

PERFORMANCE EVALUATION AND MIX OPTIMIZATION OF NA AND RECYCLED COARSE AGGREGATE BASED PERVIOUS CONCRETE

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ABSTRACT

In cold climates and on pavements and overlays that see high traffic volumes, pervious concrete is becoming more and more popular. Pervious/permeable concrete is used for flatwork concrete applications that allow water to seep through, reducing site runoff and promoting groundwater recharge and also improving water quality by capturing pollutants. These types of concretes allow water to permeate through the interconnected voids between the non-uniform sized aggregates which in turn regulate the mix design along with concrete's compressive strength. Compared to conventional concrete, pervious concrete necessitates more stringent quality control during mix proportioning. Therefore, this study attempted to evaluate the permeability and mechanical properties of different trial Portland cement based pervious concrete mixes prepared using natural aggregate (NA) and recycled coarse aggregates with size varying in the range of 19.5mm to 9.5mm. The concrete mixes were prepared with a coarse aggregate-to-cement ratio of 4.5:1 where the cement contents were kept 300kg/m³ and mixed with 78.5kg/m³ fine aggregate (sylhet sand). The findings showed how the types and amounts of coarse aggregates affect the defining characteristics of permeable concrete. Furthermore, the effect of high range water reducing admixture (with quantity varying in the range of 0.6%~0.8% of binder in addition to a w/c ratio of 0.3) were assessed in improving flow and mechanical properties of the aforementioned mix variations. The permeability, slump test, density, porosity and compressive strength test were performed to characterize all the trial mixes. The resulting pervious concrete exhibits strong mechanical resistance and enough permeability to drain rainwater in conventional pervious concrete applications, such as parking lots, sidewalks, and low-traffic roads and, temperature behavior and pollution retention sinks. Based on the performances of these trial mixes, an optimum mix proportion is recommended by balancing permeability and compressive strength requirements. The findings can be considered as a beneficial and significant addition to the extensive research opportunities in the sector of pervious concrete development owing to its numerous benefits and its potential as a sustainable and promising roadway material of future pavement industry.

Keywords: *Pervious concrete; recycled aggregate; permeability; density; void content*

1. INTRODUCTION

Pervious concrete denoted to as a porous or permeable concrete with a network of interconnected pores characterized by moderate or no fine aggregate. This typically produces 15–35% voids (Costa et al., 2018; Li et al., 2017; Nguyen et al., 2014; Yang & Jiang, 2003; Zhong et al., 2018). The interconnected pore structure allows efficient water drainage through the concrete matrix, making it an effective material for sustainable stormwater management. Much interest in pervious concrete evolved during recent decades after the Second World War because the world at large moved into action on the need to conserve all non-renewable natural resources such as minerals and energy (Zhong & Wille, 2016). The rapid growth of impervious pavements in urban areas exerts an increasingly high impact on various environmental issues, including stormwater runoff, flash flooding, groundwater depletion. By passing water to percolate into the subgrade, pervious concrete replenishes groundwater, reduces surface runoff, and cools surface temperatures. These benefits facilitate LID and environmentally sensitive urban infrastructure (Chandrappa & Biligiri, 2016; Yahia & Kabagire, 2014). Vegetation reduction and increased impervious pavements are the dominant contributing factors to the formation of urban heat islands due to the lack of evaporation cooling and the release of absorbed incident solar energy as sensible rather than latent heat (Chandrappa & Biligiri, 2016; Sriravindrarajah et al., 2012). The mechanical performance of pervious concrete is significantly influenced by the thickness of the cementitious paste and its pore characteristics, both of which are dependent on aggregate size (Sriravindrarajah et al., 2012). Recent research underlines the development of pervious concrete suitable for applications that will be subjected to heavy traffic and changing climatic conditions. This study investigates the mechanical behaviour of pervious concrete, including compressive strength, flexural strength, fracture toughness, and fatigue performance, under loading conditions relevant to pavement structures (Chen et al., 2013). The construction industry produces huge quantities of demolition and industrial waste every year. Most of these demolitions or industrial wastes are disposed of in landfills or, even worse, through illegal dumping, which causes environmental and social problems. Such wastes can be recycled in concrete production, reducing the problem at landfills and aiming for sustainable construction (Aliabdo et al., 2018). Some of the industrial by-products, like fly ash obtained from power plants, blast furnace slag resulting from iron production, and other recycled materials such as construction and demolition wastes (CDW) have been investigated as supplementary materials in the production of concrete (Bittencourt et al., 2021). Adequate utilization of these wastes will conserve natural resources, reduce environmental pollution, and offer economic advantages. ISCMs can be used as limited replacements for cement in pervious concrete mixtures a promising but not well-explored area. Most research shows limited and inconsistent results. The effects of ISCM on the mechanical properties, durability, permeability, and microstructure have been investigated in this study to identify the mix proportion for high performance and sustainability (Khankhaje et al., 2024; Z. Zhang et al., 2017; Zou et al., 2021). Traditionally, pervious concrete has been applied mainly to low-traffic areas such as parking lots, pedestrian walkways, and residential streets (Bogas et al., 2016; Saboo et al., 2020). In this research, pervious concrete is developed using a superplasticizer additive with natural aggregate, along with mixes where natural aggregates (NA) are replaced with recycled concrete aggregate (RCA) at substitution levels of 40%, 60%, and 100% (RCA40, RCA60, RCA100) (Brasileiro et al., 2024). After curing in water for 28 days, the pervious concrete specimens were tested for dry density, void content, compressive strength, permeability (Sherwani et al., 2021). The new ASTM Standard C1688 entitled “Standard Test Method for Density and Void Content of Freshly Mixed Pervious Concrete” has been established to determine the density and void content of fresh pervious concrete mixtures (Kevern et al., 2009). This research attempted to analyse the performances of developed RCA based pervious/permeable concrete by assessing their respective compressive strength, permeability and density. An optimum mix proportion is recommended by balancing permeability and compressive strength requirements. Mixes containing 60% RCA provides maximum permeability and compressive strength values of 14.7 mm/s and 6.4 MPa, respectively. On the contrary, usage of only 40% RCA of total coarse aggregate in the mix resulted in minimum value of permeability of 12.5 mm/s and compressive strength of 4.75 MPa. One of the prime objectives of this study was to evaluate the effect aggregate variation as well as RCA replacement level on key properties of porous concrete. By testing

concrete with RCA replacement of 40%, 60%, and 100%, we can observe patterns and understand how RCA influences compressive strength and permeability. Furthermore, using sand increased the overall compressive strength performance of the mix and as for permeability, mixing of sand resulted in a moderately reduced value. The main goal of this research was to optimize the trade-off between permeability and compressive strength by controlling or analysing aggregate variation. Additionally, the size, shape, and grading of the aggregates play crucial role because pervious concrete relies on interconnected voids to allow efficient water flow while maintaining adequate structural capacity. Based on the observed finding the pervious concrete matrix containing blend of 60% (of total coarse aggregate content) RCA with 40% (of total coarse aggregate content) of NA exhibited optimum performance in terms of both compressive strength and permeability and thus, can be recommended for future investigation and application. The findings of this study will play a base line for development and promoting future applicability of RCA based pervious concrete.

2. MATERIALS AND METHODOLOGY

In this part the properties of the material used and methodology followed has been outlined sequentially. The primary objective of this study was to mix optimization based on the performance of permeable concrete mixes prepared using variable proportion of Recycled Coarse Aggregate (RCA). Concrete that contains a web of pores letting water flow through easily is called no-fines or permeable or pervious concrete. The blends, tested for this particular research project, were assembled from locally sourced materials striking a balance among strength and permeability.

2.1 Materials, Mix Proportioning and Sample Preparation

All the permeable concrete mixes were prepared using Ordinary Portland Cement (OPC) and Sylhet sand with a mixture of RCA and NA. The coarse aggregate proportion was kept constant at a limiting value of 80% of total concrete volume. The coarse aggregate blends were prepared by varying RCA to NA aggregate ratio as 40:60, 60:40 and 100:0. All the coarse aggregate blends contains particles having size in the range of 19.5 mm to 9.5 mm. In order to secure a desired particle size, the recycled fraction underwent a cleaning, screening and sieving sequence. Figure 1, depicts the particle size distribution of coarse aggregate blends. To reinforce the connection between the paste and the aggregate 7% of the total aggregate was substituted with a modest dose of Sylhet sand (FM=1.66 with particle size distribution as shown in Figure 1) in some mixes. Performance of these mixes were later compared with mixes 0% sand content. Analyses confirmed that the sand contained no residues or soil. The aggregate-to-cement ratio was 4.5: 1 while the water-to-cement ratio was 0.30. However, additional High Range Water Reducing Admixture (HRWRA) was mixed at a dosage of 0.6 % of the cement's mass in an attempt to increase workability. This admixture lifts the mix's workability fostering flow and a homogeneous spread of cement grains while keeping the water proportion low. The mix proportion has been shown in Table 1.

The material was made into recycled aggregates by crushing the demolition waste. Later the crushed materials were sieved and finally brought into saturated surface dry condition (SSD) after submergence in water. Natural aggregates were cleaned and air-dried before use in the mixes. At first cement and fine aggregate blended together manually. Later two third of water was added and mixed for 2-3 minutes until homogeneity occur. After that coarse aggregate was added to the mix with the remaining one third water and superplasticizer. The whole mixing procedure was continued for another 4-5 minutes before the sample preparation. Cylindrical specimen of dimension 100 mm x 150 mm, 100 mm x 200 mm and 200 mm x 200 mm were prepared for permeability, compressive strength, density and porosity, respectively.

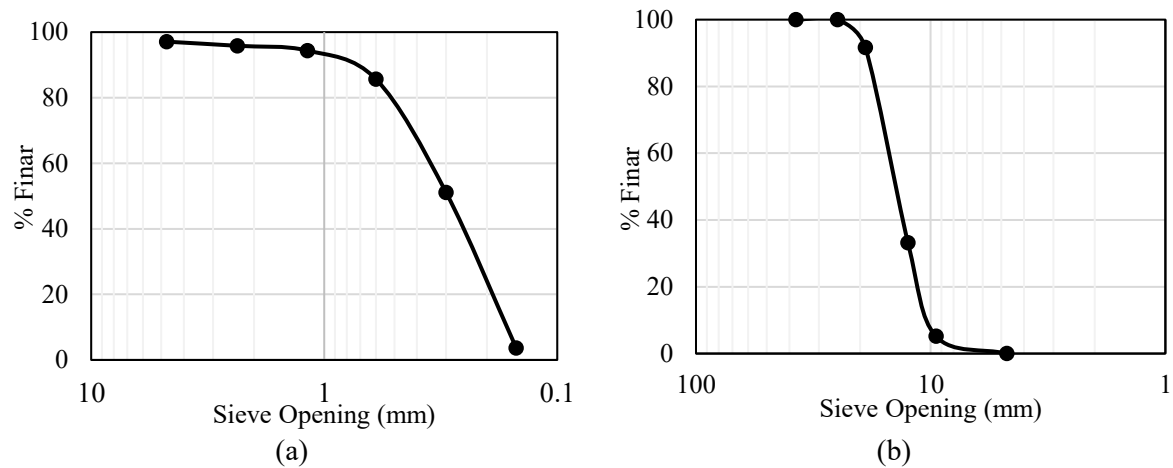


Figure 1: Particle-size distribution curves for-(a) fine aggregate and (b) coarse aggregate blend

Table 1: Mix Design

Parameter	Description / Value
Coarse Aggregate	80% by volume
Fine Aggregate	7% of total aggregate content
Cement	250–400 kg/m ³
Water/ Cement ratio	0.3
Admixture (High-Range Water Reducer)	0.6% of cement weight
Coarse aggregate to cement ratio (CA/C)	4.5:1

2.2 Curing and Testing Methodology

A total of 15 cylindrical varying dimensions (as mention earlier) where cast and cured. The test was conducted to ensure satisfactory hydration in strength development all the specimens were cured till 28 days prior to testing by covering the samples with gunny bags and periodic water spraying over them. The performance of the developed RCA based pervious concrete mixes was assessed in terms of compressive strength, permeability, porosity and density. The 28 days compressive strength test was performed on cylindrical specimen as per ASTM C39 (ASTM C39, 2023) (shown in figure 3(a)) whereas the density and porosity was measure following ASTM C1688/C1688M (shown in figure 3(c)) (ASTM C1688/C1688M, 2023). The permeability of each mix was determined following Falling Head Method (ACI 522R-10, 2010) as shown in figure 3(b).

The coefficient of permeability was determined by equation 1 (Maryl et al., 2013)

$$K = \frac{aL}{At} \ln\left(\frac{h_1}{h_2}\right) \quad (1)$$

Where K= coefficient of permeability (mm/s), a = cross-sectional area of standpipe (mm²), L = Length of the specimen (mm), A= cross-sectional area of specimen(mm²), t= time for water level to reach from h₁ to h₂ (sec), h₁= initial water level(mm) and h₂= final water level(mm)

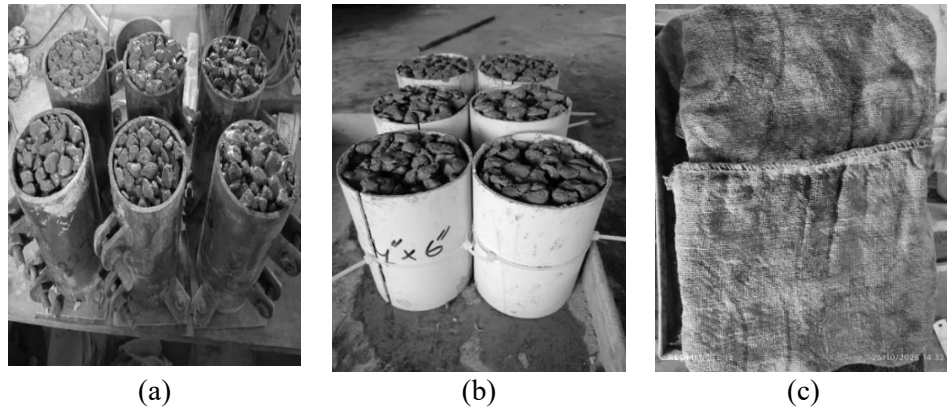


Figure 2: Casting of a) compressive strength, b) permeability and c) curing

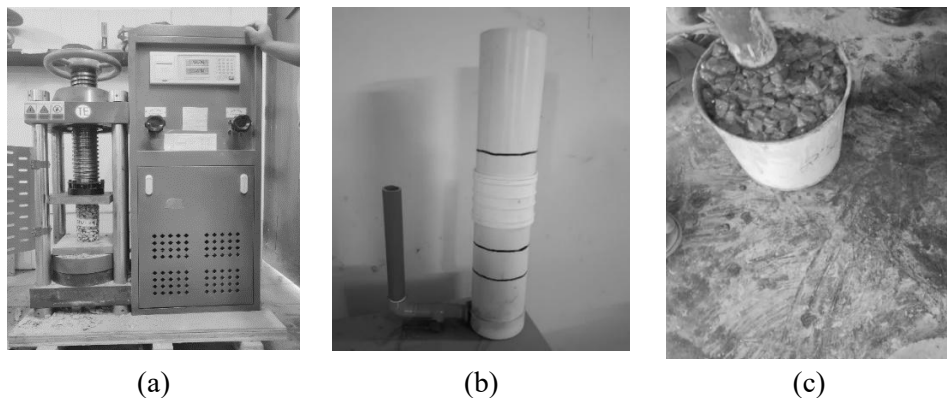


Figure 3: a) compressive testing machine, b) permeability test setup and c) apparatus of density and porosity

3. RESULT AND DISCUSSION

3.1 Variations in Compressive Strength

Figure 4, shows the outcome of different sand contents and aggregates combinations on compressive strength of the developed pervious concrete mixes. It evident from the figure that variations in RCA percentage and inclusion of certain proportion (7% of total coarse aggregate) sand have a substantial influence on overall strength development of the concrete.

When no sand was used, the compressive strength of all the mixes remained low comparatively. For instance, the compressive strength of RCA40NA60 reached around 3.2 MPa, while in case of RCA60NA40 and RCA100, the value was around 2.0 MPa, approximately. Large and interconnected voids which are typical of deformed concrete and the weak bond between RCA particles and cement paste are the main reasons behind this low strength. In contrast, the compressive strength of all the mixes increased significantly when 7% sand was added. The voids got partially filled in by the fine particles which improved the coating of paste and the bond between aggregates became stronger. Due to this, the strength of all the mixes increased by about 54%-55%, on average. The compressive strength of RCA60NA40 reached the highest value (around 6.4 MPa), while in case of RCA100 and RCA40NA60, the values were 5.4 and 4.8 MPa, respectively. Therefore, the best internal structure should be obtained by optimizing porosity and strength with appropriate RCA (around 60%) and inclusion of sand. The fine particles partially filled in the voids and therefore the interaction area between aggregate and cement paste increased. The added sand content compromises the mix's permeability very insignificantly while ensuring proper and adequate load transfer capacity. However, if too much sand is added, then the channels of pores get blocked and permeability also decreases. So,

to obtain optimum results, care should be taken that the addition does not exceed a certain amount of sand.

From the results obtained, it can be concluded that an appropriate amount of fine aggregate can pointedly improve the strength of pervious concrete, especially when it is used in combination with balanced RCA–NA mixture. Among all the mixes, RCA60NA40 with 7% sand performs the best for sustainable pavement applications by achieving required permeability and strength.

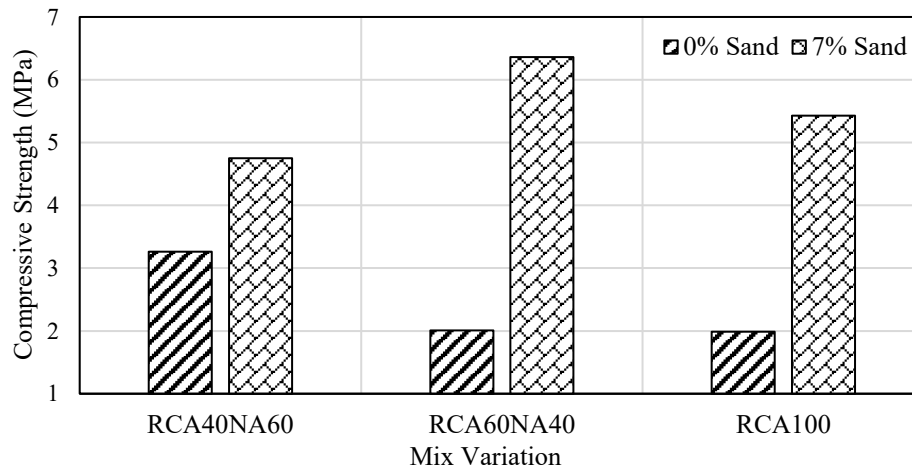


Figure 4: Variations in compressive strength values of the developed concrete mixes

3.2 Variations in Permeability

Figure 5 depicts the adverse effect of sand addition in inhibiting the permeability of liquids/water through the concrete matrix irrespective of the variations in coarse aggregate blend. In all tested mixes, the RCA40NA60 mix which had 0.40% RCA and 60% NA recorded the highest permeability, whereas the RCA100 mix had slightly lower (1.5%-2%) results. However, this does not mean that high usage of recycled aggregates (RCA) results in high permeation as the internal structure and pore interconnectivity of the concrete also play a part in the overall permeability. When the case of sand being added in the amount of 7% weight was tested all mixes showed decreased permeability, with the RCA40NA60 being the most affected one, i.e., the permeability decrement from 16 mm/s to 12 mm/s. This happened because the tiny sand particles are filling the gaps between the larger aggregates thus improving their packing, increasing the density of the concrete, and also limiting the water flow through the concrete.

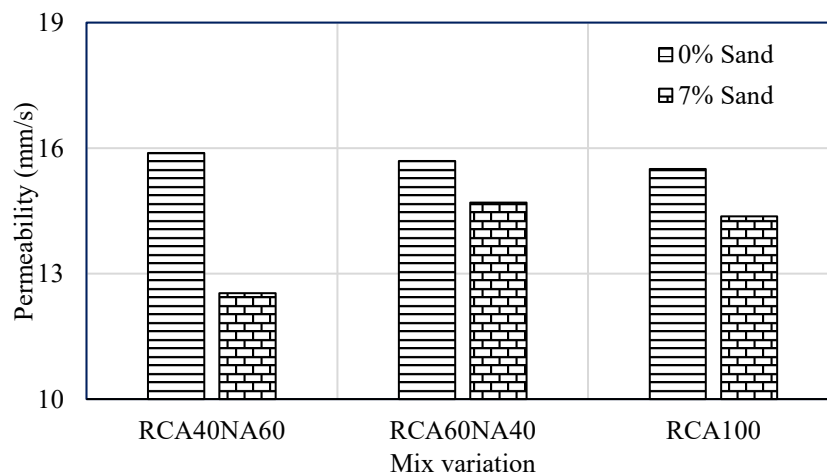


Figure 5: Variations in permeability values of the developed concrete mixes

The slightly less permeable RCA100 mix may have been attributable to the fact that obeyed mortar helped in sealing the pores and thus creating fewer flow paths. On the other hand, very high RCA content without corresponding fines or poor compaction may, to a large extent, open up the pores and thus, will affect the durability, unfavourably. It can be inferred that around 7% sand usage will not only improve the overall structure's compactness but also lower the permeability, even for the high RCA mixes. The following measures are suggested to attain better performance; RCA pre-treatment, supplementing cement with other types of materials, and optimizing the mix design.

3.3 Effect of RCA Content on Compressive Strength and Permeability

Figure 6, indicates the variations in permeability and compressive strength of pervious concrete with different RCA percentages. The graphical presentation of Figure 6 indicates that the mechanical and hydraulic characteristics of the mixes are significantly influenced by the RCA content. The previous concrete permeability was 12.5 mm/s and compressive strength was 4.88 MPa at 40% RCA replacement. When increased to 60% RCA of total aggregate mixes achieved the maximum permeability of 14.7 mm/s and highest compressive strength of 6.4 MPa. The tough texture and angularity of recycled aggregates enhance the mechanical interlocking and the bonding of adhered paste mixture. The well related pore shape can better facilitate the water movement within the matrix, which may cause the permeability improvement. Increase in RCA content to 100% of total coarse aggregate, however, caused a slight descent performance marked by 2% decrease in permeability and 17% reduction in compressive strength values. At the same time, the permeability slightly decreased to the most 14.4 mm/s and the compressive strength decreased to 5.4 MPa. The possible cause of performance descent might be due to the increased porosity associated with recycled aggregates and weaker adhered mortar than usual. Also, the aforementioned variation might be the consequences of the high water entrained into some areas and poorer bonding performance caused by the tendency of recycled aggregate to adsorb more water. All things considered, the result suggests that the best equilibrium between strength and permeability is obtained when the RCA content material is about 60%. The result shows that the using recycled coarse aggregate to partially replace the natural aggregate in pervious concrete can enhance the ability of drainage and can also maintain the structural integrity.

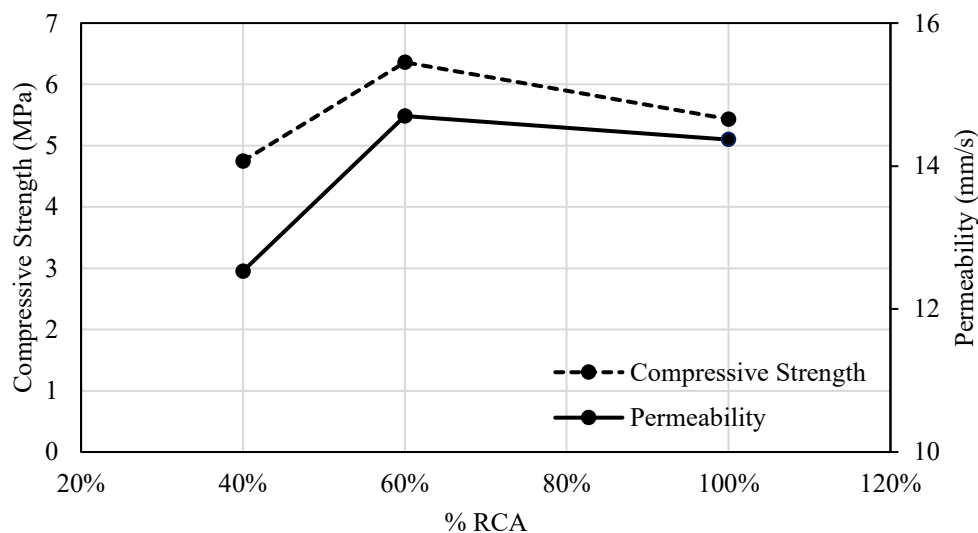


Figure 6: Effect of variations in RCA content on compressive strength and permeability of the developed pervious concrete mixes

3.4 Variations in Density, Porosity and Permeability

Table 2, demonstrates the effect of RCA content variation on the density, porosity, and permeability of the developed pervious concrete. The density of the concrete containing 60% NA and 40% RCA blend

has risen to 2.85% as compare to that of 40% NA and 60% RCA blend. When 100% RCA is mixed, however, density reduces quite considerably to 13.14%. The porosity increases (24%-31%) with the increasing proportion of the RCA content (60%-100%). The porosity of the mix containing 100% RCA increases 23.8% in comparison with mix containing 60% RCA and 40% NA and 21.3% when compared with that of 40% RCA and 60% NA concrete mix. The moderate level of porosity of 60% RCA and 40% NA can indicate a more balanced microstructure, which could be explained by a better gradation and interconnection of natural and recycled aggregates. Permeability is also higher in 40% RCA and 60% NA mixes (14.7 mm/s) which is 15% higher than that of mixes with 40% RCA and 60% NA, which can further be validated from the respective higher porosity (24.11%) forming interconnected voids. Interestingly, permeability reduces marginally to 14.4mm/s in 100% RCA although it has the greatest porosity. This may be as a result of collapsing or clogging pore channels by imposing high fines and weaker bonding at high contents of RCA. All in all, the findings suggest that pervious concrete can be provided with a good combination of density, porosity, and permeability by partial substitution of NA with RCA. Nevertheless, total replacement (100% RCA) causes major densification and extreme porosity with the risk of causing structural instability of the mix regardless of the sufficient permeability.

Table 2: Variations in density, porosity and permeability values of the developed concrete mixes

Mix Variation	Density (kg/m ³)	Porosity (%)	Permeability (mm/s)
NA60RCA40	1748.4	24.90	12.5
NA40RCA60	1800	24.11	14.7
RCA100	1563.58	31.65	14.4

4. CONCLUSIONS

This research attempted to develop and assess performances of permeable concrete mixes that contain varying proportions of RCA and stone as coarse aggregate. . The finest mix proportions, encasing RCA as coarse aggregate and 7% of river sand as fine aggregate, were derived following its optimal performance in resisting compressive force and promoting water permeability, as per ACI report on pervious concrete (ACI 522R-10, 2010). The testing findings that are reported in this paper have been concluded through the following points.

- At 40% RCA replacement, pervious concrete showed a permeability of 12.5 mm/s and compressive strength of 4.88 MPa. Increasing RCA to 60% improved performances, achieving maximum 14.7 mm/s permeability and compressive strength of 6.4 MPa. Further increase to 100% RCA caused a slight decline, with permeability reducing to 14.4 mm/s and compressive strength to 5.4 MPa.
- The use of maximum 60% of RCA as the coarse aggregate was found most suitable because pervious concrete mixes containing coarse aggregate blend of 60% RCA and 40% NA showed 6.4 MPa of 28-day compressive strength and 14.7 mm/s of permeability. These values fall within the code and literature prescribed limit of compressive strength and permeability for pervious concrete. Porous concrete is chosen to be low density to ensure a high content of voids which provides a network of flow through pores. Permeability is given priority since the primary purpose of a pervious concrete is stormwater infiltration. The mix, thus, is aimed at having sufficient strength with minimum density without losing pore connectivity. These mixes can be used in pavements of low traffic, walkways, roofs and stormwater management systems.
- Recycled aggregates' roughness and angular shape led to increased mechanical interlocking and linking with the cement paste. Recycled aggregate having attached mortar contributed to the development of secondary hydration and internal curing which resulted in a more compact and well-locked concrete.
- In the absence of sand (0%), the mixes exhibited low compressive strength yet the permeability was high since the interconnected voids were large. The fine aggregate that was used in small quantity (7% of total coarse aggregate) contributed to the decrease of voids in the matrix, the

raise in density and compressive strength while still keeping sufficient permeability necessary for drainage performance of permeable concrete.

- The right control of the mix design and compaction achieved the highest density that is best for strength, toughness, and porousness in pervious concrete since non/less porous concrete has higher density while more permeable concrete has lower density.

Pervious concrete is a sustainable practice that helps to conserve resources while at the same time diminish costs. The developed pervious concrete mixes should be adequate enough for use in parking lots or residential parking as both pavement and stainable drainage solution, especially, in densely urbanized areas. However, practical suitability of such applications must be tested and recommended prior to future use.

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DECLARATION OF USE OF AI

The authors declare that AI-based tools were only used to resolve grammatical mistakes in the manuscript. These tools were not involved in the research problem formulation, research design, data analysis, and presentation of findings or drawing of conclusions. The authors have complete responsibility of the work and its integrity.

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