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Original Research

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 to addressing environmental challenges. This study investigates the effects of incorporating rice husk-derived activated carbon, iron slag, and a 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.

Experimental findings showed that the Mix 1 (iron slag + 5% adhesive cement) achieved the highest 28-day compressive strength of 22.13 N/mm², representing an increase of 4.2% over the control mix (CM) at 21.24 N/mm². The 14-day and 7-day strengths of Mix 1 were 19.2 N/mm² and 14.52 N/mm², also higher than the control (17.24 N/mm² and 11.9 N/mm²) respectively, 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 pH from 8.65 to 7.34, bringing it within 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), though 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), 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 as a means 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 like rice husk activated carbon, iron slag, and adhesive cement to enhance the environmental and mechanical performance of pervious concrete (Hossain, 2019; Siddique, 2004). Rice husk, a by-product rich in silica, can be transformed into activated carbon with high adsorption capacity, offering benefits for filtering stormwater pollutants (Chandrasekhar et al., 2003; Kumar, 2018). Iron slag, a by-product of the steel industry, contributes to strength enhancement, while adhesive cement can improve paste-to-aggregate bonding. 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 of simultaneously achieving high permeability and sufficient structural strength.

Climate change alters weather patterns, leading to extreme weather conditions, unreliable water availability, growing water scarcity, and contamination of water resources (Urama, 2010). To facilitate stormwater management, groundwater recharge, and surface runoff reduction, pervious concrete also referred to as porous concrete 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, 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 (Heede, 2012; Butler, 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, 2021). Making good use of industrial trash can boost energy and resource efficiency and lessen potential environmental harm. (Dincer et al., 1999). The inability to achieve sufficient compressive strength while preserving porosity, however, usually limits the use of pervious concrete. It can also be utilized to save water by replacing pricey retention ponds. (Sarker etal., 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, 2008). Using industrial and agro-industrial waste materials in pervious concrete mixtures is one way to address this issue. These components, which include 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.

The purpose of this study is to examine the impacts of creating sustainable pervious concrete using waste resources such rice husk activated carbon, adhesive cement, and iron slag. With a focus on their water quality optimization qualities, the study comprises tests to ascertain the concrete mixes' compressive strength, porosity, specific gravity, fineness, and standard consistency.

Even though the need for water is continuously increasing, only 3% of the world's water is fresh, or unsalted, according to study (Martinez, 2020). Rapid industry and substantial urbanization are causing waste effluents to be released directly into river water runoff, damaging the ecosystem (Sarker etal., 2021).

Like regular concretes and mortars, pervious concrete depends heavily on cement. However, the manufacture of cement contributes significantly to environmental pollution, using roughly 2–3% of the world's total energy and contributing 8–9% of worldwide CO_2 emissions (Monteiro, 2017). Many environmental problems, including waterlogging, water pollution, and the urban heat island effect, are caused in great part by impermeable pavements that impede the normal flow of moisture and heat between the ground and the atmosphere (Kia et al., 2021). A previous concrete composition is made up of water, cement, and coarse aggregates with little to no sand or other additives. It has a high, interconnected porosity of generally 15 to 30 percent, with pores that are 2 mm to 8 mm in diameter (Debnmath, 2020). Therefore, prior to the application of pervious concrete, it is important to identify the best combination of course and fine aggregate to ultimately provide a successful interrelationship 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. If the W/C ratio increases, the amount of water in the cement paste will be excess, resulting in excessive flowing paste that could fill pore spaces and reduce the connectivity of the voids. On the contrary, If the W/C ratio is too low, then the mix may not have enough of a consistency or cohesion to produce a reasonable workability and placement (Debnmath, 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, 2018). Pervious concrete (PC) primarily consists of well-graded coarse aggregates combined with cementing materials. It offers benefits such as reduced density, lower thermal conductivity, and minimal drying shrinkage (Chandrappa, 2016). This material also offers environmental benefits such as minimizing the infiltration of pollutants into groundwater and lowering the noise produced by the interaction between tires and pavement (Haselbach,2011).

Pervious concrete (PC) provides various economic benefits, such as lower installation costs by removing the need for costly storm drains, reduced lifecycle expenses due to fewer repairs, and the ability to be recycled at the end of its lifespan. It uses less raw material 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/m² (32 THB/m²) (Priyadarshana, 2013). The use of 30% and 100% RA reduced the environmental impact by up to 8% and 23%, respectively (Mah, 2018). Using 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% when waste concrete was utilized to create RA concrete. (Wijayasundara, 2018).

Research indicates that Australia produces around 43.78 million tons of waste each year, with 38% coming from construction and demolition (C&D) activities. In China, municipal solid waste makes up nearly 30% of the global total, with C&D waste contributing about 40%. Construction activities generate approximately 100 million tons of waste annually, while the demolition of older buildings adds another 200 million tons each year (Yang, 2017).

Although pervious pavement may look like regular pavement, in fact, the major difference is voids. The voids create porosity, The voids that make up pervious pavement generate a design source which materially differentiates it from regular pavements and gives it unique physical characteristics. As mentioned, pervious concrete has its advantages, but there are also some limitations and disadvantages that affect its ability for larger use. Its typically lower strength and structural capacity limit its applications to mainly parking lots, low-traffic roads, and sidewalks. For example, for higher traffic roads and busy expressways, pervious concrete, even if the site conditions are right for its use, may not meet certain structural requirements. Another major limitation is that pervious pavement will also over time become clogged, and this can hinder hydraulic conductivity and the infiltration rate. Nevertheless, ongoing research aims to tackle these challenges and improve its structural performance. Various studies have examined different aspects of pervious concrete, including its types, structural methods, materials, pore characteristics, hydraulic conductivity, and environmental benefits like 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 is to evaluate the compressive strength and permeability of pervious concrete, for which 150mm x 150mm x 150mm cube specimens were cast and cured for a duration of 28 days.

This study considers enhancing pervious concrete through four different mix designs and how different agro-industrial spent materials change its properties. The control mix (Mix 1) is typical pervious concrete, with 331 kg cement, 149 kg water and 1400 kg coarse aggregate without any additional materials. Mix 2 incorporates 280 kg iron slag in partial replacement of coarse aggregate and includes 3.31 kg adhesive cement to improve bonding and provide structural performance. Mix 3, uses very similar materials from Mix 2 but adds 40 kg of activated carbon that is activated with rice husk, and has reduced adhesive cement with only 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 adhesive cement is lowered down to 2.60kg as the fine supplementary materials are the higher proportion of materials. The mixes were carefully designed, tested, to assess their functionalities i.e. strength, permeability, and environmental benefits to create more sustainable and green pervious concrete for use in modern construction application. By leveraging waste materials that are locally abundant and cost-effective, this research contributes to sustainable construction practices and supports circular economy principles.

2. 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 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, 2021). An extra iron platform of 120 cm in height is built into the entire structure to act as an overhead tank for controlling the sample discharge (Gros, 2021). We analyzed rice husk activated carbon during our mini project and selected this material to enhance water quality based on the results of our characterization (Sharath, 2017).

The experimental columns included four types of pervious concrete samples: the Control Mix and the Pervious Concrete with addition of Iran slag (Hesami, 2014), the Pervious Concrete with addition of iron slag, adhesive cement (Vazquez-Rivera, 2015) and the Pervious Concrete with addition of iron slag with Adhesive cement and Rice Husk Ash. the mix is 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 a roof clay lining (Manning, 2004), can be served as the basis for porous concrete and for adsorbing practices in real-world scenarios (Boscov, 2020).

Several studies have explored the role of cementitious materials and their optimal inclusion rates (Raghav,2021). 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 affecting the overall strength properties adversely.

2.1. Materials Used

Ordinary Portland Cement served as the primary binder in all pervious concrete mixes. To improve bonding and internal cohesion, a small amount of adhesive cement was added in modified mixes (Mix 2 to Mix 4). The adhesive cement used in this study is formulated using Portland cement, quartz sand, cellulose ether, re-dispersible gelatin-based powder, and alcohol-derived chemical compounds. Rice husk activated carbon, which is a by-product of the thermal degradation of rice husks generated in the rice milling process could be added to Mixes 3 and 4 to improve sustainability and improve the pore structure of the concrete. Iron slag, which is an industry by-product generated in metal processing, was added to Mixes 2, 3, and 4 as a partial replacement of course aggregate to improve durability and reduce the consumption of natural resources.

2.1.1. RICE HUSK

Rice husk refers to the tough, protective outer covering that encases the grain of rice. When tested, rice husk ash has been found to be 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,2019).

Preparation of Activated carbon from Rice husk

To get rid of any surface contaminants, rice husks are continuously cleaned with distilled water before being dried for three hours at 110 °C in the oven (Raphael, 2021). Following that, 25 g of dry rice husk is carbonized in the furnace for 90, 120, and 150 minutes at 400, 450, 500, 550, and 600 °C (Ismagilov,2009). After that, for a whole day, it is impregnated with 5% (v/v) hydrochloric acid at a carbon to acid ratio of 1:10 (p/v). It is then sieved to 100 meshes after being filtered and oven dried for three hours at 110°C (Hanum, 2017). The yield of activated carbon obtained through this process ranged from 23% to 26%, depending on temperature and duration. The Brunauer–Emmett–Teller (BET) surface area was measured between 520 and 650 m^2/g, indicating a high degree of porosity suitable for pollutant adsorption in water treatment applications.

Fig. 1a: Rice Husk. **Fig. 1b:** Rice husk activated carbon.

2.1.2. TILE ADHESIVE CEMENT

In this study, tile adhesive cement was incorporated into the pervious concrete mix to enhance its bonding capability and overall durability. This type of cement, which consists of Portland cement, quartz sand, cellulose ether, and re-dispersible polymers, enhances 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 allows for improved compressive strength without the loss of permeability. This new process is intended to provide a balance between structural performance against a desirable environmental solution, indicating potential use in sustainable construction innovations for elements such as pavements and storm-water management.

Fig. 2: Tile Adhesive Cement

2.1.3. IRON SLAG

Iron slag in pervious concrete may be used as a substitute for traditional aggregates for sustainable construction. The inclusion of iron slag improves the mechanical strength and durability of the concrete while alleviating waste disposal concerns for the reuse of industrial by-products. Pervious concrete, as a material, is a composite material made up of, primarily, coarse aggregate and cement (G. 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 greatly 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 mm/s), which are crucial for efficient stormwater management (Teymouri, 2023).

Fig. 3: Iron Slag

2.2. Mix Proportions

The goal of the research was to enhance the sustainability of pervious concrete through the inclusion of multiple agro-industrial waste products, while maintaining the structural integrity of the pervious concrete itself. Four concrete mixes (Mix 1 to Mix 4) were prepared at a fixed water-to-cement ratio of 0.5 to eliminate potential effects which may be associated with the variation in hydration and workability. The research sought to replace conventional materials with more sustainable alternatives and monitor their effect on the properties of the 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 will represent conventional pervious concrete for our review, and we can consider it the end of the first mix. In Mix 2, iron slag was used to partly substitute coarse aggregate and was a total of 280 kg. In addition, as adequate bonding among the components and prolonging performance were important, an extra 3.31 kg of the adhesive cement was added to ensure bonding and maintain structural performance, since iron slag and fine materials may influence internal cohesion and stability. Mix 3 contained 40 kg of rice husk activated carbon and with increased iron slag up to 300 kg, with the 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, so it added 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.

Table 1. Mix design of each sample for 1m^3

Mixture	Cement (kg)	Water (kg)	Coarse aggregate(kg)	Rice husk activated carbon. (kg)	Iron slag (kg)	Adhesive Cement (kg)	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

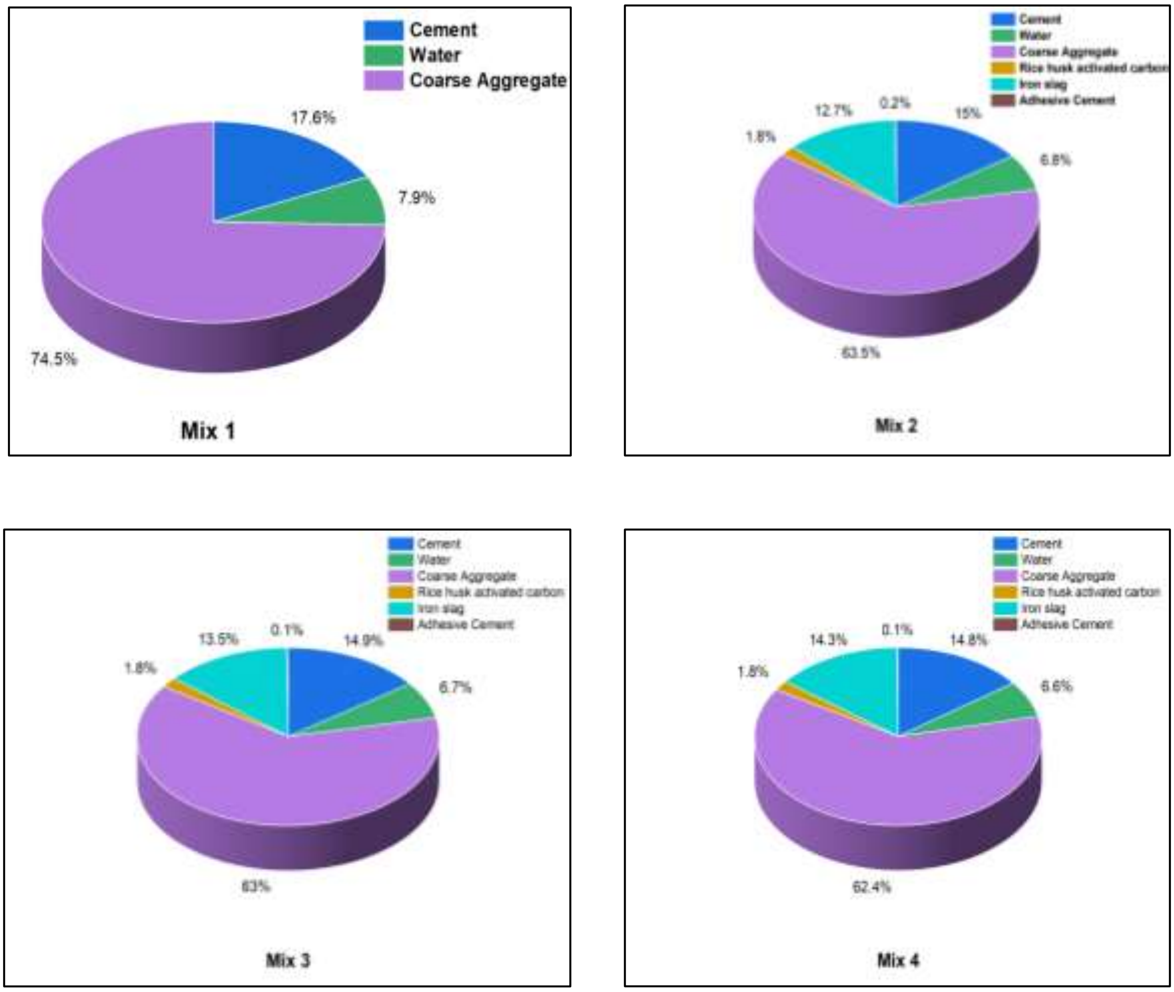

Fig. 4: Percentage of constituents in mix1, mix2, mix3 and mix4

3. RESULTS AND DISCUSSION

3.1. Compression Test

Performed compression tests on all 4 types of concrete cubes. We have done a 7-day, 14-day and 28-day compressive strength test. 3 cubes of each type were tested and an average of three was noted. he results are as follows:

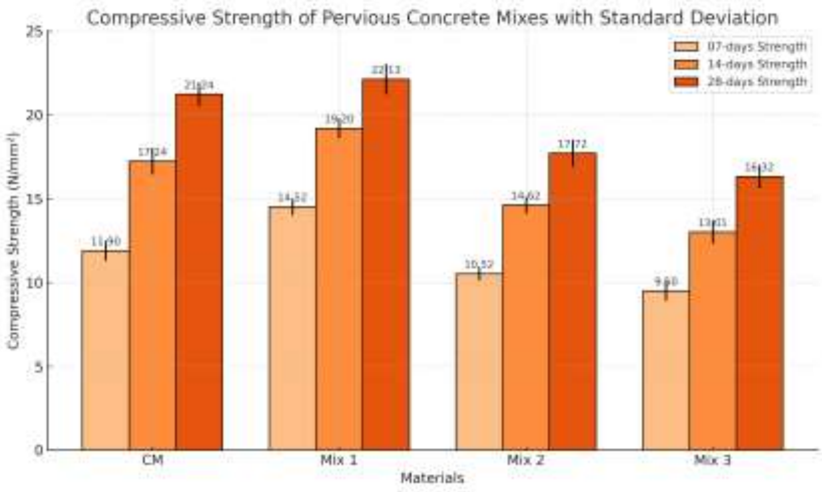

Fig. 6: Compressive strength of pervious concrete mixes at 7, 14, and 28 days with standard deviation. Strength values are shown on each bar. Mix 1 shows the highest 28-day strength (22.13 N/mm²), while Mix 3 has the lowest. Error bars reflect the standard deviation, indicating the variability across test specimens.

The increase in compressive strength across all concrete mixes can largely be attributed to the specific selection of materials and their interactions. The control mix (CM) has an observable increase in compressive strength and reached 21.24 N/mm² after a curing of 28 days. 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 early days.

In comparison, Mix 1, which had rice husk activated carbon and iron slag as supplementary materials, exhibited a greater compressive strength of 22.13 N/mm² 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 enhancing the matrix. Iron slag is an industrial waste material that adds pozzolonic compounds to the concrete matrix which can lead to increased density of the matrix and develop strength over time.

Taken together, it should be noted Mix 2 and 3, which had increased levels of supplementary materials, had reduced strength in comparison. This reduction in strength was likely a result of too great of 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 was not changed and remained at 0.5, therefore differences in strength could be attributed to the variation in mixtures.

3.2. Porosity Test

Porosity tests were run to evaluate the void ratio of a sample of permeable concrete mixes, including a control mix (CM) of 22.16 % for comparative purposes. The void ratio directly affects 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 make up of binder and possible increase in free alkali which resulted in a minor increase in the number of micro voids, therefore 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 improved 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 more dense structure.

Not only did Mix 2 improve mechanical properties and permeability properties, it demonstrated interesting pH stabilizing behavior. The adhesive cement inhibited free alkali ions, while iron slag controlled hydroxide ions during hydration to limit the pore solution alkalinity of the fresh coarse aggregate permeable concrete. Therefore, Mix 2 provides improved structure, permeability, and environmental performance.

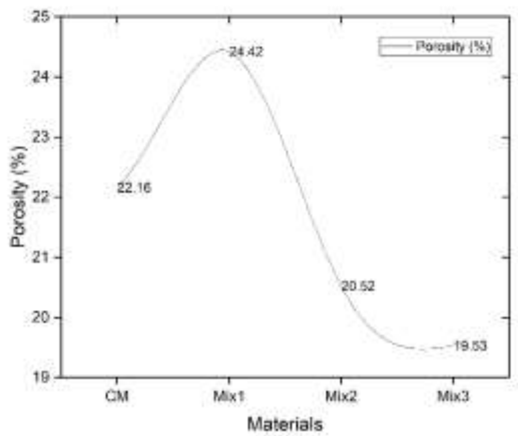

Fig. 7: Porosity test graph

3.3. 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 connection between mix design, porosity, and permeability, providing valuable insights. Research shows that greater porosity is linked to higher permeability. For example, concrete with 28% porosity demonstrated better permeability compared to lower porosity levels. Table 5 presents the value of t in seconds and the coefficient of permeability k in mm/second.

Table 2. Permeability Test

Depth (cm)	Mix 1 (k mm/sec)	Mix 2 (k mm/sec)	Mix 3 (k mm/sec)	Mix 4 (k mm/sec)
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	5.37	5.12	5.19

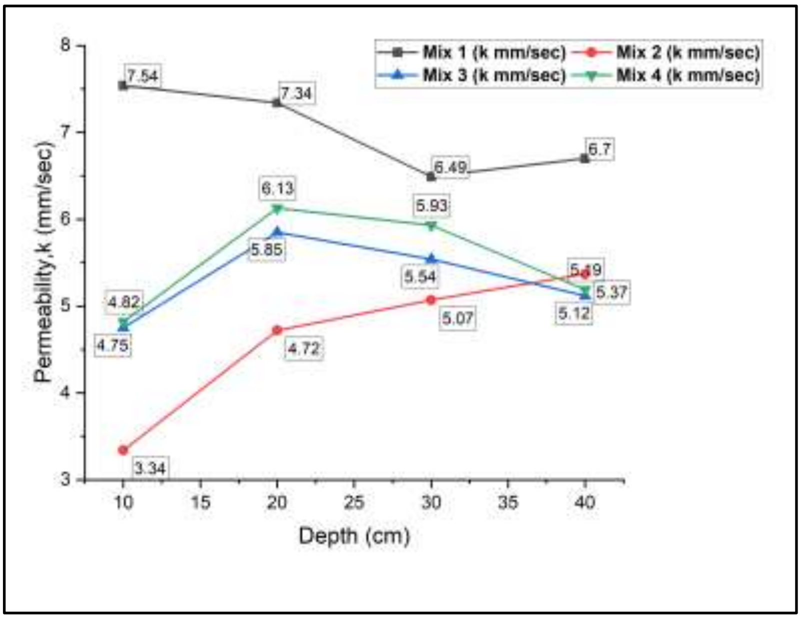

Fig. 8: Average permeability graph at depths of 10 cm, 20 cm, 30 cm, and 40 cm

The table shows the permeability data (sorted from highest to lowest) for four pervious concrete mixes at depths of 10 cm, 20 cm, 30 cm and 40 cm. The permeability values (in mm/sec) indicated a variation between 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 for Mix 2 had a very slight to moderate increase in permeability with depth back indicating improved pore connectivity at greater depths. The permeability values for Mixes 3 and 4 appeared to trend without consistency and were difficult to interpret, perhaps due to differences in compaction or differences in 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, provide examples of preferential flow paths that can improve desirable drainage performance in pervious concrete applications.

Mix 1 exhibited the highest porosity (24.42%), this also led to enhanced surface and subsurface water infiltration, ideal 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.

3.4. pH Test

The pH of untreated water samples ranged from 7.49 to 8.47, with Garage Water having the highest pH at 8.47 and Run-Off Water the lowest at 7.49. Although these values were close to the ideal range of 6.5 to 8.5 set by 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, while adhesive cement helped stabilize the pH values. Mix 3, incorporating rice husk activated carbon, showed a more gradual decrease in pH, lowering Washing Centre 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 Washing Centre 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, while Mix 4 was more aggressive in pH adjustment but requires careful application to avoid excessive acidity.

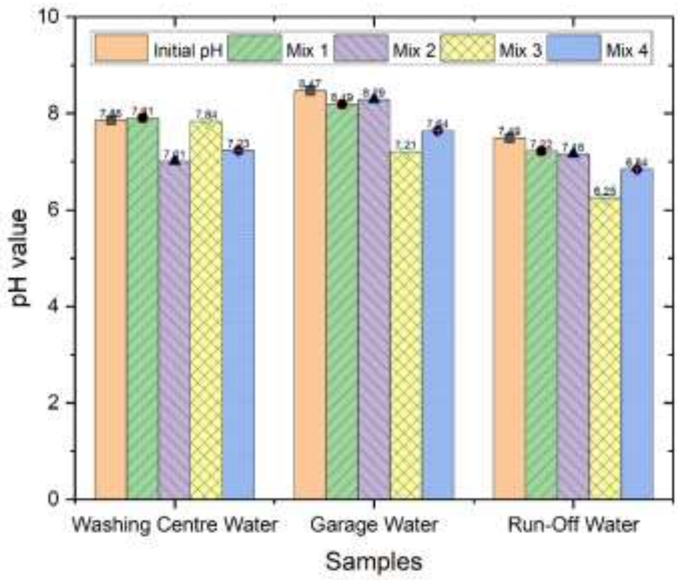

Fig. 9: pH values of Washing Centre, Garage, and Run-Off water before and after filtration through different pervious concrete mixes. Mix 2 and Mix 4 showed the most significant pH reduction, indicating effective water treatment potential.

3.5. Hardness Test

Differences in the concrete mix ingredients resulted in differences in how effective they were in reducing water hardness among many water samples. Mix 1 without any additives to reduce hardness showed slight reductions in hardness levels in the Water samples. Washing Centre Water hardness went from 679 mg/l to 616 mg/l; Garage Water went from 582 mg/l to 524 mg/l; and Run-Off Water went from 396 mg/l to 317 mg/l. Mix 2, which had the iron slag mix adhesive cement, had the most apparent reductions in hardness level, specifically in Washing Centre Water sample (679 mg/l down to 427 mg/l) and Run-Off Water (396 mg/l down to 259 mg/l). 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 since 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 leaching of calcium or magnesium ions from the cement matrix or residual impurities in iron slag.

|Mix 3 contributed a reduction in hardness but not quite as markedly as Mix 2. Garage Water sample went from 582 mg/l down to 512 mg/l, and Run-Off Water sample went from 396 mg/l down to 274 mg/l - which is consistent with the ion adsorption properties of activated carbons. However, mix 4 showed an increase in hardness for the Garage Water (582 mg/l increased to 547 mg/l) but may have also contributed to leaching of minerals or ion exchange occurring which caused the increase. However, it was recognized that it had considerable hardness reductions in the Washing.

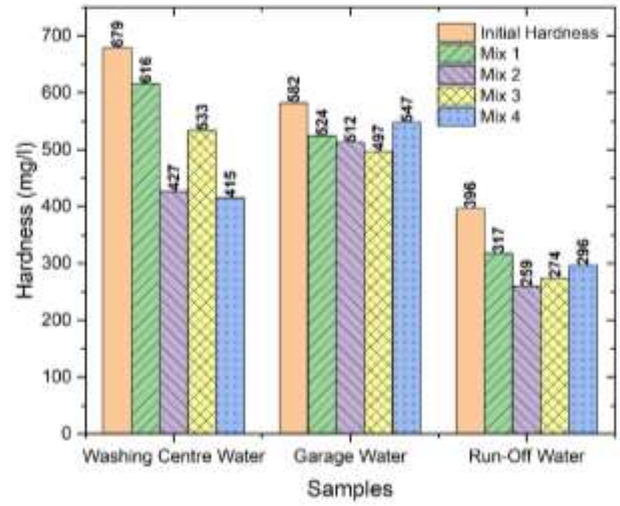

Fig. 10: Reduction in water hardness (mg/l) for Washing Centre, Garage, and Run-Off water after treatment with different pervious concrete mixes. Mix 4 showed the greatest hardness reduction across all samples, followed closely by Mix 2, highlighting their effectiveness for water softening applications.

3.4. Turbidity Test

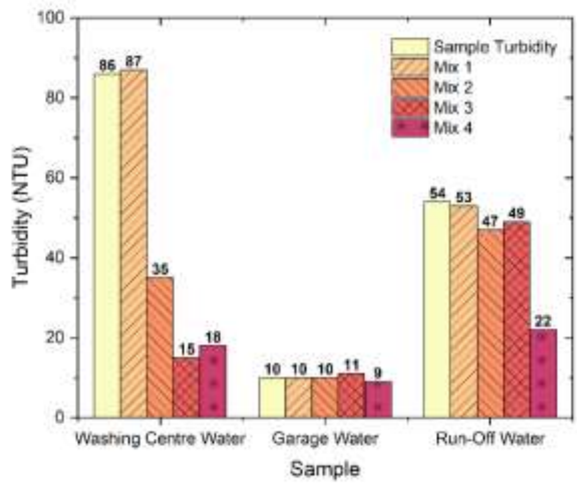

Fig. 11: Turbidity test results for different wastewater samples using pervious concrete mixes. Mix 4 showed the best turbidity reduction across all samples, while Mix 1 was the least effective. Maximum reduction was observed for Washing Centre Water.

The turbidity results for the different mixes show varying degrees of effectiveness in reducing suspended particles across the sample waters. Mix 1 (control) exhibited minimal change in turbidity across all sample types, with Washing Centre 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 Washing Centre Water turbidity to 18 NTU, demonstrating solid performance, though 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, while Mix 2 showed moderate success, particularly in Washing Centre Water.

3.5. DO Test

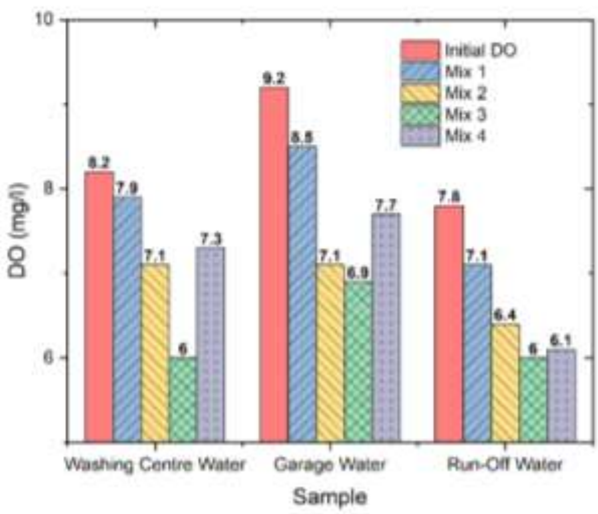

Fig. 12: Dissolved Oxygen (DO) levels in different wastewater samples before and after treatment. Initial DO levels were highest in Garage Water (9.2 mg/L). After treatment, all mixes showed reduced DO levels, with Mix 4 consistently retaining higher DO, indicating better oxygen preservation.

The Dissolved Oxygen (DO) levels in water decreased across all mixes, with the most noticeable drop observed in Mix 2 and Mix 4. Mix 2, which included iron slag and adhesive cement, caused the DO in Washing Centre Water to drop from 8.2 mg/l to 7.1 mg/l and Run-Off Water to decrease to 6.4 mg/l. 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 mg/l, 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 Run-Off Water, where it dropped to 6.1 mg/l. This combination intensified oxygen consumption due to both the hydration of iron slag and the adsorption capacity of activated carbon. On the other hand, 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 Mix 2 and Mix 4 showing the most significant oxygen depletion, which should be considered when selecting mixes for water management applications.

3.6. BOD Test

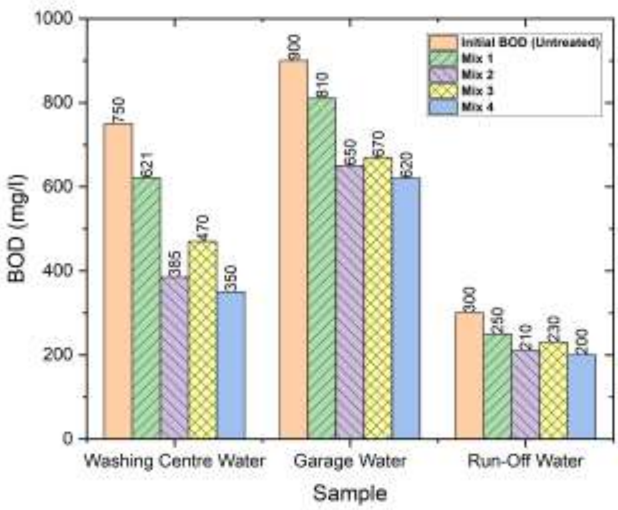

Fig. 13: Biochemical Oxygen Demand (BOD) in wastewater samples before and after treatment. All pervious concrete mixes reduced BOD levels significantly. Mix 4 achieved the greatest BOD reduction in all samples, especially in Garage and Washing Centre Water, reflecting better organic load removal.

Biochemical Oxygen Demand (BOD) indicates the degree to which microorganisms utilize dissolved oxygen to oxidize organic materials while living in water. Decreased BOD indicates that organic pollutants have been treated and/or removed. We started with untreated Washing Centre Water with initial BOD of 750 mg/l. BOD decreased all mixes, with Mix 1 reducing BOD to 620 mg/l, but only showed a small improvement. Mix 2 showed the greatest improvement with BOD 390 mg/l, 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 value of BOD of 470 mg/l, demonstrating the capacity of activated carbon to adsorb organic matter. Mix 4, which included both iron slag and activated carbon, had the lowest BOD of any mix at 350 mg/l, indicating an additive effect of the two intermediate materials to reduce organic content from the effluent. As for the Garage Water, which was at an initial BOD of 900 mg/l, mix 1 was effective only for 100 mg/l (~ 11%) reduction in BOD to 800 mg/l, while Mix 2 gave an additional and faster reduction in BOD to 650 mg/l. While Mixes 3 and 4 followed and had a final BOD of 670 mg/l and 610 mg/l, respectively, reinforcing the nature and effectiveness of the reactive and adsorptive materials used for removing biodegradable organic matter from drainage.

Run-off Water started at a BOD of 300 mg/l, which Mix 1 reduced to 260 mg/l, mix 2 further reduced to 210 mg/l, and Mixes 3 and 4 finished at 230 mg/l and 200 mg/l. Overall, mix 2 consistently had the highest VI BOD reductions across all water types studied, thus Mix 2 had the highest capacity for decreasing organic load. While mix 4 also achieved strong BOD removals, with greater efficacy in more complex wastewater like Washing Centre and Garage Water. The included assessments thus 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 due to its higher compressive strength, while Mix 4 is better suited for water treatment or low-load areas due to its superior hardness and pH reduction capabilities. Future research direction including the absence of long-term durability tests such as freeze-thaw resistance, clogging potential, and abrasion resistance.

4. Conclusion

This research 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. Then, with mixes 2, 3 and 4, materials were incorporated in increasing volumes to identify their effects on physical, hydraulic, and environmental properties. Specifically mix 2 had 280 kg of iron slag, 40 kg of rice husk activated carbon and 3.31 kg of adhesive cement. For mix 3, the iron slag was increased to 300 kg, and for mix 4, it was increased to 320 kg while keeping other input materials the same in each mix. This shows the value of adjusting specific performance measure to find the correct threshold that will yield maximum performance characteristics of the pervious concrete.

The porosity analysis indicates that Mix 1, which did not include additives, exhibited the highest, porosity at 22.16%, while Mix 2 had less porosity, at 20.52%. Given that Mix 2 included slag and Mix 2 included slag and slower curing of cement, this may explain the denser structures of particles, leading to less porosity also 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 being 19.53% and 19.32% respectively. Even though Mix 1 achieved the highest water percentages, it maintained its highest permeability, all mixes allowed water to penetrate their structures but Mixes 2,3, and 4 achieved better permeability while still maintaining structure. pH analysis showed that Mix 2 effectively neutralized alkalinity in washing and run-off water, indicating strong pH stabilization through slag hydration and adhesive cement's alkali-binding nature. 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 contains 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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