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ORIGINAL ARTICLE

Optimizing fly ash and rice husk ash as cement replacements on the mechanical characteristics of pervious concrete

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Abstract: Replacing cement with fillers while being environment-friendly contributes to the performance enhancement of conventional concrete. In the investigation, nine batches of concrete mix were prepared with different amounts of cement, fly ash (FA) and rice husk ash (RHA). This experiment investigated the consequence of substituting cement with FA at various water-to-binder (*W/B*) proportions. The FA content was ranged from 5% to 20% of cement by weight, and the *W/B* ratio was adjusted to 0.3, 0.35, 0.4, and 0.45. Furthermore, for 10% cement replacement, FA and RHA combination of 10:0, 7.5:2.5, 5:5, 2.5:7.5 and 0:10 by weight were used. When FA alone was used as cement replacement, the optimal mix achieved a 28-day compressive strength of 31.33 MPa at a *W/B* ratio 0.40 with 10% FA. Moreover, incorporating FA and RHA resulted in a cost reduction of approximately 15% per cubic meter of concrete and a decrease in CO_2 emissions by 20% compared to conventional concrete production. The findings demonstrate that FA and RHA can be effectively combined to manufacture pervious concrete that enhances performance, reduces costs, and minimizes environmental pollutants.

Keywords: Pervious concrete, fly ash, rice husk ash, compressive strength

1 Introduction

Pervious concrete offers a practical solution to significant environmental concerns, including flash flooding and groundwater replenishment, while promoting sustainable construction methods. The aforementioned concerns have heightened curiosity over the utilization of pervious concrete [1]. Although pervious concrete exhibits greater permeability, it has reduced strength compared to traditional concrete. Due to its relatively low strength, pervious concrete is suitable for pavements that experience minimal traffic volume. In various applications, such as parking lots, pervious concrete is utilized to drain and permeate water in order to decrease water runoff and improve the environment of the catchment. Generally, higher cement content is used for pervious concrete compared to conventional cement-based materials such as conventional concrete and cement blocks. Literature shows that a larger amount of carbon dioxide is emitted during cement production. Therefore, several other materials are used as cement replacements for binders to reduce the carbon footprints of concrete [2, 3]. Recent advancements in optimising cement-based materials have emphasized the important part of nanomaterials. For instance, the incorporation of nanosilica, graphene oxide, and other nanoparticles has been shown to enhance the mechanical characteristics and

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durability of cement matrices [4, 5]. These materials can improve the microstructure by filling voids, leading to denser and stronger composites. Additionally, research has demonstrated that certain nanomaterials can aid in the immobilization of heavy metals, further promoting environmental sustainability in construction [4, 5]. Such innovations not only optimize performance but also align with sustainable construction practices, making them crucial for future developments in the field.

Due to their affordability and accessibility, rice husk ash (RHA) and fly ash (FA) are two materials which are employed as cement alternates in cement-based products [6]. FA is a low-cost, supplementary cementing material produced from the combustion of coal for energy production and it contains a considerable amount of silicon and aluminum [7, 8]. Rice husks are a by-product from milling of paddy. Rice husks are generally used in boilers of the industry to produce steam or are used as a fuel in biomass power plants. The ashes produced in incineration of rice husks contain approximately 90% of unreactive silica and the colors of the ashes vary from off-white to black depending on the carbon content. About 5 million tons of rice husks are produced each year, and the residue produced increases yearly [9]. The contemporary literature indicates that partial substitute of cement with FA and RHA, as well as their combination, yields acceptable mechanical characteristics for cement-based materials [9-12].

In studies focused on conventional concrete, the integration of FA generally enhances the workability of fresh mortar, attributed to its finer particle size, smooth texture, and spherical shape [10, 13]. However, while FA improves workability, it can lead to a decrease in strength, especially at higher substitution percentages. Strength reductions are typically reasonable within a 45% FA replacement compared to control samples [14-19]. Additionally, although the presence of FA increases the porosity, it also contributes to improved long-term durability [17, 20-24]. In contrast, the workability of fresh mix reduces as the RHA replacement proportion rises [25-28]. Conversely, RHA has been demonstrated to improve the compressive and tensile strength of concrete when it replaces 10% to 20% of the cement content [27, 29-31]. Notably, the compressive strength of concrete with RHA improves with curing time. However, exceeding the optimal replacement percentage leads to a decline in compressive and splitting tensile strength. Durability parameters, including water penetration resistance, air permeability, and sulfate resistance, also improve with RHA replacement [32, 33]. The combined outcomes of FA and RHA on strength and durability have been explored, with findings indicating that a combination of 10% RHA and varying percentages of FA (10%, 20% and 30%) yields differing results. Specifically, 10% RHA and 10% FA achieve optimal compressive strength, while a mixture of 10% RHA and 30% FA results in compressive strength lesser than that of reference blocks. Importantly, the adding of FA reduces both water absorption and porosity, keeping these values lesser than those of control concrete [32].

In studies focused on pervious concrete, Aoki and Sri Ravindrarajah [34] noted that FA substitution did not significantly alter density or porosity; however, compressive strength decreased by more than 40% with higher FA concentrations. Saboo and Shivhare [35] studied the influence of metakaolin and FA as partial cement substitutes under different environmental conditions, finding that while FA and metakaolin content significantly influenced properties, curing conditions had a lesser impact. The inclusion of 2% metakaolin and a cement replacement of 5% to 15% FA resulted in reduced porosity, while increasing density and compressive strength. Shafabakhsh and Ahmadi [36] reported that increasing RHA content as a cement replacement reduced porosity and permeability up to 10% RHA; beyond which both metrics increased. The strengths—compressive, flexural tensile, and splitting tensile—improved with up to 10% RHA substitute but decreased with higher RHA content. Same trends have been documented in pervious concrete studies by various researchers [37]

Although the effects of using FA and RHA in combination to replace cement in conventional concrete have been thoroughly explored, there are currently few studies on pervious concrete using RHA and FA in combination. The mechanical characteristics of pervious concrete that incorporates various RHA and FA mixes as additional cementitious materials are compared in this study. This study also examines the impact of these additional cementitious components at varying *W/B* ratios.

2 Material and Methods

2.1 Material used

Ordinary Portland cement (OPC) was the main binding material for casting experimental pervious concrete sample cubes. The OPC utilized in this research was obtained from Tokyo Cement Company (Lanka) in Sri Lanka and is categorized as Strength Class 42.5 N for OPC as per Sri Lanka standards. The FA was sourced from the Nuraicholai Power Plant located in Puttalam, Sri Lanka, and is categorized as Class F per ASTM C618 [35]. Additionally, the RHA was collected from rice mills in Ampara, Sri Lanka, and comprises a high silica, with a minimum of 80% SiO_2. Before casting, FA and RHA were sieved through 300-micron and 800-micron sieves respectively. The particle size dissemination (PSD) of raw materials is provided in **Fig. 1**, measured using sieve analysis and hydrometer meter analysis.

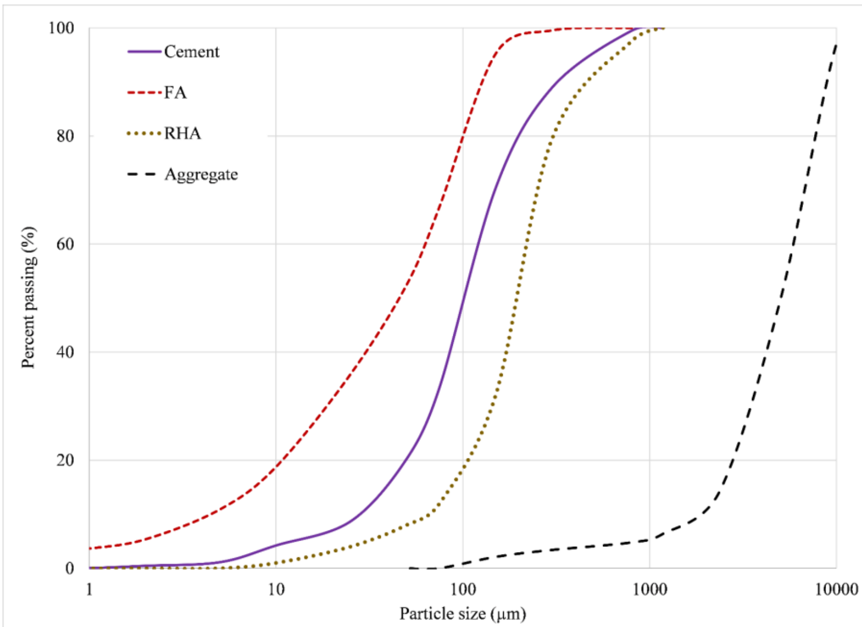


Fig. 1. Particle size distribution of the materials.

To determine the particle size distribution of the materials, both sieve analysis and hydrometer analysis were employed. In sieve analysis, samples of FA and RHA were dried and then passed through a series of standard sieves by different mesh sizes. After mechanical shaking, the material retained on each sieve was weighed to calculate the cumulative percentage of particles at each size range. For hydrometer analysis, a fine sample (RHA) was combined with water and a dispersing agent to create a suspension. A hydrometer was subsequently employed to determine the specific gravity of the suspension at specified time intervals, allowing for the calculation of particle sizes based on their settling velocities. The results from both methods were plotted to visualize the particle size distributions. Compared with OPC, FA's particle size values are smaller, while RHA particles are larger. Considering 90% cumulative percentage, OPC, FA and RHA have particle sizes of 350, 135 and 590 µm, respectively. Similarly, the cumulative passing percentage of 10% (effective diameter) of OPC, FA and RHA correspond to particle sizes of 28, 5 and 62 µm, respectively.

The chemical configuration of OPC, RHA and FA are provided in **Table 1**. OPC consists higher content of CaO and a lower content of SiO_2, Al_2O_3 and Fe_2O_3 compounds. However, the primary component of FA and RHA is SiO_2 which is 50.8% and 81.8%, respectively. The sum of SiO_3+Al_2O_3+Fe_2O_3 is 85.81% and 84.58% for FA and RHA, respectively. CaO is less than 10% for both FA and RHA. The total Alkali (Na_2O equivalent = Na_2O + 0.658 K_2O) equals 2.71% and 2.93% for FA and RHA, respectively. According to the BS standard, the aggregates used in this study were tested and the qualities and associated standards are shown in **Table 2**.

Table 1. Composition of chemical composition and physical characteristics of cement, FA and RHA.

Properties	FA	RHA	Cement
Chemical composition (%)			
CaO	6.25	3.41	66.55
SiO_2	50.81	81.81	20.60
Fe_2O_3	6.97	1.01	3.62
Al_2O_3	28.03	1.76	4.51
MgO	1.21	0.66	1.17
Na_2O	1.45	0.97	0.40
P_2O_5	1.02	0.57	-
SO_3	0.36	0.17	2.51
K_2O	1.92	2.98	0.39
Physical properties			
Specific gravity	2.39	2.11	3.15
Bulk density (kg/m^3)	1650	235	1362
Specific surface area (m^2/kg)	390	235	325

Table 2. Properties of aggregate.

Properties	Unit	Standard used	Values
Specific gravity	-	BS-EN-1097 [36]	2.72
Bulk density	kg/m ^{3}	BS-EN-1097 [36]	1490
Absorption	%	BS-EN-1097 [36]	0.20
Moisture content	%	BS-EN-1097 [36]	0.35
Flakiness Index	-	BS-EN-933 [37]	14.7
Aggregate Crushing Value	%	BS-EN-1097 [36]	30.5
Aggregate Impact value	%	BS-EN-1097 [36]	25.5
Elongation Index (%)	%	BS-EN-933 [37]	24.02

2.2 Mix design and specimen preparation

The research included the casting of pervious concrete cubes with various mix designs as shown in **Table 3**. All experimental cubes were cast with an aggregate-to-cement proportion of 2.5, while *W*/*B* was varied. Also, cement was replaced by filler materials, RHA and FA in different percentages as shown in **Table 3**. Control cubes were created to assess the effects of *W*/*B* ratio on the properties of pervious concrete, with varying *W*/*B* proportion from 0.25 to 0.45 in 0.025 increments. In this research, the selection of mix proportions and *W*/*B* ratios was determined based on both empirical evidence from the literature and the specific performance goals for pervious concrete. The optimal range for *W*/*B* ratios (0.3 to 0.45) was identified as crucial for achieving a balance between workability and strength [38, 39]. Lower *W*/*B* ratios tend to enhance compressive strength but may compromise workability, which is essential for pervious concrete to fulfill its drainage functionality. Conversely, higher ratios improve workability but can lead to reduced strength and increased porosity. Another set of experimental cubes were cast with partial cement substitution with FA content of 5, 10, 15 and 20%. The third set of cubes were cast with a substitution of cement with a mixture of RHA and FA, where the total replacement was maintained constant (10%) while the combination varied as indicated in the annotation. The chosen mix proportions, particularly the percentages of FA and RHA, were guided by prior research demonstrating their pozzolanic properties and their capacity to improve the mechanical characteristics. FA was ranged from 5% to 20% of cement by weight, aligning with findings that suggest this range optimizes strength while maintaining adequate workability [40, 41]. RHA was also included in various combinations, with a total replacement of 10% cement maintained across different mixes [42].

The necessary amounts of cement, RHA, FA, and coarse aggregate were measured and placed into an electric concrete mixer to generate the desired blend. Water was added incrementally to achieve the predetermined *W/B* ratio. The fresh mixture was thoroughly mixed until it reached a uniform consistency. A slump test was conducted on the mortar mixture according to BS 1881-102 [43]. The mortar was then poured into 150mm cubic molds and compacted in three layers using a standard compaction hammer (5.08cm diameter, 2.5kg) as specified in BS 1377-4 [44]. The hammer was discharged from a 300 mm height for each impact. The top layer was leveled with an iron rod to ensure a smooth finish. Six samples of pervious concrete were prepared and tested for each type of assessment performed. The cast cubes were air-dried for one day, demolded, and cured for 28 days.

Table 3. Mix design for experiment program

Mix ID	Cement	FA	RHA	Aggregates	*W/B* ratio
Control	1.00	-	-	2.5	0.25, 0.275, 0.30, 0.325, 0.35, 0.375, 0.40, 0.425, 0.45
F05	0.95	0.05	-	2.5	0.30, 0.35, 0.40, 0.45
F10	0.90	0.10	-	2.5	0.30, 0.35, 0.40, 0.45
F15	0.85	0.15	-	2.5	0.30, 0.35, 0.40, 0.45
F20	0.80	0.20	-	2.5	0.25, 0.30, 0.35, 0.40, 0.45
F7.5R2.5	0.90	0.075	0.025	2.5	0.3
F5.0R5.0	0.90	0.050	0.050	2.5	0.3
F2.5R7.5	0.90	0.025	0.075	2.5	0.3
R10	0.90	-	0.100	2.5	0.3

2.3 Testing

(a) W/B = 0.30 (b) W/B = 0.325 (c) W/B = 0.35

(d) W/B = 0.375 (e) W/B = 0.40 (f) W/B = 0.425

Fig. 2. Slump variation with *W/B* ratio.

The slump, density and compressive strength was measured in accordance with ASTM-C143/C143M [45], ASTM-C1688/C1688M [46], ASTM-C109 [47], respectively. The permeability of each concrete mix design was assessed using the falling head method by ASTM-D5084 [48].

3 Results and Discussion

3.1 Mechanical Characteristics of Control Blocks

Tests for slump, density, porosity and compressive strength were carried out for *W/B* ratio 0.25 to 0.425. Although high compressive strengths are not anticipated from pervious concrete, a considerable and acceptable range of compressive strength is required for industrial applications. A zero slump was obtained for the mix with a *W*/*B* proportion of 0.3 as shown in **Fig. 2a**. After that, the slump value gradually increased with *W*/*B* proportion. At a *W*/*B* proportion of 0.325 and 0.35, the slump measured 21 mm and 38 mm, respectively. These values are suitable for the use of pervious concrete, as they exhibit a higher slump value than standard concrete. There was a substantial rise in the slump when the *W*/*B* ranged from 0.35 to 0.375, reaching a measurement of 64 mm. The greatest rise in slump values occurred when the *W*/*B* proportion reached 0.375. The slump measurements for the *W*/*B* proportion values of 0.4 and 0.425 were 108 mm and 148 mm, respectively. For these *W*/*B* proportions, when the cone was lifted, the mixture collapsed immediately, as shown in **Fig. 2f**.

Fig. 3 demonstrates the impact of the *W*/*B* proportion on the wet density and porosity. Evidently, the porosity increased and the density reduced as the *W*/*B* proportion grew. As the *W*/*B* proportion grew from 0.25 to 0.45, the porosity reduced progressively from 26% to 17.8%. With an rise in the *W*/*B* proportion, there was a corresponding rise in the amount of cement gel formed on the surface of the aggregate. Consequently, the thickness of the pore walls gradually increased [49, 50]. Therefore, the technique decreased the size of open holes in pervious concrete. The decrease in pore size resulted in an elevation of the density.

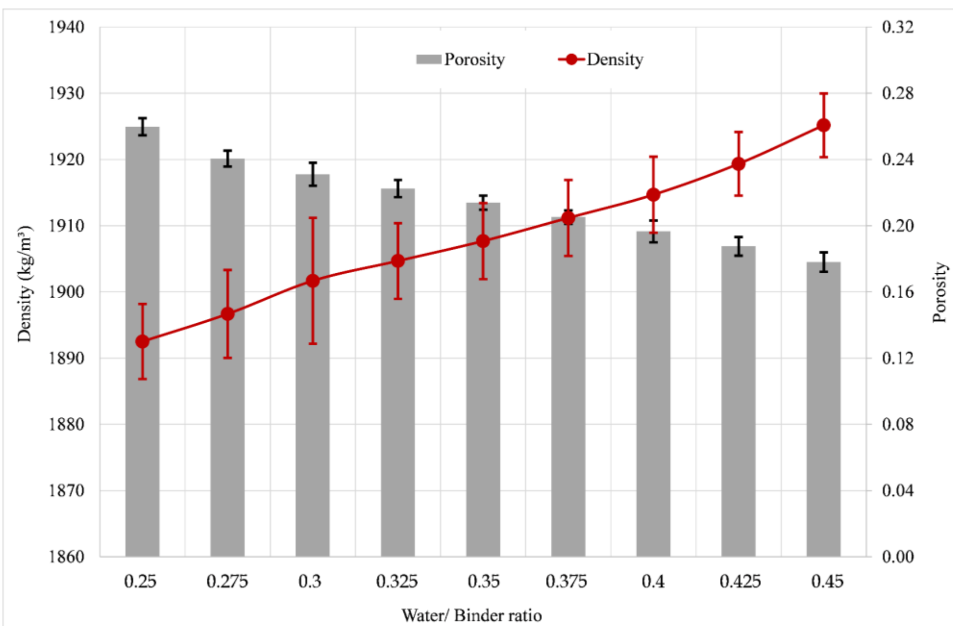


Fig. 3. Density and porosity variation with *W/B* ratio.

Fig. 4 summarizes the 7th- and 28th-day compressive strength variation with *W*/*B* ratio and corresponding slump values. It could be observed that low strength was obtained for a *W*/*B* proportion of 0.25 and 0.275. This was due to reduced water availability in the mortar to reach optimum compressive strength for that mix. However, beyond the *W*/*B* proportion of 0.3, a gradual increase in strength reached the optimum strength at a *W/B* proportion of 0.425. Yet, while higher compressive strength is advantageous, slump of mortar mix used for pervious concrete needs to be less than 20 mm (preferably zero) to ensure passage of pores through the concrete.

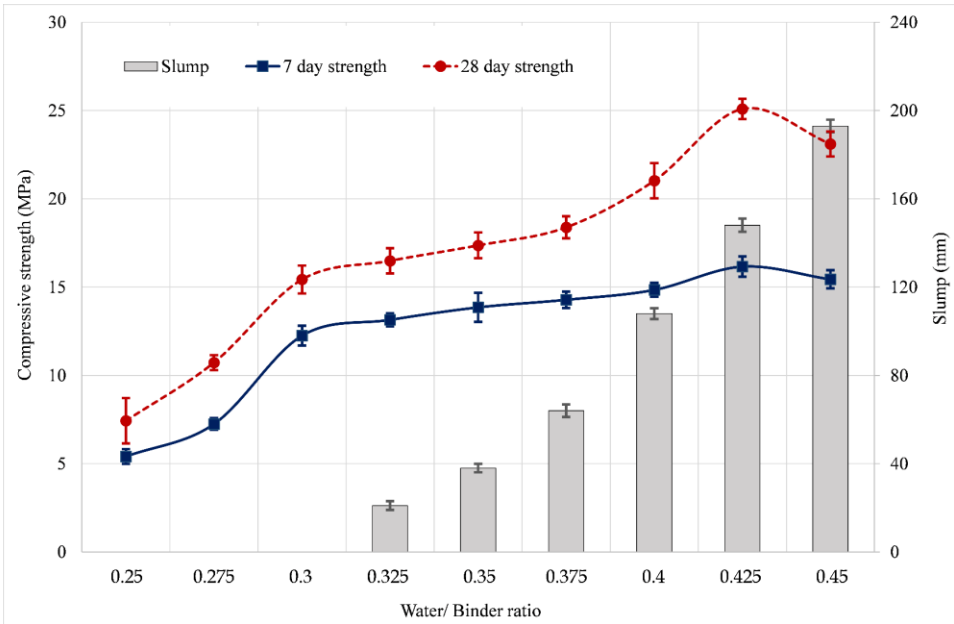


Fig. 4. Compressive strength variation with *W/B* ratio**.**

3.2 Effect of FA replacement

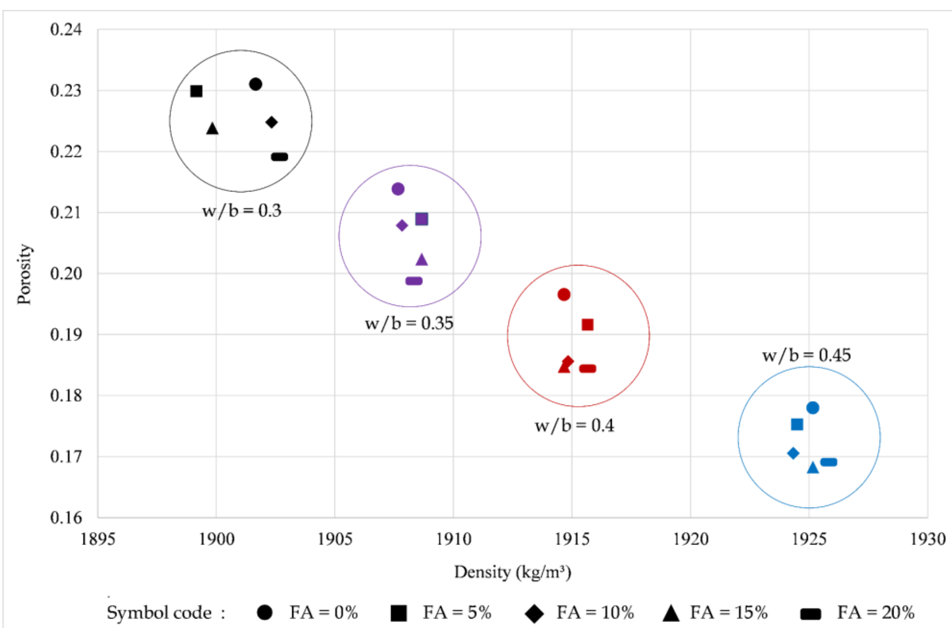


Fig. 5. Density and porosity variation with *W/B* proportion and FA substitution level.

Fig. 5 illustrates the density and porosity variation with FA content and *W/B* ratio. As FA content increases, porosity is reduced for all *W/B* ratio while density remains constant. The rise in FA quantity has a minor consequence on density as the density with FA only varied within ±2 kg/m^3 compared with control cubes which is within the uncertainty. In addition, *W*/*B* proportion has an insignificant influence on the density of resulting concrete. While the *W*/*B* proportion increase from 0.3 to 0.45, the maximum density increment observed with 15% FA replacement was limited to 1.33%. However, the *W*/*B* proportion has a significant influence on porosity. When *W*/*B* proportion rise from 0.3 to 0.45, the porosity reduced by approximately 23% for all the FA replacement percentages. Within a particular *W*/*B* ratio, maximum porosity reduction occurred for 20% FA replacement and 0.35 *W*/*B* proportion, while it is limited to only 7%.

Table 4 summarizes the slump and compressive strength variation with *W*/*B* ratio and FA replacement percentage. Workability is the critical features of pervious concrete and slump is the widely accepted indicator for workability. For a particular *W*/*B* proportion, the slump value raised with FA content. The reason for this observation can be traced to the spherical profile and smooth surface of FA particles. When FA replacement was 20% of the cement, the slump value increased to 35, 55, 67 and 78 mm for *W*/*B* proportion equal to 0.3, 0.35, 0.4 and 0.45, respectively. In other words, the inclusion of FA in mortar reduces *W*/*B* ratio without changing the workability.

Table 4. Slump and compressive strength variation with *W*/*B* proportion and FA substitution level

W/B ratio	FA replacement	Slump (mm)	7-day Compressive Strength (MPa)	28-day Compressive strength (MPa)
0.25	0	0	4.47 (0.42)	5.35 (1.29)
	5	0	-	-
	10	0	-	-
	15	4 (1.0)	-	-
	20	7 (1.3)	8.09 (0.66)	12.10 (0.78)
0.3	0	0	12.25 (0.56)	15.43 (0.88)
	5	5 (0.8)	8.85 (0.65)	14.52 (0.33)
	10	12 (1.3)	9.60 (0.42)	15.22 (0.52)
	15	20 (1.3)	10.96 (0.37)	16.15 (0.44)
	20	35 (1.6)	11.21 (0.29)	16.51 (0.57)
0.35	0	38 (1.9)	13.86 (0.82)	17.36 (0.73)
	5	45 (2.3)	11.49 (1.12)	18.09 (0.77)
	10	56 (1.7)	14.60 (0.51)	26.44 (0.72)
	15	70 (1.3)	15.38 (0.76)	26.89 (1.78)
	20	93 (1.7)	13.90 (0.39)	26.81 (0.84)
0.40	0	108 (2.4)	14.84 (0.58)	21.02 (0.79)
	5	117 (2.2)	13.82 (0.73)	27.43 (0.55)
	10	131 (1.7)	17.53 (0.94)	31.33 (1.46)
	15	145 (1.8)	16.50 (0.52)	27.61 (0.57)
	20	175 (1.8)	15.09 (0.38)	25.33 (0.91)
0.45	0	193 (2.8)	15.44 (0.66)	23.10 (1.01)
	5	206 (2.2)	19.18 (1.23)	27.96 (1.14)
	10	221 (1.9)	17.25 (1.56)	29.82 (0.65)
	15	240 (1.9)	16.12 (1.24)	25.15 (1.07)
	20	271 (1.7)	17.10 (0.82)	22.99 (1.47)

* The standard deviation is shown in brackets.

When FA was included as cement replacement in the mix, cement hydration reaction followed by a pozzolanic reaction. Hydration reaction of cement with water, it undergoes a transformation into Calcium silicate hydrate (C-S-H) gel and calcium hydroxide ($Ca(OH)_2$) gel, as represented by Eq. (1) [51, 52]. This triggered a reaction between $Ca(OH)_2$ and Silica, utilizing available water, resulting in the formation of additional C-S-H gel, as depicted in Eq (2) [53]. During the hydration, the reaction with FA becomes secondary.

$$\text{Cement hydration reaction: } Ca_3SiO_5 + H_2O \rightarrow \text{C-S-H} + Ca(OH)_2 \quad (1)$$

$$\text{Pozzolanic reaction: } Ca(OH)_2 + SiO_2 + H_2O \rightarrow \text{C-S-H} \quad (2)$$

For a particular FA content, the strength was improved with the *W*/*B* proportion up to the optimum level and reduced after that. When a low *W*/*B* proportion was used, limited water was available for cement hydration and pozzolanic reaction. Therefore, pervious concrete showed less strength in low *W*/*B* proportion and thereafter, the strength enhanced with the increase in *W*/*B* proportion. However, a high *W*/*B* proportion resulting in excessive water in the mix resulted in aggregate segregation and reduced strength.

Table 5. Optimum mix for pervious concrete

Fly ash	Optimum *W/B* ratio for slump ≤ 20mm	Slump	Corresponding compressive strength	
			7 days	28 days
0	0.30	0	12.25	15.43
5	0.30	5	8.85	14.52
10	0.30	12	9.60	15.22
15	0.30	20	10.96	16.15
20	0.25	7	8.09	12.10

Variation of compressive strength was observed to be negligible for varying FA with a *W*/*B* proportion of 0.3. This may be due to less water being available in the mix, and therefore, the pozzolanic reaction was restricted to utilizing the available FA. When the *W*/*B* proportion raised to 0.35 or above, the compressive strength improved up to 10% FA as cement substitute. This observation could be attributed to the available silica from FA for pozzolanic reaction together with higher production of C-S-H gel compared to control mixtures. The 28th day strength of the pervious concrete including 10% FA was 52.3, 49.1 and 29.1% more than control cube. However, for higher FA quantity, the compressive strength was reduced with a rise in FA quantity. This observation could be because the amount of silica from hydrated blended cement is in excess while the $Ca(OH)_2$ produces insufficient for thorough reaction with available silica. This resulted in excess silica remaining unreacted. While compressive strength is important for pervious concrete, permeability is crucial to serving its purpose of transporting fluids through them. This in turn inevitably requires slump to be minimal, or preferably zero. When slump value is limited to 20 mm, the optimum mix for pervious concrete with FA content is summarized in **Table 5**.

3.3 Effect of Combination of RHA and FA Replacement

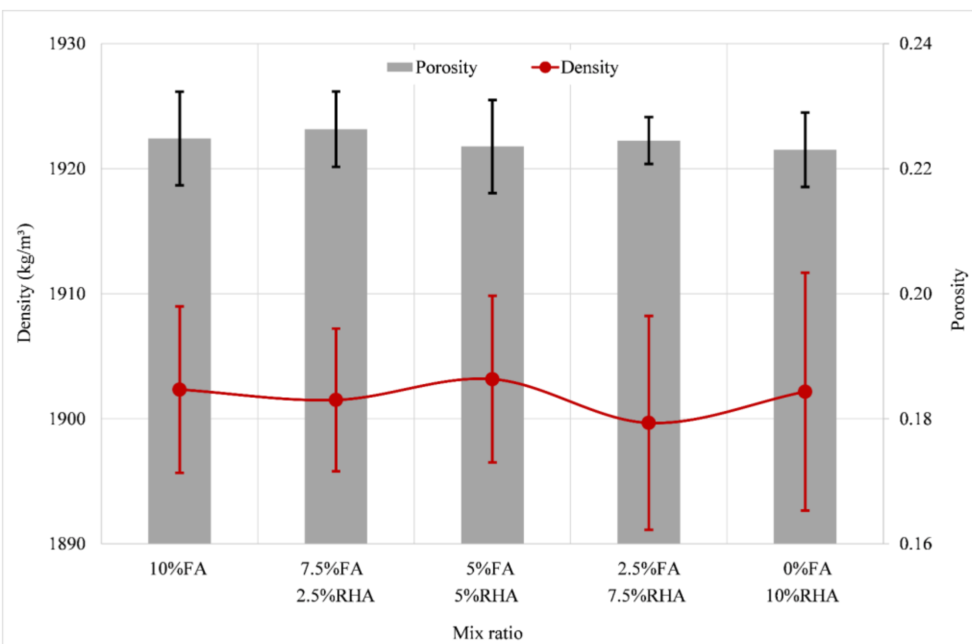


Fig. 6. Density and porosity variation with FA and RHA combination.

This research assessed the synergistic influence of FA and RHA on a *W*/*B* proportion of 0.3. The slump for all the combinations of FA and RHA is within 0 – 12 mm range. **Fig. 6** presents the discrepancy of the density and porosity with varying combinations of FA and RHA. It could be seen that the combination FA and RHA have not significantly affected density or porosity.

The observed changes in mechanical properties with increasing FA and RHA content can be attributed to several mechanisms affecting the microstructure of pervious concrete. Both FA and RHA are pozzolanic materials, that means they respond with calcium hydroxide (produced through the hydration of cement) and water, leading to the formation of more calcium-silicate-hydrate (C-S-H). This reaction provides to the densification of the concrete matrix, enhancing its mechanical properties. The finer particles of FA fill the voids among the larger aggregates, producing to a denser microstructure. This filler effect improves the packing density, that can enhance both strength and durability. As FA and RHA are incorporated, the microstructure of the concrete transitions from a more porous structure to a denser one. The increased formation of C-S-H contributes to a more robust interfacial transition zone (ITZ) among the cement paste and aggregate, which is critical for strength. Incorporating FA and RHA can substantially decrease the porosity of pervious concrete. A lower porosity leads to decreased permeability, which enhances the durability of the concrete by reducing the ingress of harmful substances.

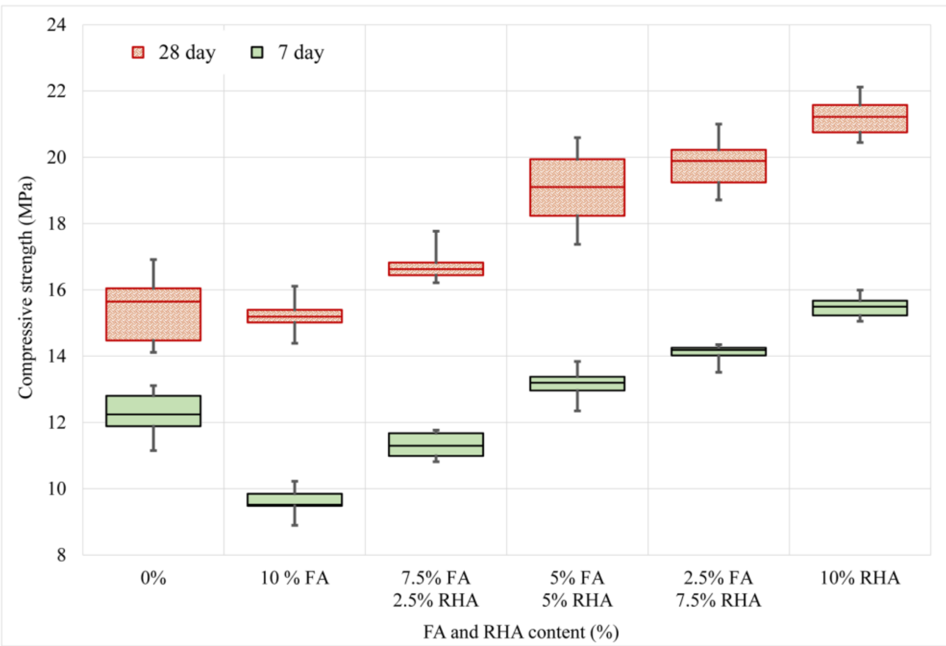


Fig. 7. Compressive strength variation with FA and RHA combination.

Fig. 7 presents 7th day and 28th-day compressive strength with a different combination of FA and RHA as cement replacement, adding up to 10% of replacement of cement in total. All combinations of FA and RHA show lower 7th to 28th day strength ratio compared to control cubes. The 7th to 28th day strength ratio for control blocks was 79.4%. For the combination of FA and RHA, this value was 63.1, 67.5, 69.0 and 71.1%, respectively for 0, 2.5, 5, 7.5 and 10% of RHA in the mix. The observed reduction in compressive strength at 7 days is likely due to the slower rate of pozzolanic reaction associated with FA. The FA typically requires more time to react fully compared to Portland cement, which can result in lower early-age strength. At 10% FA replacement, the initial hydration may not be sufficient to accomplish the similar strength as the control group within the 7-day period. However, by 28 days, the pozzolanic reaction of the FA endures to develop, leading to a notable increase in strength that approaches that of the control group. This behavior is dependable with findings in the literature, which indicate that FA contributes positively to the long-term strength and durability. It is clearly proven that RHA provides better early strength compared with FA, but still, it is less than the performance of control cubes. As observed in **Fig. 7**, the replacement of RHA in the mixture rises the strength proportionally. In general, RHA has several advantages over FA, such as:

- Higher silica content in RHA improves pozzolanic activity. Especially, RHA with larger amount of purity of amorphous silica and less carbon content could yield higher strength for binder [54].
- The lower specific surface area of RHA reduces the amount of water required for setting and thereby making additional water available for pozzolanic reaction.

As observed in **Fig. 7**, pervious concrete with 10% FA showed a similar 28th-day strength of control cubes. However, the substitution of RHA showed a gradual increase of compressive strength. For 10% RHA as replacement level, the strength was enhanced by 38% compared to control cubes. Further analysis revealed that the optimal combination of RHA with varying percentages of FA consistently caused in improved strength compared to control. However, excessive FA beyond a certain threshold led to diminished compressive strength, likely due to unreacted silica competing for available calcium hydroxide, underscoring the importance of maintaining a balanced mix.

The results indicate that both 10% FA 10% RHA serve as effective cement replacements, each yielding robust compressive strength when used individually. FA as a supplementary cementitious material, it is known for its high reactivity due to its amorphous silica content. When used at 10% replacement, it effectively enhances the cement hydration process, leading to increased formation of calcium silicate hydrate (C-S-H), which contributes to strength development. FA also improves the workability of the concrete mix, allowing for better consolidation and reduced porosity. Similarly, RHA contains a significant amount of reactive silica, which contributes to its pozzolanic behavior. Both FA and RHA have particle sizes that allow them to integrate well into the concrete mix, leading to improved packing density. When used individually, they can optimize the particle size distribution more effectively than when combined, minimizing voids and enhancing the overall strength. while FA and RHA are used together, there may be competitive reactions that limit the availability of calcium hydroxide necessary for optimal pozzolanic activity. The presence of both materials can lead to a dilution effect, where the benefits of each material are not fully realized. In contrast, using them separately allows for each material to contribute maximally to the hydration reactions without interference.

Published literature shown that, in general, it was observed that porosity reduced with increasing FA substitution up to 30% [55-58]. This trend aligned with the majority of published studies. However, except Saboo et al. [59] reported a different trend due to their unique wet-curing method. Al-Sallami et al. [58] deviated from the general trend, showing an increase in porosity at higher FA replacement levels (50%). This could be attributed to factors such as the type of the FA used or differences in the mixing and curing conditions. For low-level RHA replacement (less than 10%), the results were consistent with published literature, showing a decrease in porosity [60-62]. However, at higher RHA replacement levels, an increasing trend in porosity was observed. This suggested that the beneficial effects of RHA on porosity may diminish at higher replacement rates.

The present study supported the consensus in the literature that 20% FA replacement is optimal for achieving enhanced compressive strength [55-60, 62-65]. This was consistent with the results of Wang et al. [55] and Saboo et al. [59]. For RHA substitution, the present study and literature indicated a comparable trend: compressive strength improved with RHA substitution up to 5-10%, then decreased. This suggested that there was a maximum beneficial influence of RHA on compressive strength, beyond which the negative effects of RHA on the concrete microstructure became more pronounced.

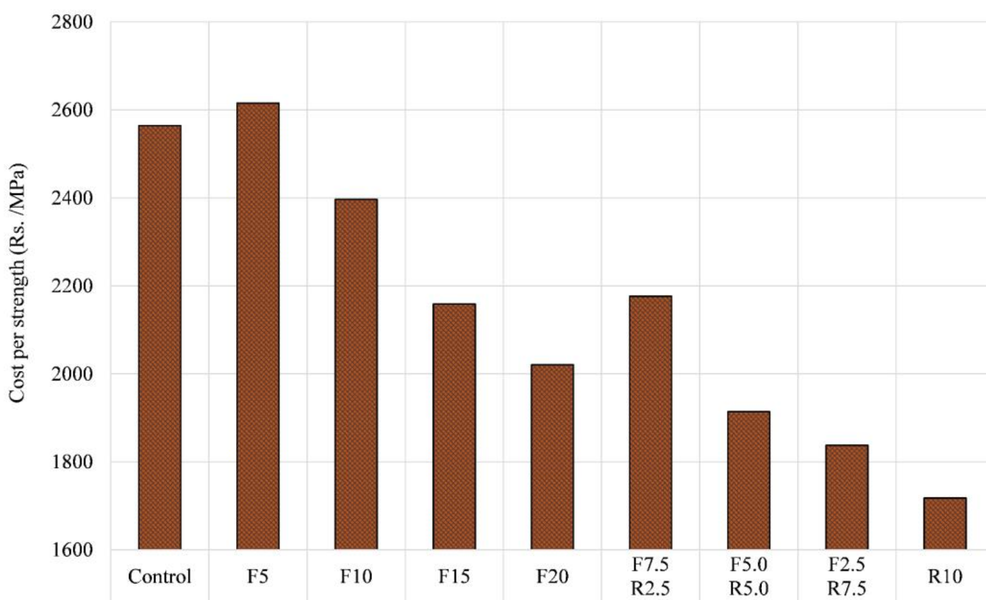
3.4 Permeability

Understanding how mix design affects permeability is vital for practical applications of pervious concrete. It is planned to allow rainwater to infiltrate, reducing surface runoff and promoting groundwater recharge. Therefore, optimizing permeability is crucial for the effectiveness of pervious surfaces in mitigating flooding and erosion. The application of pervious concrete should consider local environmental conditions, including soil type, rainfall patterns, and groundwater levels. Adjusting the mix design to enhance permeability can help tailor pervious concrete to specific site requirements, ensuring optimal performance in real-world scenarios.

The permeability is primarily influenced by its mix design, including the proportions of cement, aggregates, and supplementary materials such as FA and rice RHA. The inclusion of FA can improve workability, allowing for better compaction and potentially reducing voids. However, at higher replacement levels, the increased volume of FA may lead to increased porosity, thus affecting permeability. Present results suggest that while 10% FA enhances compressive strength, it also contributes to a balance between permeability and strength. RHA has been found to fill voids within the aggregate matrix effectively, which can reduce permeability when used at optimal levels. However, excessive RHA may lead to a less dense microstructure, potentially increasing permeability. Our findings indicate that 10% RHA maintains a favorable balance, providing adequate strength without compromising permeability significantly. The permeability may vary with the amount of binder used, aggregate size and density of the mixture, but preferred within the range of 2-6 mm/s and may go up to 10 mm/s [66, 67]. A moderate permeability of pervious concrete used for pavement system would typically have an infiltration rate of 143 liters per minute per square meter (2.4 mm/s) [68].

Permeability of all mix designs used in this study had been observed to be higher than 90 mm/s. This is observed to be very high whereas the average permeability of soil is in the range of approximately 0.25 mm/hr to 25 mm/hr [68]. The pervious concrete cast in this study is therefore capable of transporting large amounts of water through the structure where the native soil would become the limiting factor. This indicates that when the slump value of the fresh mix less than 20 mm, the permeability is not the controlling factor to decide the optimum mix.

3.5 Cost Analysis



	Control	F5	F10	F15	F20	F7.5 R2.5	F5.0 R5.0	F2.5 R7.5	R10
Cost/Strength ratio	2564	2615	2397	2159	2021	2176	1914	1838	1718
Cost (Rs.)	39572	37968	36476	34876	33373	36454	36480	36407	36448
Strength (Mpa)	15.43	14.52	15.22	16.15	16.51	16.75	19.06	19.81	21.22

Fig. 8. Cost analysis of pervious concrete with various mix ratios.

To analysis the economic advantages of RHA and FA as cement substitution in pervious concrete, the raw material consumption was computed. For here mix with *W*/*B* proportion of 0.3 was considered. The usage of materials was determined as of the amount of cement, RHA, FA and coarse aggregate required. **Fig. 8** shows the price of the raw materials needed to produce one cubic meter of pervious concrete. Cement and FA cost SLR 3,000 and SLR 400 per bag (50kg), respectively, on the local market. Even though RHA is considered as agricultural waste, still preparation of RHA involves loading and unloading, transportation and grinding and heat treatment. Based on the building schedule of rates of Sri Lanka [69], the cost for these sets is SLR 1,075 for one-meter cube loading/ unloading, SLR 101 for one-meter cube/ km transportation, SLR 10 for 1 kg grinding and SLR 6.4 for 1 kg RHA heat treatment. According to the local market, coarse aggregate costs SLR 3,700 for one-meter cube. According to this, the prices for 1 kg of cement, RHA, FA and coarse aggregates in SLR were 60.00, 7.60, 8.00 and 2.50, respectively.

When comparing the raw material cost of pervious concrete with FA, the cost decreases by approximately 15.7% for a 20% FA content. When the combination of FA and RHA is used as a cement replacement, the cost decreases by approximately 8%. However, when the cost per unit compressive strength was considered, the combination of FA and RHA used as cement replacement shows more cost-benefit, especially for higher RHA content in the mortar mix. The reduction in cost for unit compressive strength is 15.1, 25.3, 28.3 and 33.0% for 2.5, 5.0, 7.5 and 10% RHA content, respectively. These values are generally higher than 20% FA replacement, where the reduction in cost for unit compressive strength is 21.2%. Therefore, this shows that the pervious concrete with a combination of FA and RHA is cost-effective than the control one.

3.6 CO_2 Emission Analysis

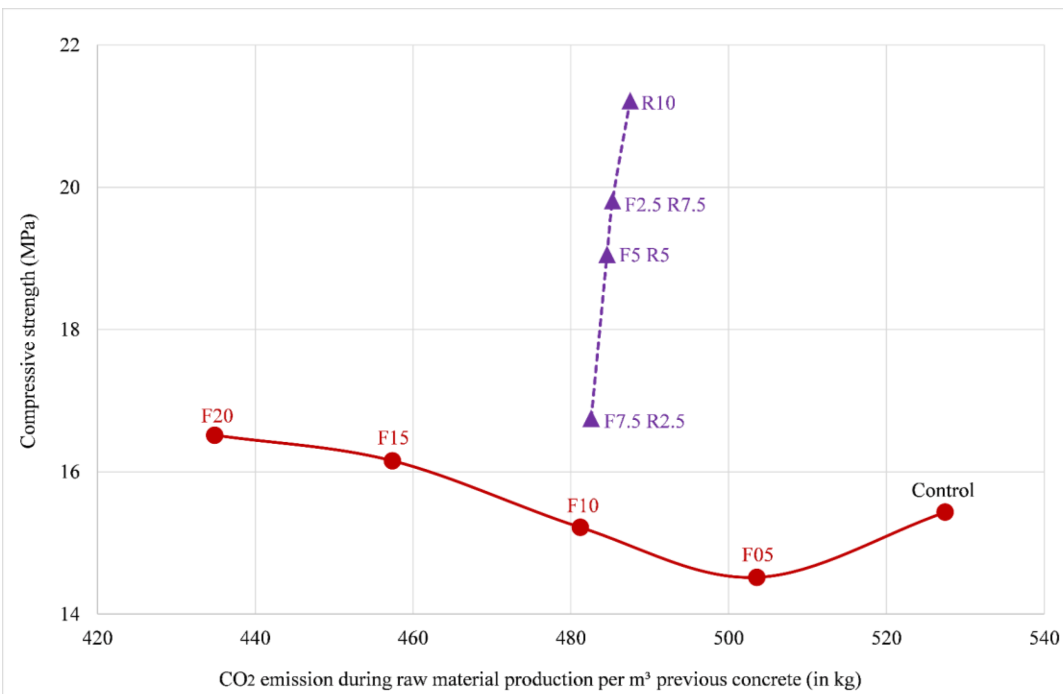


Fig. 9. CO_2 emission analysis of raw material used for pervious concrete with various mix ratios.

In terms of consideration of sustainability reduction in carbon footprint of concrete is considered an appropriate parameter. In the manufacture of concrete, cement as a constituent contributes to the carbon footprint of resulting concrete, compared to others, owing mainly to power-intensive processes in cement production. To analyses the environmental benefits of the production of pervious concrete with RHA and FA as cement substitution, carbon emission analysis was conducted. The CO_2 emissions for the production of cement, FA and coarse aggregates were collected from available literature [70-74]. Furthermore, the grinding process and the heat treatment of RHA also contribute to CO_2 emissions [75]. For one-tonne material production of cement, FA, RHA and coarse aggregates, the CO_2 emissions were computed to be 780, 8, 5 and 41 kg, respectively. The CO_2 emissions from material transportation and wet mix stirring were not taken into consideration in this research. Using the above estimations, CO_2 emissions of the raw material production for one-meter cube pervious concrete were computed.

Fig. 9 presents the compressive strength versus CO_2 emissions of pervious concrete with different cement substitutions, computed based on emissions during the production of raw material for concrete production. It is shown that incorporating FA as a cement replacement, significantly reduces the CO_2 emission without significantly compromising the compressive strength. When the combination of RHA and FA is used as a 10% cement replacement, there is a slight increase in CO_2 emission with the increase in RHA content. However, compressive strength is significantly improved simultaneously.

Table 6 presents a comparison of the embodied energy and carbon associated with cement and various SCMs. Silica fume, FA and RHA are by-products with relatively low embodied energy and carbon due to their minimal processing requirements. In contrast, ground granulated blast furnace slag and pulverized fuel ash require additional processing steps, such as heating and grinding, resulting in higher embodied energy and carbon. Metakaolin, a manufactured SCM, also has higher embodied energy and carbon compared to by-product SCMs but remains a more sustainable choice than cement. The reduced embodied energy and carbon emissions of FA and RHA compared to Portland cement offer significant potential for enhancing the sustainability of pervious concrete. Incorporating these can lead to lower energy consumption and reduced CO_2 emissions during pervious concrete production. Moreover, the utilization of these SCMs can divert waste materials from landfills, mitigating their environmental impact.

Table 6. Embodied energy and embodied carbon for cement and supplementary cementitious materials

Materials	Embodied energy (MJ/kg)	CO_2 emission ($kgCO_2/kg$)	Ref.
Cement	4.5 - 5.3	0.73 – 0.91	[76, 77]
Fly ash	0.1	0.008	[76]
Granulated blast furnace slag	1.6	0.067	[76]
Silica fume	0.1	0.014	[78]
Metakaolin	3.48	0.33 – 0.40	[79, 80]
Palm oil fuel ash	0.76	0.110	[81]
Rice husk ash	0.008	0.005	[82]
Waste glass powder	0.06 – 0.14	0.007 – 0.016	[83]

4 Conclusion

In the current study, FA and RHA are used as partial cement replacements and their effect on porosity and compressive strength of pervious concrete was analyzed. According on the study's findings, the following conclusions have been made:

- Although compressive strength of pervious concrete increases with *W*/*B* ratio up to 0.425, slump is the deciding factor for optimum *W*/*B* ratio. For pervious concrete, slump flow should be closer or equal to zero for better permeability. Considering both slump and compressive strength, a *W*/*B* ratio of 0.3 is considered optimum for control cubes.
- When slump value is limited to 20 mm, 15% cement replacement with FA and *W*/*B* ratio of 0.3, yields the optimum mix for pervious concrete. For a particular combination, compressive strength was 16.15 MPa, which is 4.7% higher than the control design.
- When the combination of RHA and FA was used, higher RHA replacement showed increased strength without compromising density and porosity. When 10% RHA was used as cement substitution in the mix, the compressive strength reached 21.2 MPa, which is 37.5% and 39.4% higher than the control cube and 10 % FA replaced pervious concrete, respectively.

- The permeability of all mix designs was higher than 90 mm/s. This is observed to be very high and in the present study, the permeability is not the controlling factor to decide the optimum mix with FA or RHA as cement replacement.
- Replacement of cement with FA or RHA, not only reduces the raw material cost but also reduces CO_2 emission during raw material production.

The successful integration of FA and RHA into pervious concrete production offers several practical implications. This research supports the transition towards more sustainable construction methods by reducing reliance on traditional cement, which is responsible for significant carbon emissions. The use of by-products like FA and RHA not only minimizes waste but also contributes to a greener construction industry. Also, Implementing FA and RHA as partial cement replacements can lower material costs, making pervious concrete a more economically viable option for various applications. This aspect is particularly beneficial for large-scale infrastructure projects where budget constraints are critical.

To further advance the knowledge in this field, the following research directions are recommended:

- Investigating the durability and long-term performance of pervious concrete incorporating FA and RHA under various environmental conditions can provide insights into its viability for different applications.
- Conducting field trials to assess the practical application of this concrete mix in real-world scenarios will help validate laboratory findings and determine its effectiveness in managing stormwater in urban settings.
- Future studies should focus on optimizing mix designs for specific applications, considering factors such as traffic load, environmental exposure, and local availability of materials.
- Expanding research to include other supplementary cementitious materials, such as slag or metakaolin, in combination with FA and RHA could yield further improvements in mechanical properties and sustainability.

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CRediT authorship contribution statement

Navaratnarajah Sathiparan: Conceptualization, Investigation, Formal analysis, Writing – original draft. **Daniel Niruban Subramaniam**: Conceptualization, Investigation, Formal analysis, Writing – review & editing.

Conflicts of Interest

The authors declare that they have no conflicts of interest related to this study.

Data Availability Statement

Data can be made available on request by interested parties.

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