concrete in developing a cement-free and permeable pavement material. This paper concentrated on the assessment of compressive strength, porosity, permeability, density and durability related features under ambient curing conditions which are more realistic in the field. Copper slag was used as a substitute material and was introduced in different proportions and its implications on the pore connectivity and mechanical behavior were examined. The findings indicated that the values of compressive strength were 16 to 28 Mpa with the optimum performance observed at moderate SiO_2 levels of copper slag content since, there was an enhanced particle packing and formation of the geopolymer gel. Porosity had been kept at 1825% to have sufficient interconnected spaces enough to allow infiltration. The coefficient of permeability ranged between 2.0 and 5.5 mm/s which showed that addition of slag did not hamper hydraulic performance. When the level of copper slag was too high, it resulted in low permeability because it plugged the pores.

Chandra Pal, Panda, and Bhuyan (2025) [10] carried out an extensive experimental study on the quality of concrete in pavements with the inclusion of fly ash and copper slag to ensure sustainable construction of the structures. The fresh properties, compressive strength, flexural strength, abrasion resistance, durability and microstructural characteristics were evaluated as an evaluation of suitability in the use of rigid pavement. The Fly ash was considered as a partial replacement of cement and copper slag as a natural fine aggregate replacement at different degrees. The findings also revealed that concrete mixes obtained compressive strengths of 35 to 50 Mpa with maximum performance being recorded at moderate levels of replacement. The addition of copper slag enhanced density and bonding between the particles, creating increased strengths and abrasion resistance which was complemented by fly ash to enhance the long-term improvement of strength and decreasing the permeability. Durability tests indicated increased resistance to chloride intrusion and sulfate assault, as well as reduced water uptake when compared to the conventional pavement concrete. The microstructural examination established a more compact matrix with decreased connectivity of pores.

Li, Xia and Tang (2024) [11] focused on investigating the effectiveness of travertine-based pervious concrete pavement as a new solution to urban storm water management and mitigation of heavy metals. The experiment involved the analysis of mechanical strength, porosity, permeability and removal efficiency of pollutants and especially with the heavy metals like lead and zinc found in urban runoff. The conventional coarse aggregates were substituted with travertine aggregate which had porous nature and was tested as to its structural and environmental performance. The findings showed that the compressive strength values were between 14 and 26 MPa, implying that the material can be applied in light to medium traffic pavement. The levels of porosity were within 2030% and the permeability coefficients were 2.5-6.0 mm/s and ensured effective infiltration. It is worth noting that, the travertine pervious concrete exhibited up to 6075 percent efficiencies of heavy metal removal that could be ascribed to adsorption and physical filtration process. Though it was found that some reduction of strength was experienced, in relation to traditional pervious concrete, the environmental impact was great.

Ahmad et al. (2024) [12] also explored the effect of using waste glass granules in place of natural coarse aggregate on fresh and mechanical characteristics of pervious concrete. The purpose of the study was to determine the viability of recycling of waste glass and at the same time preserve the pore structure needed to make the pavements permeable. Compressive strength, split tensile strength, porosity, permeability and workability were evaluated experimentally at different replacement levels. It was found that the compressive strength values were between 13 and 24 Mpa with 20-30 percent replacement of glass giving optimal performance. The porosity values were contained with a range of 1827% and the permeability coefficient fell between 2.0 and 5.8 mm/s which is satisfactory hydraulic performance. Workability was enhanced by the angular and smooth surface of glass granules and the paste agglomerate bonding reduced at high levels of replacement resulting in loss of strength. Microstructural images showed that the connectivity of voids was more at moderate replacement levels which led to a stable permeability.

Lyu, Dai, and Chen (2024) [13] explored the relationships between physical characteristics of pervious concrete that were manufactured through the use of varying aggregate sizes and mix ratios. The research was aimed at learning the interrelationships of porosity, permeability, compressive strength, density, and pore structure to enhance predictability between mix designs. Various mix combinations were run with experimental data produced and correlation analyzed statistically and regression based. The findings indicated that the compressive strength was between 15 and 34 Mpa whereas the permeability coefficients were between 1.5 and 7.0 mm/s based on the aggregate size and paste content. It was established that there were strong negative relationships between compressive strength and porosity and strong positive relationship between permeability and porosity. The size of the aggregate used was larger which enhanced permeability but decreased strength owing to weaker bonding of the paste.

Zheng et al. (2023) [14] investigated the use of copper slag waste to produce alkali-activated metakaolin based on pervious concrete to produce a cement-free and environmentally sustainable permeable pavement material. The test was done on compressive strength, permeability, porosity, microstructure, and durability properties at various levels of copper slag replacement. The findings showed that the compressive strength ranged between 18 and 30 Mpa with optimum performance at moderate slag contents because the geopolymer matrix is densified. Porosity had a range of 17-26 percent and permeability coefficients were found to be between 2.2 and 5.6 mm/s, an indication of good drainage ability. Microstructural observations showed the existence of better gel formation and enriched aggregate-binder bonding when there was an optimum decomposition. The too large content of copper slag caused pore blocking and low permeability, however.

Mirnezami, Hassani, and Bayat (2023) [15] assessed the effects of metallurgical aggregates, which are steel slag and copper slag, on thermal and mechanical properties of concrete applied to conjoint plain concrete pavements (JPCP). The experiment involved the evaluation of compressive strength, flexural strength, thermal conductivity, density, and such properties involving durability to determine how slag aggregates can be used in pavement work. The findings revealed that concrete containing copper and steel slag resulted to compressive strength of 32–48 Mpa, which was almost identical or greater than standard concrete as a result of angularity and rigidity of slag particles. Thermal conductivity was improved with a range of 10 to 25 per cent and this means that the dissipation ability of heat has been enhanced and this is good in the field of pavement temperature control. The flexural strength was between 4.5 and 6.0 Mpa which is within the pavement design requirements. The tests of durability were able to show better performance against abrasion and freeze-thaw cycles.

Table 1 Review Content of Pervious Study

Ref.	Materials Used	Key Findings
1	FA, GGBS as cement replacement	FA–GGBS blends improved workability and long-term strength while maintaining drainage capacity.
2	Optimized mix parameters	Optimum porosity (18–22%) achieved balanced strength and permeability.
3	Crushed clay brick aggregate	Sustainable aggregate with acceptable strength; clogging mitigated by maintenance.
4	BOF slag aggregate	BOF slag enhanced strength and abrasion resistance in porous pavements.
5	Variable w/c ratio, porosity	Strength inversely related to porosity; numerical results matched experiments.
6	Coal combustion residuals (CCR)	CCR-based concrete showed high strength, durability, and reduced carbon footprint.
7	Pervious concrete layer in blocks	Modified block pavements significantly improved infiltration and runoff reduction.
8	Copper slag (fine aggregate)	Optimum copper slag improved strength and durability; excess caused segregation.
9	Copper slag, alkali-activated binder	Ambient-cured AAPC achieved good strength and permeability.
10	Fly ash + copper slag	Enhanced pavement quality with superior durability and sustainability.

3. PROBLEM STATEMENT

The rapid urbanization and the expanded infrastructure growth have also caused the significant increase of impervious pavement areas which gives rise to the challenges of surface runoff, urban floods, groundwater degradation and environmental degradation. The pervious pavements, also known as pervious concrete pavements, have become a viable substitute to the traditional pavements because they are capable of facilitating the storm water penetration and the ground water recharge. Nevertheless, the large-scale application of pervious concrete in pavement has been hindered by its disadvantages, specifically, low mechanical strength, poor durability, and weakness in terms of wearing off on the surface, which only allows it to be used in low traffic situations.

The past research has shown that the performance of pervious concrete can be enhanced with the use of additional cementitious material and other types of aggregates. Fly ash and GGBS, silica fume, and recycled aggregates have also been studied independently presenting different levels of enhancement to strength and permeable properties. With a high pozzolanic reactivity Metakaolin can be used to improve the quality of binder and interfacial bonding whereas copper slag aggregate, which is an industrial by-product, can be used to provide high strength, angularity and durability. Although all these benefits exist, the combination of their application in pervious concrete pavement systems is not well researched. Majority of the literature undertaken is based on the modification of binder or replacement of aggregate with little work done on the synergistic relationship of utilizing a combination of metakaolin and copper slag aggregate in pervious concrete. Also, no extensive experimental data has been provided to compare the mechanical strength, permeability, and durability of such materials in the event that they are used in combination. The effect of different replacement degrees on the pavement-related parameters including compressive strength, infiltration capacity, porosity, and resistance to abrasion has not been properly established.

4. OUTCOME OF THE STUDY

On the basis of the extensive literature review of the pervious concrete pavements that used the alternative material substitution, the following major findings can be outlined:

1. Pervious concrete pavements are always highly permeable (1.5-7.0 mm/s) and porous (15-30

2. percent) which is suitable in storm water management and ground water recharge in urban regions.
3. The inverse relationship between compressive strength and porosity is clear, thus, the balance between the structural capacity and hydraulic performance is necessary due to the essentiality of optimal mix design.
4. Additional cementitious products like fly ash, GGBS, silica fume, and metakaolin have a significant impact on improving the strength of the paste, interfacial transition zones, and long-term strength as well as minimizing cement use and carbon footprint.
5. Aggregates (copper slag, BOF slag, recycled aggregates, waste glass, and clay bricks) made of industrial by-products enhance sustainability and have at the optimal levels of replacement, a positive effect on compressive strength, abrasion resistance, and durability.
6. The copper slag, specifically, has a great potential on enhancing mechanical strength and durability because it is angular in shape and dense enough as long as it is not replaced excessively to avoid blocking of pore.
7. The majority of researches are devoted to strength or permeability, and little work is done on the optimization of the two properties as well as durability in real field conditions.
8. The literature is characterized by an evident research gap on the research conducted on the use of metakaolin as a binder substitute and copper slag as an aggregate substitute in pervious concrete pavements.

5. CONCLUSION

Based on this review, pervious concrete pavement is an emerging and viable alternative to the traditional pavements to help solve urban storm water runoff, flooding, and environmental issues. The use of other materials e.g. addition of supplementary cementitious materials and industrial by-products has been effective in overcoming the historical weaknesses of pervious concrete in terms of low strength and durability. The literature validates the fact that optimization of SCMs enhances mechanical performance and lifespan, whereas aggregates of comparable waste can lead to resource conservation and the objectives of a circular economy. The important issue, however, is to attain maximum compromise between permeability and strength. Despite the high number of reports on individual effects of metakaolin and copper slag, there is lack of studies on the application of the two in pervious concrete pavement systems. Further studies are recommended to be conducted in systematic optimization of mixes, long-term stability, resistance to clogging, and environmental analysis of metakaolin-copper slag-based pervious concrete in the context of life-cycle analysis. These studies could lead to creating a new generation of the high-strength, durable and environmentally friendly pervious concrete pavements that could be used in medium- and high-traffic areas.

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