



# Performance Evaluation of Sustainable Pervious Concrete Incorporating Industrial and Agricultural Byproducts

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## ABSTRACT

The sustainable advancement of pervious concrete through the integration of industrial and agro-industrial waste materials presents a promising approach for addressing environmental challenges. This study investigated the effects of incorporating rice husk-derived activated carbon, iron slag, and 5% replacement of adhesive cement (by weight) into pervious concrete mixtures. The performance was evaluated in terms of compressive strength, porosity, permeability, and water purification capabilities, which are particularly relevant in pervious concrete applications, such as stormwater management, where both infiltration and pollutant filtration are crucial. The experimental findings showed that Mix 1 (iron slag + 5% adhesive cement) achieved the highest 28-day compressive strength of 22.13 N.mm<sup>-2</sup>, representing an increase of 4.2% over the control mix (CM) at 21.24 N.mm<sup>-2</sup>. The 14-day and 7-day strengths of Mix 1 were 19.2 N/mm<sup>2</sup> and 14.52 N.mm<sup>-2</sup>, respectively, which were higher than those of the control (17.24 N.mm<sup>-2</sup> and 11.9 N.mm<sup>-2</sup>), indicating improved early and long-term strength. This mix also achieved the highest porosity (24.42%), a 13.5% improvement over the control (21.52%), leading to enhanced permeability and drainage capacity. Water quality testing demonstrated that Mix 2 reduced the pH from 8.65 to 7.34, bringing it within the WHO acceptable limits, and functioned effectively as a passive water treatment solution. While Mix 3 provided moderate pH neutralization (to 7.86), Mix 4 showed the greatest reduction (to 6.82), however, it may require buffering to prevent over-acidity. Regarding water hardness, Mix 4 achieved a 38.9% reduction (from 232.5 to 142 mg.L<sup>-1</sup>), likely due to enhanced ion exchange and precipitation mechanisms contributed by the activated carbon and iron slag. Mix 2 also showed a significant 26.2% decrease, confirming its potential to improve water filtration. This study supports the incorporation of waste-derived materials into pervious concrete to enhance environmental sustainability, promote groundwater recharge, and improve urban infrastructure through eco-conscious construction methods.

## INTRODUCTION

The sustainable development of pervious concrete using industrial and agro-industrial waste materials offers a promising pathway to address pressing environmental concerns. Traditional concrete, despite its widespread use, significantly contributes to global carbon emissions and hinders natural groundwater recharge due to its impermeability. (Mehta 2001). Pervious concrete, characterized by its high porosity, allows water to percolate through its structure, reducing surface runoff and facilitating stormwater management. (Tennis et al. 2004). In recent years, researchers have explored the integration of waste materials, such as rice husk-activated carbon, iron slag, and adhesive cement, to enhance the environmental and mechanical performances of pervious concrete (Hossain 2019, Siddique 2004). Rice husk, a by-product rich in silica, can be transformed into activated carbon with a high adsorption capacity, offering benefits for filtering stormwater pollutants (Chandrasekhar et al. 2003, Kumar & Rai 2018). Iron slag, a by-product of the steel industry, contributes to strength enhancement, whereas

adhesive cement can improve the bonding between the paste and aggregate. However, the combined use of these three materials in a single pervious concrete system has not been extensively studied. This study fills that gap. The novelty of this research lies in the synergistic integration of rice husk-derived activated carbon (for pollutant adsorption), iron slag (for mechanical strength), and adhesive cement (for internal cohesion), aiming to address the key limitation of pervious concrete: the difficulty in achieving high permeability and sufficient structural strength simultaneously.

Climate change alters weather patterns, leading to extreme weather conditions, unreliable water availability, growing water scarcity, and contamination of water resources (Urama & Ozor 2010). To facilitate stormwater management, groundwater recharge, and surface runoff reduction, pervious concrete, also referred to as porous or permeable concrete, is a type of concrete that permits water to flow through it. Utilizing agricultural and industrial waste, our project's primary goal is to create pervious concrete that will improve water quality (Pandey & Kumar 2022). The long-term environmental benefits are significant. Incorporating such waste materials into concrete diverts them from landfills, reduces the carbon footprint associated with cement production, and promotes circular economy practices (Van den Heede & De Belie 2012, Butler & Guthrie 2009). Furthermore, the performance of pervious concrete in urban areas enhances groundwater recharge and alleviates urban heat island effects by allowing natural infiltration and evaporation processes (Haselbach 2010, Bozorg-Haddad et al. 2021). Making good use of industrial trash can boost energy and resource efficiency and lessen potential environmental harm. (Dincer & Rosen 1999). The inability to achieve sufficient compressive strength while preserving porosity usually limits the use of pervious concrete. It can also be utilized to save water by replacing pricey retention ponds. (Sarker et al. 2021). The critical role that precedent plays in addressing significant environmental concerns and promoting sustainable growth (Tota-Maharaj 2010). Among the many artificial sources available today, rice husk, sugarcane bagasse, maize cob, and coconut husk are examples of agricultural biomass materials that are reasonably priced (Rees & Wackernagel 2008). Using industrial and agro-industrial waste materials in pervious concrete mixtures is one way to address this issue. These components, including iron slag and rice husk activated carbon, improve the sustainability of pervious concrete and offer a means of recycling waste materials, which benefits the environment and the economy.

This study aimed to examine the impacts of creating sustainable pervious concrete using waste resources, such as rice husk activated carbon, adhesive cement, and iron slag.

Focusing on their water quality optimization qualities, the study performed tests to ascertain the compressive strength, porosity, specific gravity, fineness, and standard consistency of concrete mixes.

Although the need for water is continuously increasing, only 3% of the world's water is fresh or unsalted (Martinez 2020). Rapid industrialization and urbanization are causing waste effluents to be released directly into river water runoff, thereby damaging the ecosystem (Sarker et al. 2021).

Similar to regular concrete and mortars, pervious concrete depends significantly on cement. However, cement production contributes significantly to environmental pollution, consuming approximately 2–3% of the world's total energy and contributing 8–9% of worldwide CO<sub>2</sub> emissions (Monteiro et al. 2017). Many environmental problems, including waterlogging, water pollution, and the urban heat island effect, are largely caused by impermeable pavements that impede the normal flow of moisture and heat between the ground and the atmosphere (Kia et al. 2021, Huang et al. 2021). A pervious concrete composition comprised water, cement, and coarse aggregates with little to no sand or other additives. It has a high, interconnected porosity of generally 15% to 30%, with pores that are 2 mm to 8 mm in diameter (Debnath & Sarkar 2020). Therefore, before the application of pervious concrete, it is important to identify the optimal combination of coarse and fine aggregates to establish a successful relationship between porosity, permeability, and compressive strength.

This study addresses both challenges by evaluating the trade-off between strength and porosity while testing the mix's ability to reduce pH and water hardness, critical indicators of urban runoff quality. An increase in the W/C ratio results in an excess amount of water in the cement paste, resulting in an excessive flowing paste that can fill pore spaces and reduce the connectivity of the voids. In contrast, if the W/C ratio is too low, the mix may not have sufficient consistency or cohesion to produce reasonable workability and placement (Debnath & Sarker 2020). Pervious concrete (PC) mainly comprises well-graded coarse aggregates along with cementing materials. It provides advantages like reduced density, lower thermal conductivity, and minimal drying shrinkage (Aliabdo et al. 2018). Pervious concrete (PC) primarily comprises well-graded coarse aggregates combined with cementing materials. It offers advantages, such as reduced density, lower thermal conductivity, and minimal drying shrinkage (Aliabdo et al. 2018, Chandrappa & Biligiri 2016). PC also offers environmental benefits, such as minimizing the infiltration of pollutants into groundwater and lowering the noise produced by the interaction between tires and pavements (Haselbach et al. 2011, Martinez et al. 2020).

Pervious concrete (PC) provides various economic benefits, such as lower installation costs by removing the need for costly storm drains, reduced lifecycle expenses owing to fewer repairs, and the ability to be recycled at the end of its lifespan. It uses fewer raw materials than traditional concrete and offers improved insulation properties. A previous study that compared the costs of using PC versus traditional concrete for a car park in Thailand revealed total savings of ₹135.m<sup>2</sup> (32 THB.m<sup>2</sup>) (Priyadarshana & Dissanayake 2013). The use of 30% and 100% RA reduces the environmental impact by up to 8% and 23%, respectively (Mah 2018). The use of 30% recycled aggregate (RA) and 100% RA instead of natural aggregate (NA) in concrete led to cost savings of 9% and 28%, respectively. Additionally, the environmental and cost impacts decreased by 50.8% and 68.1%, respectively, when waste concrete was utilized to create RA concrete. (Wijayasundara et al. 2018).

Research indicates that Australia produces approximately 43.78 million metric tons of waste annually, with 38% originating from construction and demolition (C&D) activities. In China, municipal solid waste accounts for nearly 30% of the global total, and C&D waste contributes approximately 40%. Construction activities generate approximately 100 million metric tons of waste annually, whereas the demolition of older buildings adds approximately 200 million metric tons each year (Yang et al. 2017).

Although pervious pavement may look similar to regular pavement, the major difference is the presence of voids. The voids create porosity, and the voids that make up pervious pavement generate a design source that differentiates it materially from regular pavements and provides it with unique physical characteristics. As mentioned, pervious concrete has advantages; however, it has limitations and disadvantages that affect its ability for larger use. It typically has lower strength and structural capacity, limiting its applications to parking lots, low-traffic roads, and sidewalks. For example, for higher-traffic roads and busy expressways, pervious concrete, even if the site conditions are appropriate for its use, may not meet certain structural requirements. Another major limitation is that pervious pavements can become clogged over time, which can hinder hydraulic conductivity and infiltration rate. Nevertheless, ongoing research aims to address these challenges and improve the structural performance of pervious pavements. Various studies have examined different aspects of pervious concrete, including its types, structural methods, materials, pore characteristics, hydraulic conductivity, and environmental benefits, such as heat and noise reduction. The 'RMC Research & Education Foundation' has gathered research on the application, construction, maintenance, and design

of pervious pavements from structural, hydrological, and environmental viewpoints (Brown 2006).

This study investigates the application of pervious concrete in road pavement construction. Pervious concrete, often termed 'no-fines' concrete, is characterized by the absence or minimal use of fine aggregates, such as sand. The primary aim of this research was to evaluate the compressive strength and permeability of pervious concrete. For this purpose, 150 mm × 150 mm × 150 mm cube specimens were cast and cured for 28 days.

This study enhances pervious concrete through four different mix designs and investigates how different agro-industrial spent materials alter its properties. The control mix (Mix 1) is typical pervious concrete, comprising 331 kg cement, 149 kg water, and 1400 kg coarse aggregate, without any additional materials. Mix 2 incorporates 280 kg of iron slag as a partial replacement for coarse aggregate and includes 3.31 kg of adhesive cement to improve bonding and provide structural performance. Mix 3 uses materials similar to those in Mix 2 but adds 40 kg of activated carbon treated with rice husk and reduces the amount of adhesive cement to 2.90 kg. This was done to enhance sustainability and evaluate the effect of combining industrial and agro-waste materials on permeability and internal bonding. Mix 4 further modifies the composition by maintaining 40 kg of rice husk carbon and increasing the iron slag content to 320 kg. The amount of adhesive cement is reduced to 2.60 kg as the fine supplementary materials constitute a higher proportion of the total material. The mixes were carefully designed and tested to assess their functionalities, that is, strength, permeability, and environmental benefits, to create more sustainable and green pervious concrete for use in modern construction applications. By leveraging locally abundant and cost-effective waste materials, this research contributes to sustainable construction practices and supports circular economy principles.

## MATERIALS AND METHODS

This approach offers a thorough framework for evaluating the environmental effects and technical performance of sustainable pervious concrete mixtures.

The experiment consisted of constructing columns using acrylic glass tubing with an internal diameter of 9.38 cm. The base was made from a PVC foam sheet material, and a metal frame measuring 27.5 cm × 27.5 cm × 50 cm served as the stand for the entire setup (Moskaleva et al. 2021). An iron platform extending to a height of 120 cm was incorporated into the structure to function as an overhead tank for managing sample discharge (Gros et al. 2021). We analyzed

rice husk-derived activated carbon during a mini-project and selected this material to enhance water quality based on the results of our characterization (Sharath et al. 2017).

The experimental columns included four types of pervious concrete samples: the control mix and pervious concrete with the addition of Iran slag (Hesami et al. 2014), pervious concrete with the addition of iron slag and adhesive cement (Vazquez-Rivera et al. 2015), and pervious concrete with the addition of iron slag, adhesive cement, and rice husk ash. The mix was manufactured using a mechanical tilt-type concrete mixer. The experiment involved the use of fine gravel as a filtering agent beneath the concrete blocks and clay roofing (Manning & Vetterlein 2004), which can serve as the basis for porous concrete and for adsorbing practices in real-world scenarios (Bosco & Hemsli 2020).

Several studies have explored the role of cementitious materials and their optimal inclusion rates (Raghav et al. 2021). In particular, indicated that small amounts (5–10%) of adhesive cement could significantly improve the bonding between aggregates, particularly in high-performance concrete. This proportion of adhesive cement allows for improved hydration and densification of the concrete matrix without adversely affecting its overall strength properties.

### Materials Used

Ordinary Portland cement was used as the primary binder in all pervious concrete mixes. To improve bonding and internal cohesion, a small amount of adhesive cement was added to the modified mixes (Mixes 2–4). The adhesive cement used in this study was formulated using Portland cement, quartz sand, cellulose ether, redispersible gelatin-based powder, and

alcohol-derived chemical compounds. Rice husk-activated carbon, a by-product of the thermal degradation of rice husks generated in the rice milling process, was added to Mixes 3 and 4 to improve sustainability and improve the pore structure of the concrete. Iron slag, an industrial by-product generated in metal processing, was added to Mixes 2, 3, and 4 as a partial replacement for coarse aggregate to improve durability and reduce the consumption of natural resources.

### Rice husk

Rice husk refers to the tough, protective outer covering that encases the grain of rice. Rice husk ash is a source of amorphous reactive silica (Chandrasekhar 2003). When untreated water passes through rice husk, calcium and magnesium ions are absorbed into its surface, resulting in a decrease in the hardness of the sample water (Zainal et al. 2019).

### Preparation of Activated Carbon From Rice Husk

To get rid of any surface contaminants, rice husks were continuously cleaned with distilled water before being dried for three hours at 110°C in an oven (Emmanuel 2021). Following that, 25 g of dry rice husk was carbonized in a furnace for 90, 120, and 150 min at 400, 450, 500, 550, and 600 °C (Ismagilov et al. 2009). Thereafter, it was impregnated with 5 % (v/v) hydrochloric acid at a carbon-to-acid ratio of 1:10 (p/v) for a whole day. It was then sieved to 100 meshes after being filtered and oven dried for three hours at 110°C (Hanum et al. 2017). The yield of activated carbon obtained through this process ranged from 23% to 26%, depending on the temperature and duration. Fig. 1a & b shows pictorial



Fig. 1a: Rice Husk.



Fig. 1b: Rice husk activated carbon.



Fig. 2: Tile adhesive cement.



Fig. 3: Iron Slag.

representation of the rice husk and rice husk activated carbon. The Brunauer–Emmett–Teller (BET) surface area was measured between  $520$  and  $650 \text{ m}^2.\text{g}^{-1}$ , indicating a high degree of porosity suitable for pollutant adsorption in water treatment applications.

### Tile Adhesive Cement

In this study, tile adhesive cement (Fig. 2) was incorporated into a pervious concrete mix to enhance its bonding capability and overall durability. This cement type, which consists of Portland cement, quartz sand, cellulose ether, and redispersible polymers, enhances the cohesion and adhesion properties. By adding it to the mix, the interlocking of particles is further enhanced to reduce segregation while maintaining porosity. The adhesive components improve the mechanical properties of the mix and allow for improved compressive strength without a loss of permeability. This new process is intended to provide a balance between structural performance and desirable environmental solutions, indicating potential use in sustainable construction innovations for elements such as pavements and stormwater management.

### Iron Slag

The iron slag (Fig. 3) in pervious concrete can be used as a substitute for traditional aggregates in sustainable construction. The inclusion of iron slag improves the mechanical strength and durability of concrete while alleviating waste disposal concerns for the reuse of industrial by-products. Pervious concrete is a composite material composed primarily of coarse aggregates and cement (Xu et al. 2017). Research shows that adding iron slag can improve the compressive strength of pervious concrete while still ensuring sufficient porosity and permeability, which makes it ideal for urban drainage uses.

Research indicates that iron slag can significantly enhance the compressive strength of pervious concrete. For example, one study demonstrated that substituting 75% of the coarse aggregate with iron slag achieved a maximum compressive strength of 16.80 MPa. Additionally, while iron slag boosts strength, it also preserves adequate porosity (over

15%) and permeability (greater than  $1.17 \text{ mm}.\text{s}^{-1}$ ), which are crucial for efficient stormwater management (Teymouri et al. 2023).

### Mix Proportions

The goal of this research was to enhance the sustainability of pervious concrete by including multiple agro-industrial waste products while maintaining the structural integrity of the pervious concrete. Four concrete mixes (Mix 1–Mix 4) were prepared at a fixed water-to-cement ratio of 0.5 to eliminate potential effects associated with variations in hydration and workability (Table 1 and Fig. 4). This study sought to replace conventional materials with more sustainable alternatives and monitor their effects on the properties of concrete. Mix 1 was being treated as a control sample with 331 kg of cement, 149 kg of water, and 1400 kg of coarse aggregate (with no other modifications). This mix represented conventional pervious concrete for our review, and it can be considered the end of the first mix. In Mix 2, iron slag was used to partly substitute coarse aggregate, and the total amount was a total of 280 kg. In addition, as adequate bonding among the components and prolonged performance were important, an extra 3.31 kg of adhesive cement was added to ensure bonding and maintain structural performance, because iron slag and fine materials may influence internal cohesion and stability. Mix 3 contained 40 kg of rice husk activated carbon and increased iron slag to 300 kg, with an additional 3.31 kg of adhesive cement. As part of our motivation to have further sustainability in this mix, we were looking to add more industrial by-products to the mix. Mix 4 was the most modified composition, containing 40 kg of rice husk carbon and further increasing the iron slag content to 320 kg, again with 3.31 kg of adhesive cement. The study developed in this way allowed the examination of how increasing supplementary materials affects a mix's permeability, strength, and cohesion. The use of rice husk carbon as an additive was intended to build a more sustainable carbon footprint for the concrete, while potentially providing better filtration and pore structure because of its high surface area and porousness. Iron slag is a heavier industrial by-product; therefore, it adds mass and structure while lowering the

use of natural aggregates. The consistent use of adhesive cement across all the modified mixes aided internal bonding despite the use of non-traditional materials. Overall, the systematic substitution of materials is a clear step toward more sustainable construction practices, increased waste diversion, and reduced environmental impact of concrete. Further experimental work is being performed on these mixes to measure mechanical properties, water permeability, and long-term durability, which will provide valuable knowledge about how agro-industrial waste can be incorporated into sustainable and environmentally friendly infrastructure development.

## RESULTS AND DISCUSSION

### Compression Test

Compression tests were performed on all four types of concrete cubes. We conducted 7-, 14-, and 28-day compressive strength tests. Three cubes of each type were tested, and the average was noted. The results are presented in Fig. 5.

The increase in compressive strength observed in all concrete mixes can be attributed to the specific selection of materials and their interactions. The control mix (CM)

Table 1: Mix design of each sample for 1m<sup>3</sup>.

Mixture	Cement [kg]	Water [kg]	Coarse aggregate [kg]	Rice husk-activated carbon [kg]	Iron slag [kg]	Adhesive Cement [k]	Free water cement ratio
Mix 1	331	149	1400	-	-	-	0.5
Mix 2	331	149	1400	-	280	3.31	0.5
Mix 3	331	149	1400	40	300	3.31	0.5
Mix 4	331	149	1400	40	320	3.31	0.5

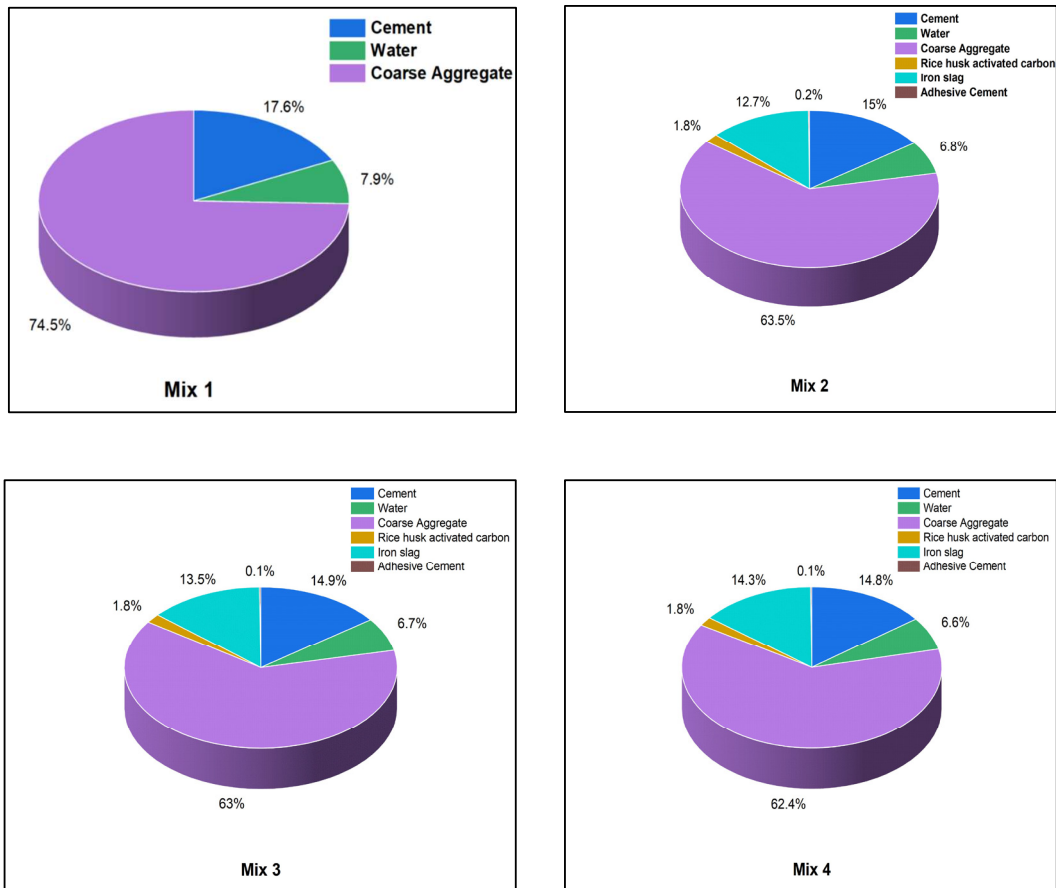


Fig. 4: Percentage of constituents in mix1, mix 2, mix 3 and mix 4.

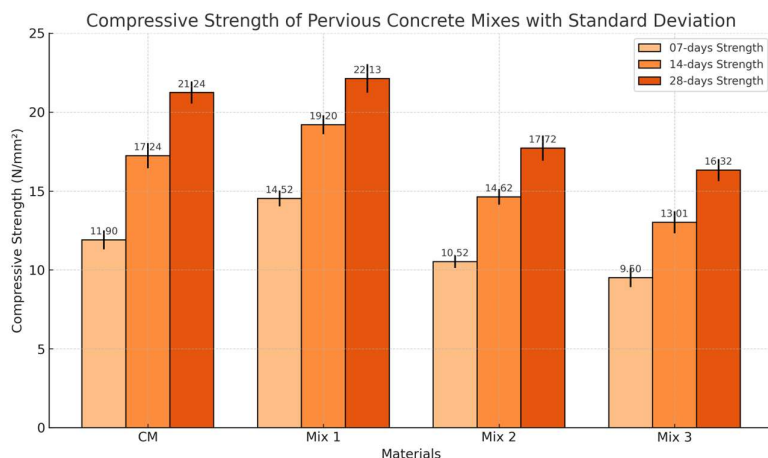


Fig. 5: Compressive strength of pervious concrete mixes at 7, 14, and 28 days with standard deviation. Strength values are shown for each bar. Mix 1 exhibited the highest 28-day strength (22.13 N.mm<sup>2</sup>), whereas Mix 3 exhibited the lowest. Error bars reflect the standard deviation, indicating the variability across the test specimens.

exhibited an observable increase in compressive strength, reaching 21.24 N.mm<sup>-2</sup> after 28 days of curing. This strength gain can be attributed to the presence of Portland cement and coarse aggregates, which created a stable matrix that allowed for early hydration and contributed to the compressive strength gain in the early days.

In contrast, Mix 1, which contained rice husk-activated carbon and iron slag as supplementary materials, exhibited a greater compressive strength of 22.13 N.mm<sup>2</sup> at 28 days. It is tempting to suggest that rice husk-activated carbon contributed pozzolonic properties by, in the presence of calcium hydroxide released during hydration, allowing for reactive species to accumulate and form additional calcium silicate hydrate (C-S-H) gel, thereby enhancing the matrix. Iron slag is an industrial waste material that adds pozzolonic compounds to the concrete matrix, which can lead to an increased density of the matrix and development of strength over time.

In summary, Mixes 2 and 3, which had increased levels of supplementary materials, exhibited reduced strength compared with the reference mix. This reduction in strength was likely a result of too high a quantity of additive affecting optimal hydration or producing a microstructure that was not cohesive. As noted earlier, the water-to-cement ratio of all mixes remained at 0.5; therefore, the differences in strength could be attributed to variations in the mixtures.

### Porosity Test

Porosity tests were performed to evaluate the void ratios of a sample of permeable concrete mixes, including a control mix (CM) of 22.16% for comparative purposes (Fig. 6). The void ratio directly affects the hydraulic performance and

permeability. Mix 1 was the next trial mix (5% adhesive cement). It exhibited a porosity of 24.42%, where the increase in porosity may reflect a slight increase in the makeup of binder and a possible increase in free alkali, which resulted in a minor increase in the number of microvoids. The water permeability of Mix 1 may have shown improvement. The mix containing 20% iron slag and 5% adhesive cement (Mix 2) had a porosity percentage of 20.52%, which was a lower porosity than Mix 1, which was because iron slag is denser than the gravel and improves packing density and particle gradation. Mix 3, which contained 20% iron slag, had the lowest porosity at 19.53%, due to the iron slag particles increasing packing efficiency, which formed a denser structure.

In addition to improving the mechanical and permeability properties, Mix 2 demonstrated interesting pH-stabilizing behavior. The adhesive cement inhibited free alkali ions,

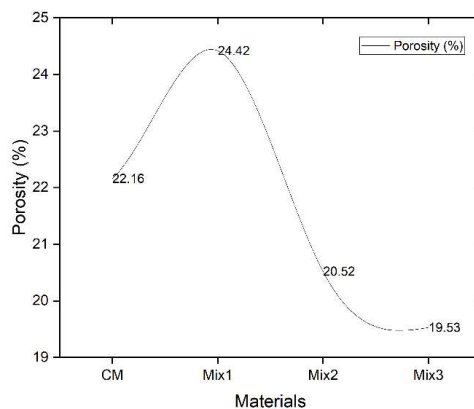


Fig. 6: Porosity test graph.

Table 2: Permeability test.

Depth [cm]	Mix 1 [k mm.sec <sup>-1</sup> ]	Mix 2 [k mm.sec <sup>-1</sup> ]	Mix 3 [k mm.sec <sup>-1</sup> ]	Mix 4 [k mm.sec <sup>-1</sup> ]
10	7.54	3.34	4.75	4.82
20	7.34	4.72	5.85	6.13
30	6.49	5.07	5.54	5.93
40	6.7	5.12	5.12	5.37

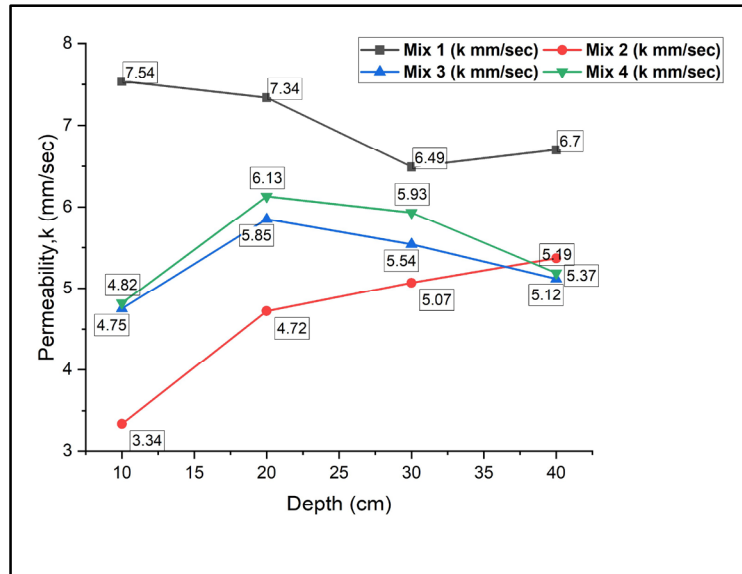


Fig. 7: Average permeability graph at depths of 10 cm, 20 cm, 30 cm, and 40 cm.

whereas iron slag controlled hydroxide ions during hydration to limit the pore solution alkalinity of the fresh coarse aggregate permeable concrete. Therefore, Mix 2 provides an improved structure, permeability, and environmental performance.

### Permeability Test

Permeability tests on pervious concrete are essential for assessing its effectiveness in drainage applications. Pervious concrete, known for its high porosity, allows water to flow through, which helps reduce surface runoff and encourages groundwater recharge. Numerous studies have investigated the relationship between mix design, porosity, and permeability, providing valuable insights. Research has shown that greater porosity is linked to higher permeability. For example, concrete with 28% porosity demonstrated better permeability than concrete with lower porosity levels.

Table 2 presents the permeability data (sorted from highest to lowest) for four pervious concrete mixes at depths of 10, 20, 30, and 40 cm (Fig. 7). The permeability values (in mm.s<sup>-1</sup>) indicated variations among the mixes. Mix 1 had the highest permeability, and as depths increased, there was a small downward trend in permeability values, indicating

a relatively uniform structure within the concrete with progressively denser layers at depths. The permeability of Mix 2 slightly to moderately increased with depth, indicating improved pore connectivity at greater depths. The permeability values for Mixes 3 and 4 appeared to trend inconsistently and were difficult to interpret, perhaps due to differences in compaction or uniformity within the concrete matrix. Overall, the data suggest that the mix design of the pervious concrete was significant in controlling the permeability characteristics and, if warranted by further corroboration, provides examples of preferential flow paths that can improve desirable drainage performance in pervious concrete applications.

Mix 1 exhibited the highest porosity (24.42%), which led to enhanced surface and subsurface water infiltration, indicating its suitability for stormwater management systems. Mix 2, although slightly lower in porosity, showed higher permeability in deeper layers, likely due to better pore connectivity and distribution enhanced by the adhesive cement, which reduced clogging and improved vertical flow.

### pH Test

The pH of untreated water samples ranged from 7.49 to 8.47, with Garage Water having the highest pH (8.47) and Run-off

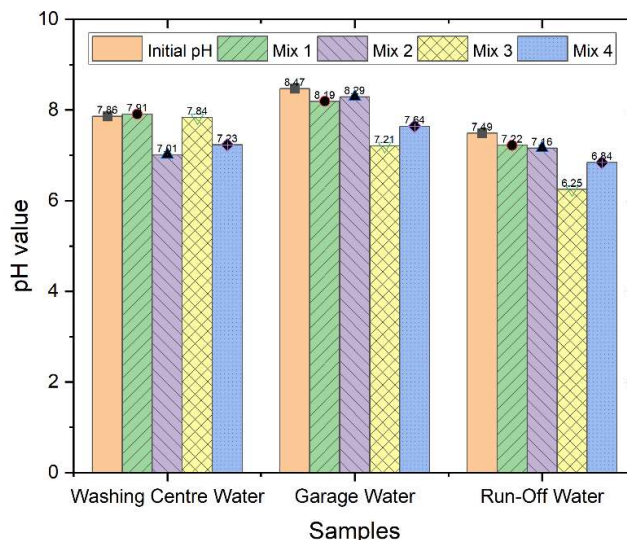


Fig. 8: pH values of washing center, garage, and runoff water before and after filtration through different pervious concrete mixes. Mix 2 and Mix 4 showed the most significant pH reduction, indicating effective water treatment potential.

Water the lowest (7.49) (Fig. 8). Although these values were close to the ideal range of 6.5–8.5 set by the World Health Organization (WHO), treatment was still necessary. Mix 2, which contained iron slag and adhesive cement, reduced the pH of Washing Centre Water to 7.01, Garage Water to 8.29, and Run-Off Water to 7.16. The pH reduction in these samples is attributed to the neutralizing effect of iron slag on excess alkalinity, whereas adhesive cement helped stabilize the pH values. Mix 3, incorporating rice husk-activated carbon, showed a more gradual decrease in pH, lowering the pH of Washing Center Water to 7.84, Garage Water to 7.21, and Run-off Water to 6.25. This mix achieved a balanced reduction, maintaining the pH within a safe range. Mix 4, also containing activated carbon, lowered the pH of Washing Center Water to 7.23 and Run-off Water to 6.84, demonstrating effective pH reduction. However, it appears that this mix may risk lowering the pH too much in some cases, suggesting careful control over its use. The control samples showed no significant pH changes, confirming that the observed effects were due to the mixes. Overall, Mix 3 provided stable results, whereas Mix 4 was more aggressive in pH adjustment but requires careful application to avoid excessive acidity.

### Hardness Test

Differences in the concrete mix ingredients resulted in differences in their effectiveness in reducing water hardness in many water samples (Fig. 9). Mix 1, without any additives to reduce hardness, showed slight reductions in hardness levels in the water samples. The water hardness in the washing center decreased from 679 mg.L<sup>-1</sup> to 616 mg.L<sup>-1</sup>, in

the garage, it decreased from 582 mg.L<sup>-1</sup> to 524 mg.L<sup>-1</sup>, and in runoff water, it decreased from 396 mg.L<sup>-1</sup> to 317 mg.L<sup>-1</sup>. Mix 2, which had the iron slag mix adhesive cement, had the most apparent reductions in hardness level, specifically in the Washing Centre Water sample (679 mg.L<sup>-1</sup> down to 427 mg.L<sup>-1</sup>) and the Run-Off Water (396 mg.L<sup>-1</sup> down to 259 mg.L<sup>-1</sup>). This is expected based on the data, as iron slag can facilitate the adsorption of ions that contribute to hardness, while adhesive cement may help stabilize ions, which also contribute to hardness, because the adhesive cement has soluble materials that can facilitate only temporary stability of hardness ions. The unexpected increase in hardness in Mix 4 for garage water is now discussed, with a plausible explanation being the leaching of calcium or magnesium ions from the cement matrix or residual impurities in iron slag.

Mix 3 contributed to a reduction in hardness, but not as markedly as Mix 2. The garage water sample decreased from 582 to 512 mg.L<sup>-1</sup>, and the runoff water sample decreased from 396 to 274 mg.L<sup>-1</sup>, which is consistent with the ion adsorption properties of activated carbons. However, Mix 4 showed an increase in hardness for garage water (582 mg.L<sup>-1</sup> increased to 547 mg.L<sup>-1</sup>) and may have contributed to mineral leaching or ion exchange, which caused the increase. It was recognized that it had considerable hardness reductions in washing.

### Turbidity Test

The turbidity results for the different mixes showed varying degrees of effectiveness in reducing suspended particles in the sample waters (Fig. 10). Mix 1 (control) exhibited minimal change in turbidity across all sample types, with

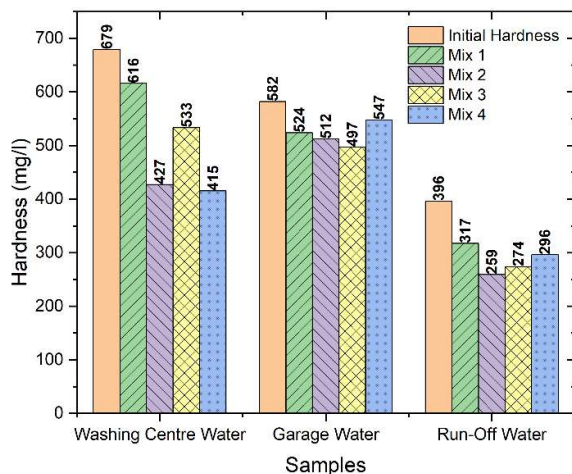


Fig. 9: Reduction in water hardness ( $\text{mg.L}^{-1}$ ) for washing center, garage, and runoff water after treatment with different pervious concrete mixes. Mix 4 showed the greatest hardness reduction across all samples, followed closely by Mix 2, highlighting its effectiveness for water softening applications.

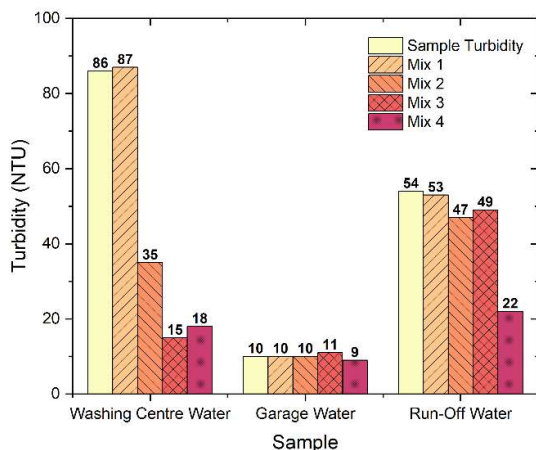


Fig. 10: Turbidity test results for different wastewater samples using pervious concrete mixes. Mix 4 showed the best turbidity reduction across all samples, whereas Mix 1 was the least effective. The maximum reduction was observed for washing center water.

Washing Center Water remaining at 87 NTU, Garage Water at 10 NTU, and Run-Off Water at 53 NTU, indicating no significant impact on particle removal. In contrast, mix 2, containing iron slag and adhesive cement, demonstrated a notable reduction in Washing Centre Water turbidity from 86 NTU to 35 NTU, suggesting that iron slag effectively adsorbs suspended particles, and the adhesive cement further aids in particle binding. However, turbidity reduction was less significant for Garage Water and Run-Off Water, where turbidity remained relatively constant or showed minor improvement. Mix 3, with activated carbon, proved highly effective for Washing Centre Water, reducing turbidity to 15 NTU, likely due to activated carbon's ability to adsorb and remove fine particulate matter. It showed less pronounced effects on Garage Water and Run-Off Water, where turbidity reductions were moderate. Mix 4, which combined activated

carbon and iron slag, reduced the Washing Centre Water turbidity to 18 NTU, demonstrating good performance, although slightly less effective than mix 3. Garage Water showed minor improvements, dropping to 9 NTU, while Run-Off Water turbidity decreased to 22 NTU, reflecting the combined effects of both materials. Overall, mix 3 proved to be the most effective in reducing turbidity, especially in high-turbidity waters, whereas mix 2 showed moderate success, particularly in Washing Centre Water.

### Dissolved Oxygen Test

Dissolved oxygen (DO) levels in water decreased across all mixes, with the most noticeable drop observed in Mixes 2 and 4 (Fig. 11). Mix 2, which included iron slag and adhesive cement, caused the DO in Washing Centre Water to drop from  $8.2 \text{ mg.L}^{-1}$  to  $7.1 \text{ mg.L}^{-1}$  and Run-Off Water to

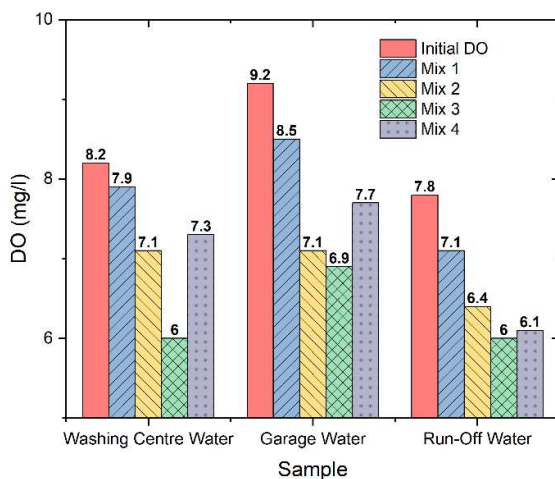


Fig. 11: Dissolved oxygen (DO) levels in different wastewater samples before and after treatment. The initial DO levels were highest in garage water ( $9.2 \text{ mg.L}^{-1}$ ). After treatment, all samples showed reduced DO levels, with Mix 4 consistently retaining higher DO, indicating better oxygen preservation.

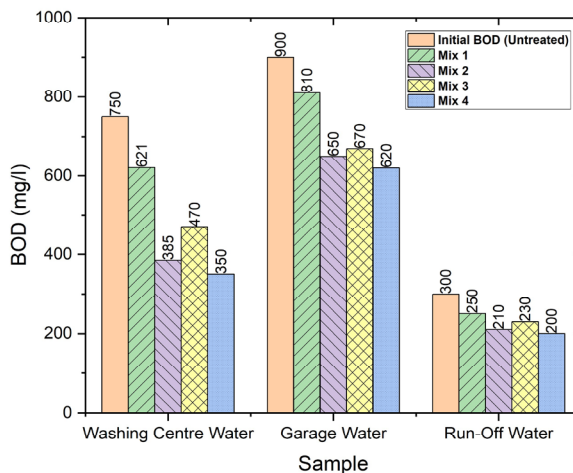


Fig. 12: Biochemical oxygen demand (BOD) in wastewater samples before and after treatment. All previous concrete mixes significantly reduced BOD levels. Mix 4 achieved the greatest BOD reduction in all samples, especially in Garage and Washing Center Water, reflecting better organic load removal.

decrease to  $6.4 \text{ mg.L}^{-1}$ . This reduction can be attributed to the oxygen-consuming reactions of iron slag with water, as it undergoes hydration, and the oxygen demand from adhesive cement during the curing process. Mix 3, which contained activated carbon, also caused a decrease in DO, with Washing Centre Water dropping to  $6.0 \text{ mg.L}^{-1}$ , as activated carbon adsorbs organic materials, consuming oxygen in the process. The combination of both iron slag and activated carbon in Mix 4 led to the most significant reduction in DO levels, especially in runoff water, where it decreased to  $6.1 \text{ mg.L}^{-1}$ . This combination intensified oxygen consumption due to both the hydration of iron slag and the adsorption capacity of activated carbon. In contrast, Mix 1 (control)

showed minimal reduction in DO, as the standard hydration of Portland cement consumed only a small amount of oxygen. These results highlight the potential environmental impact of these mixes, with Mixes 2 and 4 showing the most significant oxygen depletion, which should be considered when selecting mixes for water management applications.

### BOD Test

Biochemical oxygen demand (BOD) indicates the degree to which microorganisms utilize dissolved oxygen to oxidize organic materials while living in water. A decrease in BOD indicates that organic pollutants have been treated and/or removed. We initiated treatment with untreated washing

center water, which had an initial BOD of 750 mg.L<sup>-1</sup>. BOD decreased in all samples, with Mix 1 reducing the BOD to 620 mg.L<sup>-1</sup>, but only showed a small improvement (Fig. 12). Mix 2 showed the greatest improvement with BOD 390 mg.L<sup>-1</sup>, likely due to the synergistic effects of iron slag and cement adhesive interventions, as both materials may have combined to adsorb organic pollutants while enhancing hydration reactions that trap contaminants.

Mix 3 obtained a final BOD value of 470 mg.L<sup>-1</sup>, demonstrating the capacity of activated carbon to adsorb organic matter. Mix 4, which included both iron slag and activated carbon, had the lowest BOD (350 mg.L<sup>-1</sup>), indicating an additive effect of the two intermediate materials in reducing organic content in the effluent. For garage water, which had an initial BOD of 900 mg.L<sup>-1</sup>, mix 1 was effective only for a 100 mg.L<sup>-1</sup> (~ 11%) reduction in BOD to 800 mg.L<sup>-1</sup>, whereas mix 2 provided an additional and faster reduction in BOD to 650 mg.L<sup>-1</sup>. Mixes 3 and 4 had final BOD values of 670 mg.L<sup>-1</sup> and 610 mg.L<sup>-1</sup>, respectively, reinforcing the nature and effectiveness of the reactive and adsorptive materials used to remove biodegradable organic matter from drainage.

Run-off water started at a BOD of 300 mg.L<sup>-1</sup>, which was reduced to 260 mg.L<sup>-1</sup> in Mix 1, 210 mg.L<sup>-1</sup> in Mix 2, 230 mg.L<sup>-1</sup> in Mix 3, and 200 mg.L<sup>-1</sup> in Mix 4. Overall, Mix 2 consistently had the highest VI BOD reductions across all water types studied; thus, Mix 2 had the highest capacity for decreasing the organic load. While Mix 4 also achieved strong BOD removal, it had greater efficacy in more complex wastewater, such as Washing Center and Garage Water. The included assessments demonstrate that combinations of iron slag, adhesive cement, and activated carbon can increase the water purification ability of pervious concrete.

The discussion highlights Mix 1 as optimal for structural applications owing to its higher compressive strength, whereas Mix 4 is better suited for water treatment or low-load areas owing to its superior hardness and pH reduction capabilities. Future research directions include the absence of long-term durability tests, such as freeze–thaw resistance, clogging potential, and abrasion resistance.

## CONCLUSIONS

This study focuses on the performance testing of pervious concrete using sustainable industrial by-products, such as iron slag, rice husk activated carbon, and adhesive cement. A standard base mix (Mix 1) was established for all samples, consisting of 331 kg of cement (+5%), 149 kg of water (-5%), and 1400 kg of coarse aggregate. Subsequently, in Mixes 2, 3, and 4, materials were incorporated in increasing volumes to identify their effects on the physical, hydraulic,

and environmental properties. Specifically, Mix 2 contained 280 kg of iron slag, 40 kg of rice husk activated carbon, and 3.31 kg of adhesive cement. For Mix 3, the amount of iron slag was increased to 300 kg, and for Mix 4, it was increased to 320 kg, while keeping the other input materials the same in each mix. This demonstrates the value of adjusting specific performance measures to determine the correct threshold that yields the maximum performance characteristics of the pervious concrete.

The porosity analysis indicates that Mix 1, which did not include additives, exhibited the highest porosity (22.16%), while Mix 2 had less porosity (20.52%). Given that Mix 2 included slag and slower cement curing, this may explain the denser structures of the particles, leading to less porosity as well, because the denser structures indicate more cement/slag adhesion, therefore better packing of the particles with lower voids. Mixes 3 and 4 followed the loss of porosity with values of 19.53% and 19.32%, respectively. Although Mix 1 achieved the highest water percentage, it maintained its highest permeability; all mixes allowed water to penetrate their structures, but Mixes 2, 3, and 4 achieved better permeability while maintaining the structure. pH analysis showed that Mix 2 effectively neutralized alkalinity in washing and runoff water, indicating strong pH stabilization through slag hydration and the alkali-binding nature of adhesive cement. Mixes 3 and 4 were more effective in turbidity and hardness reduction due to the adsorption capacity of activated carbon. Additionally, Mix 3 delivered the most consistent performance in balancing pH control and pollutant removal, without over-acidifying water samples.

The gradual improvement of the concrete mixes resulted in a broad understanding of the function of each additive. The results suggest that Mix 2 contained the best combination of mechanical strength, permeability, and environmental treatment performance. Accordingly, the use of adhesive cement, iron slag, and rice husk-activated carbon in pervious concrete can contribute to sustainable construction efforts and provide a potential solution for urban stormwater management systems.

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