



ORIGINAL ARTICLE

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

Navaratnarajah Sathiparan*, Daniel Niruban Subramaniam

Department of Civil Engineering, Faculty of Engineering, University of Jaffna, Jaffna 40000, Sri Lanka.

*Corresponding Author: Navaratnarajah Sathiparan. Email: sakthi@eng.jfn.ac.lk.

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 CO₂ 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



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% SiO₂. 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.

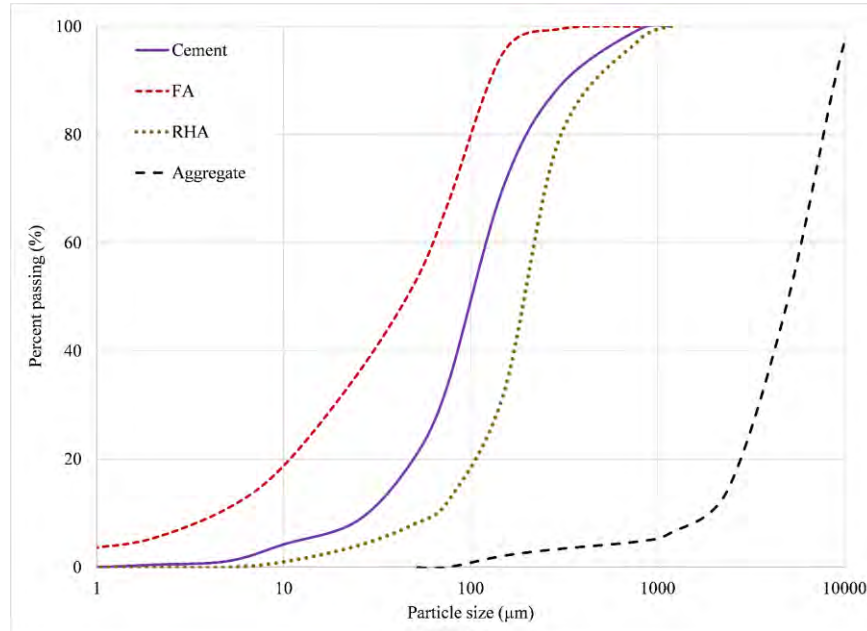


Fig. 1. Particle size distribution of the materials.

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 SiO₂, Al₂O₃ and Fe₂O₃ compounds. However, the primary component of FA and RHA is SiO₂ which is 50.8% and 81.8%, respectively. The sum of SiO₂+Al₂O₃+Fe₂O₃ is 85.81% and 84.58% for FA and RHA, respectively. CaO is less than 10% for both FA and RHA. The total Alkali (Na₂O equivalent = Na₂O + 0.658 K₂O) 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 ₂ O ₃	6.97	1.01	3.62
Al ₂ O ₃	28.03	1.76	4.51
MgO	1.21	0.66	1.17
Na ₂ O	1.45	0.97	0.40
P ₂ O ₅	1.02	0.57	-
SO ₃	0.36	0.17	2.51
K ₂ O	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



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.

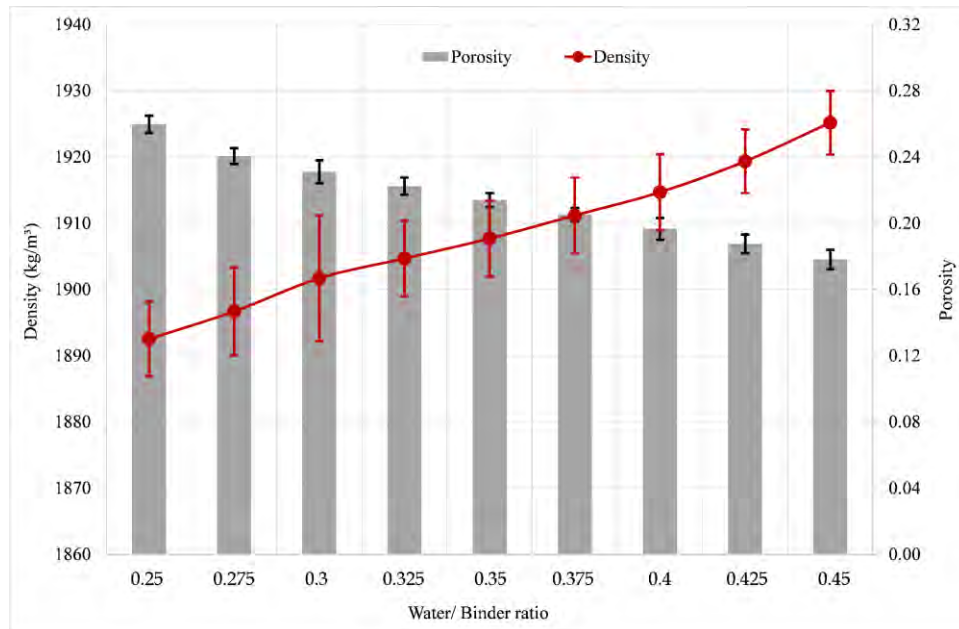


Fig. 3. Density and porosity variation with W/B ratio.

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.

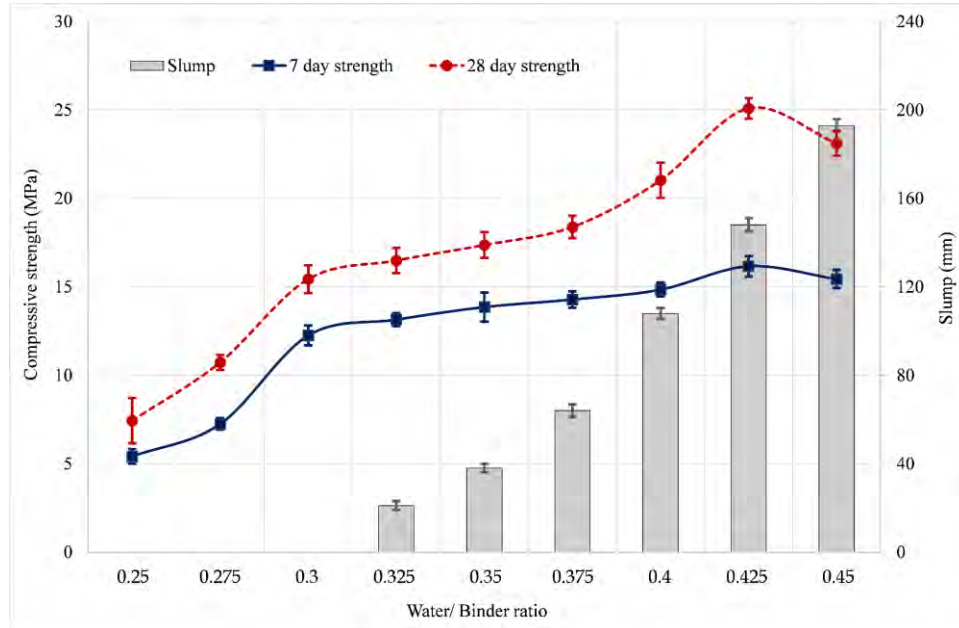


Fig. 4. Compressive strength variation with W/B ratio.

3.2 Effect of FA replacement

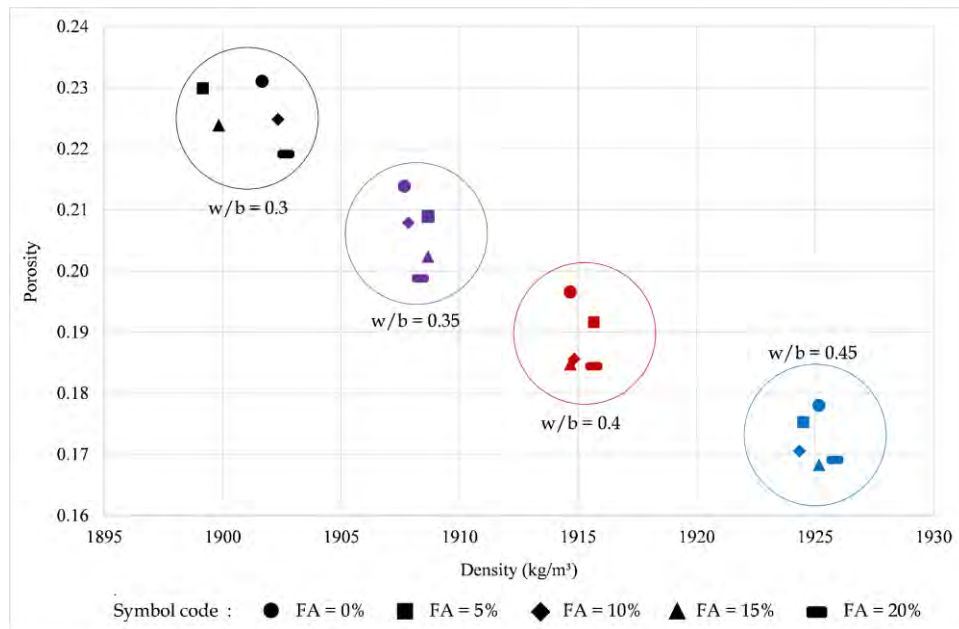


Fig. 5. Density and porosity variation with W/B proportion and FA substitution level.

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 $\pm 2 \text{ kg/m}^3$ 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%.

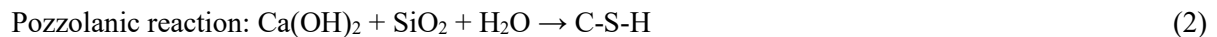
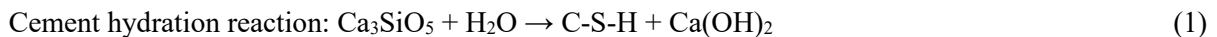
Table 4 summarizes the slump and compressive strength variation with W/B ratio and FA replacement percentage. Workability is the critical features of pervious concrete and slump is the widely accepted indicator for workability. For a particular W/B proportion, the slump value raised with FA content. 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 ($\text{Ca}(\text{OH})_2$) gel, as represented by Eq. (1) [51, 52]. This triggered a reaction between $\text{Ca}(\text{OH})_2$ 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.



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 ≤ 20 mm	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 $\text{Ca}(\text{OH})_2$ 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

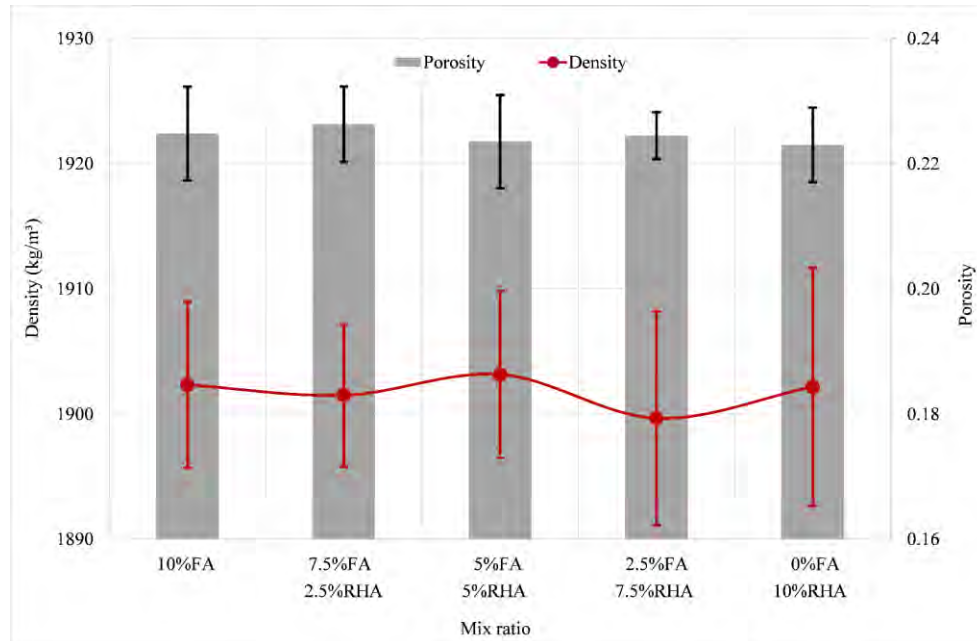


Fig. 6. Density and porosity variation with FA and RHA combination.

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.

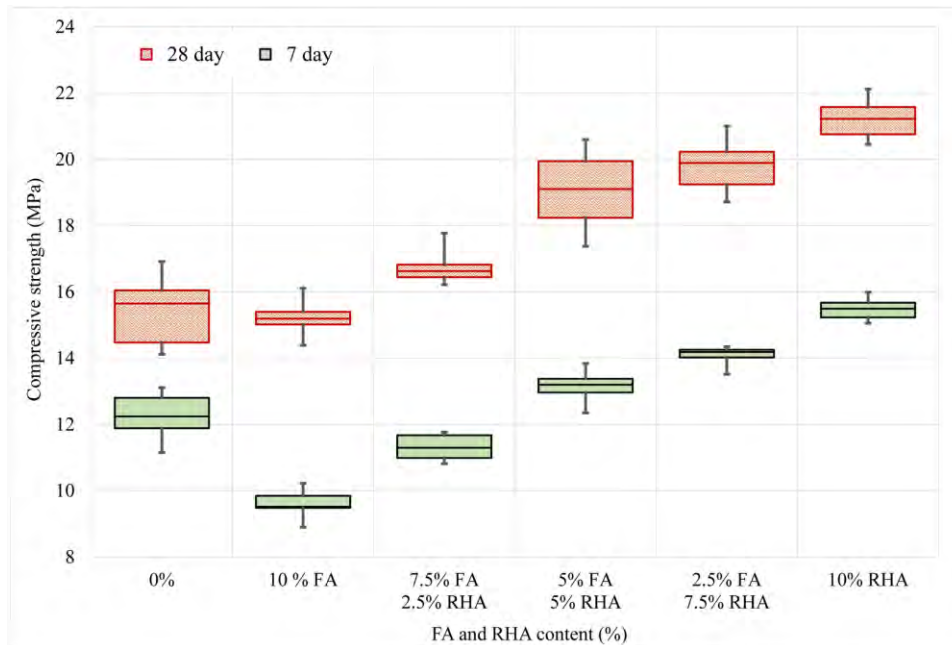


Fig. 7. Compressive strength variation with FA and RHA combination.

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

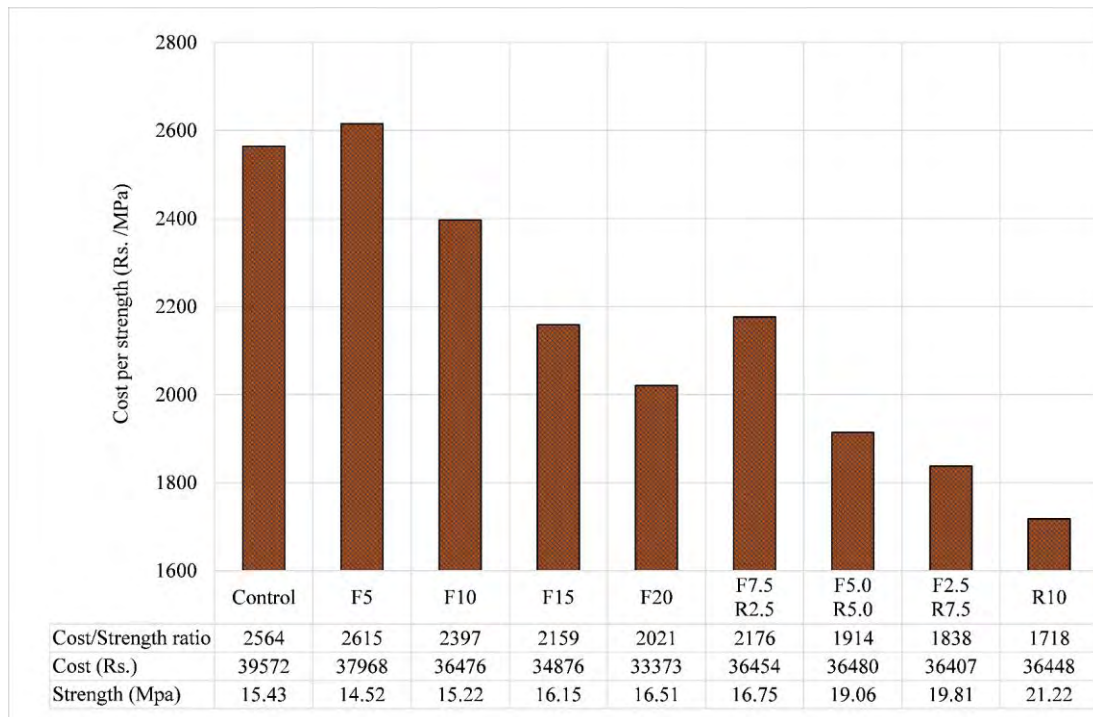


Fig. 8. Cost analysis of pervious concrete with various mix ratios.

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 CO₂ Emission Analysis

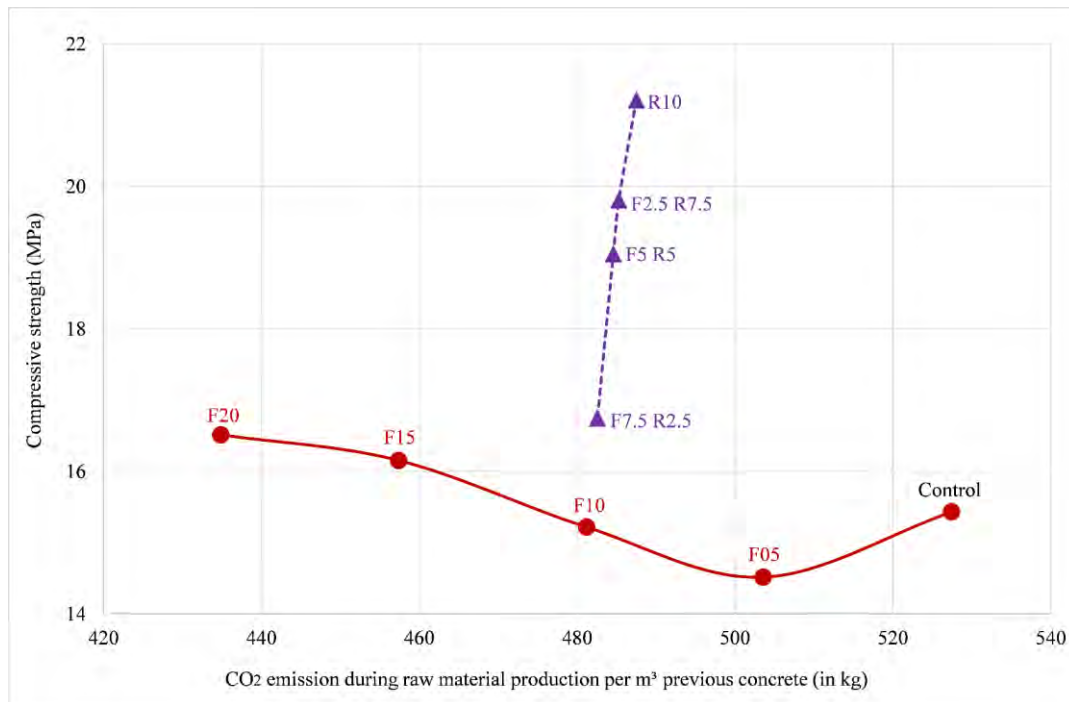


Fig. 9. CO₂ emission analysis of raw material used for pervious concrete with various mix ratios.

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 CO₂ 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 CO₂ emissions [75]. For one-tonne material production of cement, FA, RHA and coarse aggregates, the CO₂ emissions were computed to be 780, 8, 5 and 41 kg, respectively. The CO₂ emissions from material transportation and wet mix stirring were not taken into consideration in this research. Using the above estimations, CO₂ emissions of the raw material production for one-meter cube pervious concrete were computed.

Fig. 9 presents the compressive strength versus CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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.

Acknowledgement

The authors gratefully acknowledge the support provided by the Department of Civil Engineering, Faculty of Engineering, University of Jaffna.

Funding Statement

The authors received no specific funding for this study.

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.

References

- [1] Subramaniam DN, Sathiparan N. Comparative study of fly ash and rice husk ash as cement replacement in pervious concrete: mechanical characteristics and sustainability analysis, *International Journal of Pavement Engineering* 2023; 2: 2075867. <https://doi.org/10.1080/10298436.2022.2075867>.
- [2] Poorveekan K, Ath KMS, Anburuvel A, Sathiparan N. Investigation of the engineering properties of cementless stabilized earth blocks with alkali-activated eggshell and rice husk ash as a binder, *Construction and Building Materials* 2021; 277: 122371. <https://doi.org/10.1016/j.conbuildmat.2021.122371>.
- [3] Sathiparan N. Utilization prospects of eggshell powder in sustainable construction material – A review, *Construction and Building Materials* 2021; 293: 123465. <https://doi.org/10.1016/j.conbuildmat.2021.123465>.
- [4] Chi L, Lu S, Li Z, Huang C, Jiang H, Peng B. Recycling of ferronickel slag tailing in cementitious materials: Activation and performance, *Science of The Total Environment* 2023; 861: 160706. <https://doi.org/10.1016/j.scitotenv.2022.160706>.
- [5] Chi L, Huang C, Li Z, Ruan S, Peng B, Li M, Liang Q, Yin K, Lu S. Heavy metals immobilization of LDH@bi-ochar-containing cementitious materials: Effectiveness and mechanisms, *Cement and Concrete Composites* 2024; 152: 105667. <https://doi.org/10.1016/j.cemconcomp.2024.105667>.
- [6] Sathiparan N, Subramaniam DN. Potential use of crushed waste glass and glass powder in sustainable pervious concrete: A review, *Cleaner Waste Systems*, 2024; 1: 100191. <https://doi.org/10.1016/j.clwas.2024.100191>.
- [7] Bae S, Meral C, Oh J, Moon J, Kunz M, Monteiro PJM. Characterization of morphology and hydration products of high-volume fly ash paste by monochromatic scanning x-ray micro-diffraction (μ -SXRD), *Cement and Concrete Research* 2014; 59: 155-164. <https://doi.org/10.1016/j.cemconres.2014.03.001>.
- [8] Sarker PK, McBeath S. Fire endurance of steel reinforced fly ash geopolymer concrete elements, *Construction and Building Materials* 2015; 90: 91-98. <https://doi.org/10.1016/j.conbuildmat.2015.04.054>.
- [9] Kunchariyakun K, Asavapisit S, Sombatsompop K. Properties of autoclaved aerated concrete incorporating rice husk ash as partial replacement for fine aggregate, *Cement and Concrete Composites* 2015; 55: 11-16. <https://doi.org/10.1016/j.cemconcomp.2014.07.021>.
- [10] Sahmaran M, Yaman IO. Hybrid fiber reinforced self-compacting concrete with a high-volume coarse fly ash, *Construction and Building Materials* 2007; 21(1): 150-156. <https://doi.org/10.1016/j.conbuildmat.2005.06.032>.
- [11] Mayooraan S, Ragavan S, Sathiparan N. Comparative study on open air burnt low- and high-carbon rice husk ash as partial cement replacement in cement block production, *Journal of Building Engineering* 2017; 13: 137-145. <https://doi.org/10.1016/j.jobe.2017.07.011>.
- [12] Seevaratnam V, Uthayakumar D, Sathiparan N. Influence of rice husk ash on characteristics of earth cement blocks, *MRS Advances* 2020; 5(54): 2793-2805. <https://doi.org/10.1557/adv.2020.294>.
- [13] Yoon S, Monteiro PJM, Macphree DE, Glasser FP, Imbabi MSE. Statistical evaluation of the mechanical properties of high-volume class F fly ash concretes, *Construction and Building Materials* 2014; 54: 432-442. <https://doi.org/10.1016/j.conbuildmat.2013.12.077>.
- [14] Siddique R, Kapoor K, Kadri EH, Bennacer R. Effect of polyester fibres on the compressive strength and abrasion resistance of HVFA concrete, *Construction and Building Materials* 2012; 29: 270-278. <https://doi.org/10.1016/j.conbuildmat.2011.09.011>.
- [15] Filho JH, Medeiros MHF, Pereira E, Helene P, Isaia GC. High-volume fly ash concrete with and without hydrated lime: chloride diffusion coefficient from accelerated test, *Journal of Materials in Civil Engineering* 2013; 25(3): 411-418. [https://doi.org/10.1061/\(ASCE\)MT.1943-5533.0000596](https://doi.org/10.1061/(ASCE)MT.1943-5533.0000596).
- [16] Yoshitake BI, Wong H, Ishida T, Nassif AY. Thermal stress of high volume fly-ash (HVFA) concrete made with limestone aggregate, *Construction and Building Materials* 2014; 71: 216-225. <https://doi.org/10.1016/j.conbuildmat.2014.08.028>.
- [17] Yanbo L, Francisco PM. Effect of Elevated Temperature Curing on Compressive Strength and Electrical Resistivity of Concrete with Fly Ash and GGBS, *ACI Materials Journal* 2014; 111(5): <https://doi.org/10.14359/51686913>.
- [18] Silva P, de Brito J. Electrical resistivity and capillarity of self-compacting concrete with incorporation of fly ash and limestone filler, *Advances in concrete construction* 2013; 1(1): 65-84. <https://doi.org/10.12989/ACC.2013.1.1.065>.
- [19] Huang CH, Lin SK, Chang CS, Chen HJ. Mix proportions and mechanical properties of concrete containing very high-volume of Class F fly ash, *Construction and Building Materials* 2013; 46: 71-78. <https://doi.org/10.1016/j.conbuildmat.2013.04.016>.
- [20] Gesoğlu M, Güneyisi E, Özbay E. Properties of self-compacting concretes made with binary, ternary, and quaternary cementitious blends of fly ash, blast furnace slag, and silica fume, *Construction and Building Materials* 2009; 23(5): 1847-1854. <https://doi.org/10.1016/j.conbuildmat.2008.09.015>.

- [21] Mardani-Aghabaglou A, Andiç-Çakir Ö, Ramyar K, Freeze–thaw resistance and transport properties of high-volume fly ash roller compacted concrete designed by maximum density method, *Cement and Concrete Composites* 2013; 37: 259-266. <https://doi.org/10.1016/j.cemconcomp.2013.01.009>.
- [22] Shaikh FUA, Supit SWM. Mechanical and durability properties of high volume fly ash (HVFA) concrete containing calcium carbonate (CaCO₃) nanoparticles, *Construction and Building Materials* 2014; 70: 309-321. <https://doi.org/10.1016/j.conbuildmat.2014.07.099>.
- [23] Yerramala A, Ganesh Babu K. Transport properties of high volume fly ash roller compacted concrete, *Cement and Concrete Composites* 2011; 33(10): 1057-1062. <https://doi.org/10.1016/j.cemconcomp.2011.07.010>.
- [24] Younsi A, Turcry P, Rozière E, Ait-Mokhtar A, Loukili A. Performance-based design and carbonation of concrete with high fly ash content, *Cement and Concrete Composites* 2011; 33(10): 993-1000. <https://doi.org/10.1016/j.cemconcomp.2011.07.005>.
- [25] Anwar M, Miyagawa T, Gaweesh M. Using rice husk ash as a cement replacement material in concrete, in: Woolley, GR, Goumans, JJM, Wainwright, PJ (Eds.), *Waste Management Series*, Elsevier, Amsterdam, 2000; 671-684.
- [26] Bui DD, Hu J, Stroeve P. Particle size effect on the strength of rice husk ash blended gap-graded Portland cement concrete, *Cement and Concrete Composites* 2005; 27(3): 357-366. <https://doi.org/10.1016/j.cemconcomp.2004.05.002>.
- [27] Ganesan K, Rajagopal K, Thangavel K. Rice husk ash blended cement: Assessment of optimal level of replacement for strength and permeability properties of concrete, *Construction and Building Materials* 2008; 22(8): 1675-1683. <https://doi.org/10.1016/j.conbuildmat.2007.06.011>.
- [28] Pavia S, Walker R, Veale P, Wood A. Impact of the Properties and Reactivity of Rice Husk Ash on Lime Mortar Properties, *Journal of Materials in Civil Engineering* 2014; 26(9): 04014066. [https://doi.org/10.1061/\(ASCE\)MT.1943-5533.0000967](https://doi.org/10.1061/(ASCE)MT.1943-5533.0000967).
- [29] Ferraro RM, Nanni A. Effect of off-white rice husk ash on strength, porosity, conductivity and corrosion resistance of white concrete, *Construction and Building Materials* 2012; 31: 220-225. <https://doi.org/10.1016/j.conbuildmat.2011.12.010>.
- [30] Saraswathy V, Song HW. Corrosion performance of rice husk ash blended concrete, *Construction and Building Materials* 2007; 21(8): 1779-1784. <https://doi.org/10.1016/j.conbuildmat.2006.05.037>.
- [31] Silva FGD, Liborio JBL, Helene P. Improvement of physical and chemical properties of concrete with brazilian silica rice husk (SRH), *Revista ingeniería de construcción* 2008; 23: 18-25.
- [32] Chopperla ST, Yamuna V, Bahurudeen A, Santhanam M, Gopinath A. Durability of concrete with agro-waste: a local approach to sustainability, *Green Materials* 2018; 7(2): 84-96. <https://doi.org/10.1680/jgrma.18.00005>.
- [33] Feng Q, Yamamichi H, Shoya M, Sugita S. Study on the pozzolanic properties of rice husk ash by hydrochloric acid pretreatment, *Cement and Concrete Research* 2004; 34(3): 521-526. <https://doi.org/10.1016/j.cemconres.2003.09.005>.
- [34] Aoki Y, Sri Ravindrarajah R, Khabbaz H. Properties of pervious concrete containing fly ash, *Road Materials and Pavement Design* 2012; 13(1): 1-11. <https://doi.org/10.1080/14680629.2011.651834>.
- [35] Saboo N, Shivhare S, Kori KK, Chandrappa AK, Effect of fly ash and metakaolin on pervious concrete properties, *Construction and Building Materials* 2019; 223: 322-328. <https://doi.org/10.1016/j.conbuildmat.2019.06.185>.
- [36] Shafabakhsh G, Ahmadi S. Evaluation of coal waste ash and rice husk ash on properties of pervious concrete pavement, *International Journal of Engineering* 2015; 29(2): 192-201.
- [37] Adamu M, Olalekan SS, Aliyu MM. Optimizing the mechanical properties of pervious concrete containing calcium carbide and rice husk ash using response surface methodology, *Journal of Soft Computing in Civil Engineering* 2020; 4(3): 106-123. <https://doi.org/10.22115/scce.2020.229019.1216>.
- [38] ASTM-C618, Standard specification for coal fly ash and raw or calcined natural pozzolan for use in concrete, ASTM International, West Conshohocken, PA, 2012.
- [39] BS-EN-1097, Tests for mechanical and physical properties of aggregates, British Standards Institution (BSI), London, 2020.
- [40] BS-EN-933, Tests for geometrical properties of aggregates British Standards Institution (BSI), London, 2017.
- [41] Adresi M, Yamani A, Karimaei TM, Rooholamini H. A comprehensive review on pervious concrete, *Construction and Building Materials* 2023; 407: 133308. <https://doi.org/10.1016/j.conbuildmat.2023.133308>.
- [42] Pedram M, Madandoust R, Arabani M. Investigation of the physical and mechanical properties and durability of pervious concrete: a review, *Archives of Civil Engineering* 2022; 68(2): 577-591. <https://doi.org/10.24425/ace.2022.140660>.
- [43] Xie HZ, Li LG, Ng PL, Liu F. Effects of Solid Waste Reutilization on Performance of Pervious Concrete: A

- Review, *Sustainability*, 2023; 15(7): 6105; <https://doi.org/10.3390/su15076105>.
- [44] Khankhaje E, Kim T, Jang H, Kim CS, Kim J, Rafieizonooz M. A review of utilization of industrial waste materials as cement replacement in pervious concrete: An alternative approach to sustainable pervious concrete production, *Heliyon* 2024; 10(4): e26188. <https://doi.org/10.1016/j.heliyon.2024.e26188>.
- [45] Sathiparan N, Dassanayake DHHP, Subramaniam DN. Utilization of supplementary cementitious materials in pervious concrete: a review, *International Journal of Environmental Science and Technology* 2024; 21(6): 5883-5918. <https://doi.org/10.1007/s13762-023-05440-4>.
- [46] BS 1881-102, Testing Concrete - Part 102: Method for Determination of Slump, British Standards Institution, United Kingdom, 1983.
- [47] BS-1377, Methods of test for soils for civil engineering purposes, British Standards Institution (BSI), London, 1990.
- [48] ASTM-C143/C143M, Standard test method for slump of hydraulic-cement concrete, ASTM International, West Conshohocken, PA, 2020.
- [49] ASTM-C1688/C1688M, Standard test method for density and void content of freshly mixed pervious concrete, ASTM International, West Conshohocken, PA, 2014.
- [50] ASTM-C109, Standard test method for compressive strength of hydraulic cement mortars (using 2-in. or [50-mm] cube specimens), ASTM International, West Conshohocken, PA, 2020.
- [51] ASTM-D5084, Standard Test Methods for Measurement of Hydraulic Conductivity of Saturated Porous Materials Using a Flexible Wall Permeameter, ASTM International, West Conshohocken, PA, 2016.
- [52] Song H, Yao J, Xiang J. The role of aggregate and cement paste in the deterioration of the transitional interface zone of pervious concrete during freeze-thaw cycles, *Case Studies in Construction Materials* 2022; 16: e01086. <https://doi.org/10.1016/j.cscm.2022.e01086>.
- [53] Akkaya A, Çağatay İH. Investigation of the density, porosity, and permeability properties of pervious concrete with different methods, *Construction and Building Materials* 2021; 294: 123539. <https://doi.org/10.1016/j.conbuildmat.2021.123539>.
- [54] Gauffinet-Garrault S. The rheology of cement during setting, in: Roussel, N (Ed.), *Understanding the Rheology of Concrete*, Woodhead Publishing, Sawston, 2012; 96-113.
- [55] Fink J. Cement additives, in: Fink, J (Ed.), *Petroleum Engineer's Guide to Oil Field Chemicals and Fluids (Second Edition)*, Gulf Professional Publishing, Boston, 2015; 317-367.
- [56] Boateng AA, Skeete DA. Incineration of rice hull for use as a cementitious material: the guyana experience, *Cement and Concrete Research* 1990; 20(5): 795-802. [https://doi.org/10.1016/0008-8846\(90\)90013-N](https://doi.org/10.1016/0008-8846(90)90013-N).
- [57] Thiedeitz M, Schmidt W, Härder M, Kränkel T. Performance of rice husk ash as supplementary cementitious material after production in the field and in the lab, *Materials* 2020; 13(19): 4319. <https://doi.org/10.3390/ma13194319>.
- [58] Wang H, Li H, Liang X, Zhou H, Xie N, Dai Z. Investigation on the mechanical properties and environmental impacts of pervious concrete containing fly ash based on the cement-aggregate ratio, *Construction and Building Materials* 2019; 202: 387-395. <https://doi.org/10.1016/j.conbuildmat.2019.01.044>.
- [59] Muthaiyan UM, Thirumalai S. Studies on the properties of pervious fly ash–cement concrete as a pavement material, *Cogent Engineering* 2017; 4(1): 1318802. <https://doi.org/10.1080/23311916.2017.1318802>.
- [60] Al-sallami ZHA, Marshdi QSR, Mukheef RAAH. Effect of cement replacement by fly ash and epoxy on the properties of pervious concrete, *Asian Journal of Civil Engineering* 2020; 21(1): 49-58. <https://doi.org/10.1007/s42107-019-00183-5>.
- [61] Hesami S, Ahmadi S, Nematzadeh M. Effects of rice husk ash and fiber on mechanical properties of pervious concrete pavement, *Construction and Building Materials* 2014; 53: 680-691. <https://doi.org/10.1016/j.conbuildmat.2013.11.070>.
- [62] Ramadhansyah P, Masri K, Mangi S, Mohd Yusak M, Mashros N, Mohd Warid M, Satar M, Haziman W. Strength and porosity of porous concrete pavement containing nano black rice husk ash, *IOP Conf. Series: Materials Science and Engineering* 2015; 712: 012037.
- [63] Sathiparan N, Jeyananthan P, Subramaniam DN. Prediction of compressive strength of fly ash blended pervious concrete: A machine learning approach, *International Journal of Pavement Engineering*, 2023; 24(2): 2287146. <https://doi.org/10.1080/10298436.2023.2287146>.
- [64] Talsania S, Pitroda J, Vyas C. Effect of rice husk ash on properties of pervious concrete, *International Journal of Advanced Engineering Research and Studies* 2015; 4(2): 296-299.
- [65] Haji A, Parikh K, Shaikh M, Jamnu M. Experimental investigation of pervious concrete with use of fly ash and silica fume as admixture, *International Journal of Innovative Research in Science and Engineering* 2016; 2(10):

- 154-161.
- [66] Montes F, Valavala S, Haselbach LM. A New test method for porosity measurements of portland cement pervious concrete, *Journal of ASTM International* 2005; 2(1): 1-13. <https://doi.org/10.1520/JAI12931>.
- [67] Cui X, Zhang J, Huang D, Liu Z, Hou F, Cui S, Zhang L, Wang Z. Experimental study on the relationship between permeability and strength of pervious concrete, *Journal of Materials in Civil Engineering* 2017; 29(11): 04017217. [10.1061/\(ASCE\)MT.1943-5533.0002058](https://doi.org/10.1061/(ASCE)MT.1943-5533.0002058).
- [68] Karthik HO. Pervious concrete – An overview, *The Indian Concrete Journal* 2010; 84(8): 9-18.
- [69] BSR, Building schedule of rates Engineering organization western province-provincial council, Sri Lanka, 2019.
- [70] He Z, Zhu X, Wang J, Mu M, Wang Y. Comparison of CO₂ emissions from OPC and recycled cement production, *Construction and Building Materials* 2019; 211: 965-973. <https://doi.org/10.1016/j.conbuildmat.2019.03.289>.
- [71] Jiménez LF, Domínguez JA, Vega-Azamar RE. Carbon footprint of recycled aggregate concrete, *Advances in Civil Engineering* 2018; 1: 7949741. <https://doi.org/10.1155/2018/7949741>.
- [72] Lee JW, Jang YI, Park WS, Yun HD, Kim SW. The effect of fly ash and recycled aggregate on the strength and carbon emission impact of FRCCs, *International Journal of Concrete Structures and Materials* 2020; 14(1): 17. <https://doi.org/10.1186/s40069-020-0392-6>.
- [73] Sathiparan N, Jaasim JHM, Banujan B. Sustainable production of cement masonry blocks with the combined use of fly ash and quarry waste, *Materialia* 2022; 26: 101621. <https://doi.org/10.1016/j.mtla.2022.101621>.
- [74] Sathiparan N. Performance of sustainable cement mortar containing different types of masonry construction and demolition wastes, *Clean Technologies and Environmental Policy* 2023; 26: 1861-1881. <https://doi.org/10.1007/s10098-023-02681-2>.
- [75] Mellado A, Catalán C, Bouzón N, Borrachero MV, Monzó JM, Payá J. Carbon footprint of geopolymeric mortar: study of the contribution of the alkaline activating solution and assessment of an alternative route, *RSC Advances* 2014; 4(45): 23846-23852. <https://doi.org/10.1039/C4RA03375B>.
- [76] ICE, Embodied carbon: The inventory of carbon and energy (ICE), Sustainable Energy Research Team, University of Bath, Bath, United Kingdom, 2011.
- [77] El-Hassan H, Kianmehr P. Sustainability assessment and physical characterization of pervious concrete pavement made with GGBS, *MATEC Web Conf.* 2017; 120.
- [78] Kuruscu A, Girgin Z, Efficiency of structural materials in sustainable design, *Journal of Civil Engineering and Architecture* 2014; 8(10): 1260-1265.
- [79] Meddah MS, Ismail MA, El-Gamal S, Fitriani H. Performances evaluation of binary concrete designed with silica fume and metakaolin, *Construction and Building Materials* 2018; 166: 400-412. <https://doi.org/10.1016/j.conbuildmat.2018.01.138>.
- [80] Park KB, Lin RS, Han Y, Wang XY. Model-based methods to produce greener metakaolin composite concrete, *Applied Sciences* 2021; 11(22): 10704. <https://doi.org/10.3390/app112210704>.
- [81] Alnahhal MF, Alengaram UJ, Jumaat MZ, Abutaha F, Alqedra MA, Nayaka RR. Assessment on engineering properties and CO₂ emissions of recycled aggregate concrete incorporating waste products as supplements to Portland cement, *Journal of Cleaner Production* 2018; 203: 822-835. <https://doi.org/10.1016/j.jclepro.2018.08.292>.
- [82] Pode R. Potential applications of rice husk ash waste from rice husk biomass power plant, *Renewable and Sustainable Energy Reviews* 2016; 53: 1468-1485. <https://doi.org/10.1016/j.rser.2015.09.051>.
- [83] Letelier V, Henríquez-Jara BI, Manosalva M, Parodi C, Ortega JM. Use of waste glass as a replacement for raw materials in mortars with a lower environmental impact, *Energies* 2019; 12(10): 1974. <https://doi.org/10.3390/en12101974>.

Publisher’s Note: Sustainable Development Press Limited (SDPL) remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.