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RESEARCH ARTICLE

Comparative study of fly ash and rice husk ash as cement replacement in pervious concrete: mechanical characteristics and sustainability analysis

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ABSTRACT
Pervious concrete is a special type of concrete consisting of cement, coarse aggregate and water. Cement is a widely used raw material for construction including pervious concrete and had led to the release of huge amounts of CO_2 to the environment. Therefore, there is lot of research interest in finding supplementary cementitious materials. The present study examined and compared the feasibility of using industrial waste fly ash (FA) and agricultural waste rice husk ash (RHA) for sustainable pervious concrete production. An experimental program was performed with substitution of FA and RHA contents of 5%, 10%, 15% and 20% as cement replacement and water to binder ratio of 0.3, 0.35, 0.4 and 0.45. The characteristics of pervious concrete and sustainability analysis were compared for both FA and RHA replacement with control concrete mortar. The results showed that both FA and RHA have a negative effect on permeability. The compressive strength was optimum for FA content lies between 10% and 15% replacement level and RHA content of 5% replacement level. Furthermore, the utilisation of FA and RHA decreased production cost, the total embodied energy and carbon emission, resulting in cost-effective and eco-friendly pervious concrete.

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KEYWORDS
Pervious concrete; fly ash; rice husk ash; cement

1. Introduction

Pervious concrete is a composite material comprising of cement, coarse aggregate and water. It is highly porous and so, is an environment-friendly material that is in great demand in Europe, Japan and North America for the last four decades (Aamer Rafique Bhutta *et al.* 2013). Pervious concrete is used in many applications like parking lots where there is a need for draining and permeating water-reducing surface runoff and thereby improve the environmental performance of the existing site such as maintain the water quality, reduce flooding around the site, increase base flow and reservation of parking areas for the property owner. It is also beneficial as it helps maintain a quiet environment by absorbing the noise of vehicles and also prevent flash of surface and does not glisten at night improving the comfort and safety of drivers. Moreover, the pores of pervious concrete can cumulate heat, adjusting the humidity and temperature of the earth's surface (Yang and Jiang 2003).

At the same time, cement is a widely used raw material for construction and had led to the release of huge amounts of CO_2 to the environment. It is a pressing issue in recent years challenging efforts for a cleaner environment (Poorveekan *et al.* 2021). On the other hand, after COVID 19 pandemic, there is a severe material shortage for the construction industry especially cement in Sri Lanka due to import restrictions. To overcome this issue, researchers have been focusing on finding supplementary cementitious materials. Some of the most regularly used supplementary cementitious materials are granulated blast furnace slag (GBFS) (Özbay *et al.* 2016), fly ash (Hemalatha and Ramaswamy 2017), rice husk ash (RHA) (Fapohunda *et al.* 2017, Mayooran *et al.* 2017, Seevaratnam *et al.* 2020), volcanic pozzolanas (Robayo-Salazar and Mejía de Gutiérrez 2018), silica fume (Khan and Siddique 2011), metakaolin (Saand *et al.* 2016), limestone (Panesar and Zhang 2020) and eggshell powder (Sathiparan 2021). Generally, the use of particular supplementary cementitious material depends on several factors such as local availability, quality and transportation cost. In Sri Lanka (present study area), except rice husk ash, fly ash and limestone, other materials are not readily available or in very limited supply to satisfy the demand. On the other hand, limestone is not geographically distributed and only available in the northern part of the country and transportation of it over a long distance could compensate for the environmental benefits of using it as supplementary cementitious material.

There are several studies on fly ash as supplementary cementitious materials in pervious concrete, and Table 1 summarises the recent studies conducted on fly ash incorporated pervious concrete. Al-sallami *et al.* (2020) investigated the effect of using fly ash and epoxy as partial replacement for cement in pervious concrete. In addition, the effect of sand as a partial replacement for gravel and gravel to cement ratio was also evaluated. Results showed that porosity was marginally decreased while compressive strength significantly increased for 30% fly ash replacement for cement. However, the increment in porosity and reduction in compressive strength were observed for 50% fly as replacement for cement.

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Table 1. Summary of the recent studies conducted on fly ash incorporated pervious concrete.

Reference	c/a	Fly ash replacement (%)	w/b	Aggregate size (mm)	Porosity range (%)	Compressive strength range (MPa)	Permeability range (mm/s)
(Al-sallami *et al.* 2020)	0.17	0, 30, 50	0.45	10–20	19.8–35.3	3.0–12.6	–
(Wang *et al.* 2019)	0.22	0, 10, 20, 30, 40	0.31	2.36–13.2	20.9–23.3	20.1–25.7	6.1–7.1
(Saboo *et al.* 2019)	0.20	0, 5, 10, 15, 20	0.33	4.75–9.5	23.5–34.5	3.8–9.5	–
(Peng *et al.* 2018)	0.19	0, 10, 20, 30	0.35	16–19	25.0–35.2	3.1–11.1	4.4–25.0
(Muthaiyan and Thirumalai 2017)	0.15	0, 10, 20	0.30	4.75–19	16.7–28.6	8.5–13.8	3.5–16.5
(Haji *et al.* 2016)	0.25	0, 5, 10, 15, 20, 25	0.44	4.75–20	–	19.4–27.3	16.3–23.5
(Aoki *et al.* 2012)	0.40	0, 20, 50	0.35	–	32.0–36.0	12.1–15.9	5.66–10.1

c/a, cement to aggregate ratio; w/b, water to binder ratio.

Saboo *et al.* (2019) studied fly ash as a partial supplementary cementitious material in pervious concrete under different curing conditions. Results revealed that the curing period had a weak effect on the characteristics of pervious concrete and fly ash replacement level had a strong influence on the properties of pervious concrete.

Wang *et al.* (2019) studied the influence of cement to aggregates and fly ash on the physical and mechanical properties of pervious concrete. Results show that incorporating fly ash improved the mechanical properties of pervious concrete when the fly ash replacement level was less than 30% of cement.

Mohammed *et al.* (2018) explored the effect of nano-silica on the properties of fly ash incorporated pervious concrete. Results showed that high FA replacement in the fresh mortar resulted in higher flow value and longer setting time. When fly ash content increases, the porosity of cementitious paste increased and the compressive strength of pervious concrete decreased. Also, the finding indicates that the inclusion of nano-silica in pervious concrete improved the compressive strength without affecting the porosity and permeability.

Peng *et al.* (2018) investigated the hydraulic and mechanical properties of pervious concrete containing fly ash and blast furnace slag. Results show that both fly ash and blast furnace slag decreased the effective porosity, permeability coefficient and compressive strength. Also, when fly ash and blast furnace slag content increased, the reduction rate of hydraulic and mechanical properties values was larger.

Muthaiyan and Thirumalai (2017) investigated the characteristic of pervious concrete with the variation of fly ash as partial replacement for cement (0, 10 and 20%), fine aggregates replacement for coarse aggregates (0, 5, 10, 15%) and addition of plasticiser. Results show that the incorporation of fly ash has an effect of reduction in compressive strength, porosity and permeability. A similar finding was also reported by Sata *et al.* (2016), where the increase in fly ash replacement level slightly reduced the compressive and flexural tensile strength of pervious concrete.

Haji *et al.* (2016) investigated the effect of aggregates size and fly ash content on permeability and compressive strength of pervious concrete. Results show that the use of coarse aggregate increases the porosity but reduces the compressive strength. On the other hand, increasing the replacement of fly ash from 5 to 25% shows a decrease in compressive strength by 4–28% compared with the control samples. Also, permeability decreased by 30% compared to control samples for 25% fly ash replacement.

Aoki *et al.* (2012) investigated the properties of pervious concrete containing 0, 20, 50% fly ash as cement replacement. Results indicated that fly ash replacement in pervious concrete has neither affected the density nor porosity. However, for higher fly ash replacement (50%) for cement, the compressive strength decreased by more than 40%.

Rice husk ash is another supplementary cementitious materials material commonly used in construction materials such as convention concrete (Siddika *et al.* 2021), self-compacting concrete (Haruna and Adamu 2012), cement mortar (Ambas *et al.* 2015) and stabilised earth blocks (Muntohar 2011). Table 2 summarised the recent studies conducted on RHA incorporated pervious concrete.

Adamu *et al.* (2021) experimentally investigated the hydraulic and mechanical properties of pervious concrete comprising rice husk ash and calcium carbide as cement replacement. Results show that permeability of the pervious concrete decreased significantly with increasing RHA replacement. The compressive strength of pervious concrete increased with increasing RHA replacement.

Shafabakhsh and Ahmadi (2015) examined the usage of RHA and coal waste ash in pervious concrete. The optimum RHA replacement was 8%, where pervious concrete achieved the maximum mechanical properties. For the 8% RHA replacement, compared with the control sample, the compressive, flexural and splitting tensile strength increased by 41, 29 and 42%, respectively.

Ramadhansyah *et al.* (2020) evaluated the properties of pervious concrete containing nano-black RHA. Results found that the compressive strength of pervious concrete increased up to 10% RHA replacement level and then began to decrease for higher RHA replacement level. On the other hand, porosity increased with an increase in RHA replacement.

Hesami *et al.* (2014) investigated the mechanical properties of the pervious containing RHA as cement replacement and glass fibre, steel fibre and polyphenylene sulphide fibre used as reinforcement. Results show that the optimum RHA replacement was 8% for specimens without fibre and 8–10% for specimens with fibres. The compressive, tensile and flexural strengths of pervious concrete with 12% RHA replacement were slightly less than those of 10% of RHA replacement. However, permeability is significantly higher for pervious concrete with 12% RHA replacements than those with 10% RHA replacement. Therefore, the study recommended the pervious concrete with 12% RHA replacement was more suitable for pavement construction.

The disposal of waste generated is an environmental problem in several countries like Sri Lanka (Thanushan and Sathiparan 2022). Recycling and reusing these wastes in engineering applications is one of the sustainable solutions to overcome environmental issues due to the damping of these wastes. Among them, industrial waste fly ash, and agricultural waste rice husk ash, are available abundantly throughout Sri Lanka. In Sri Lanka, around 200,000 metric tons of fly ash per

Table 2. Summary of the recent studies conducted on RHA incorporated pervious concrete.

Reference	c/a	RHA replacement (%)	w/b	Aggregate size (mm)	Porosity range (%)	Compressive strength range (MPa)	Permeability range (mm/s)
(Adamu *et al.* 2021)	0.18	0, 5, 10, 15, 20	0.40	12.5	–	5.3–9.5	9.6–11.0
(Talsania *et al.* 2015)	0.25	0, 10, 20	0.30, 0.35, 0.40	4.75–20	–	7.9–11.0	–
(Shafabakhsh and Ahmadi 2015)	0.23	0, 2, 4, 6, 8, 10, 12	0.34	2.36–12.5	15.0–22.4	14.5–20.6	2.1–2.7
(Ramadhansyah *et al.* 2020)	0.40	0, 10, 20, 30, 40	0.34	20	14.7–23.9	22.9–27.8	–
(Hesami *et al.* 2014)	0.23	0, 2, 4, 6, 8, 10, 12	0.27, 0.33, 0.40	2.36–19	9–29	13.6–29.8	0.8–4.5

c/a, cement to aggregate ratio; w/b, water to binder ratio.

annum are produced from Norochcholai coal power plant, which is the main source of power that meets around 50% of the electricity requirement of the country (Gimhan *et al.* 2018). The disposal of this fly ash is a challenge as fly ash generated here contains heavy metals such as arsenic. Therefore, they should be dumped in a specially designed landfill, where the drinking water supplies are not affected by the leaching of heavy metals. Also, storing fly ash in landfills can be possibly hazardous if the filled embankment collapsed. Therefore, recycling fly ash in construction materials can reduce the environmental footprint due to fly ash dumping. Also, when fly ash is used as cement replacement for construction materials, it can save cost and energy in the construction industry. According to the Central Bank Report 2019 (Lanka), on average, one million metric tons of rice husk (RH) per annum is produced in Sri Lanka. In recent years, rice husk waste use for power generation. Roughly one ton of rice husk waste can generate 800 kW h of electric power (Pode 2016). During electric power generation for RH biomass power plants, rice husk produces ash and almost one-quarter of the rice husk will transform into ash. These generated RHA generally end up as waste and it has little commercial value. Disposal of RHA also induces several environmental issues as RHA does not biodegrade easily (Riza and Rahman 2015). As RHA is of amorphous silica, it has a potential application in construction industry.

Considering both cost and environmental issues pertaining to the usage of cement and disposal of waste, it is always recommended to use potential wastes as a supplementary cementitious material in construction activities. The present study focuses on using widely available waste materials; FA and RHA as cement replacement in pervious concrete. Published literature shows wide-ranging studies on hydraulic and mechanical properties of pervious concrete with fly ash and RHA as partial replacement for cement. To the best of author's knowledge, comparative study between fly ash and RHA is still scarce in contemporary literature. Even though past studies recommended the water to cement ratio around 0.33 for conversional pervious concrete, FA and RHA may alter water demand for the fresh mortar and it may affect hydraulic and mechanical properties of pervious concrete. Therefore, varying water to binder ratio, which is crucial in the strength of pervious concrete, have to studied.

Considering the above discussion, this study aims to compare mechanical characteristics of pervious concrete, where the waste materials: fly ash and rice husk ash are used as supplementary cementitious materials. A comprehensive experimental program was developed including varying fly ash and RHA as cement replacement as 0, 5, 10, 15 and 20% with water to binder ratio varying as 0.3, 0.35, 0.4 and 0.45. The experimental program comprised of determination of fresh mortar properties (slump), physical parameters (density and porosity), hydraulic parameter (permeability) and

Table 3. Mechanical properties of aggregate.

Properties	Test standard	Value
Bulk density (kg/m^3)	BS-EN-1097 (2020)	1491
Specific gravity	BS-EN-1097 (2020)	2.72
Absorption (%)	BS-EN-1097 (2020)	0.20
Moisture content (%)	BS-EN-1097 (2020)	0.35
Aggregate Impact value – AIV (%)	BS-EN-1097 (2020)	25.5
Aggregate Crushing Value – ACV (%)	BS-EN-1097 (2020)	30.5
Flakiness Index	BS-EN-933 (2017)	14.7
Elongation Index (%)	BS-EN-933 (2017)	24.02


(a) Cement (b) Fly ash (c) Rice husk ash (d) Aggregates

Figure 1. Raw materials used for casting of pervious concrete mix.

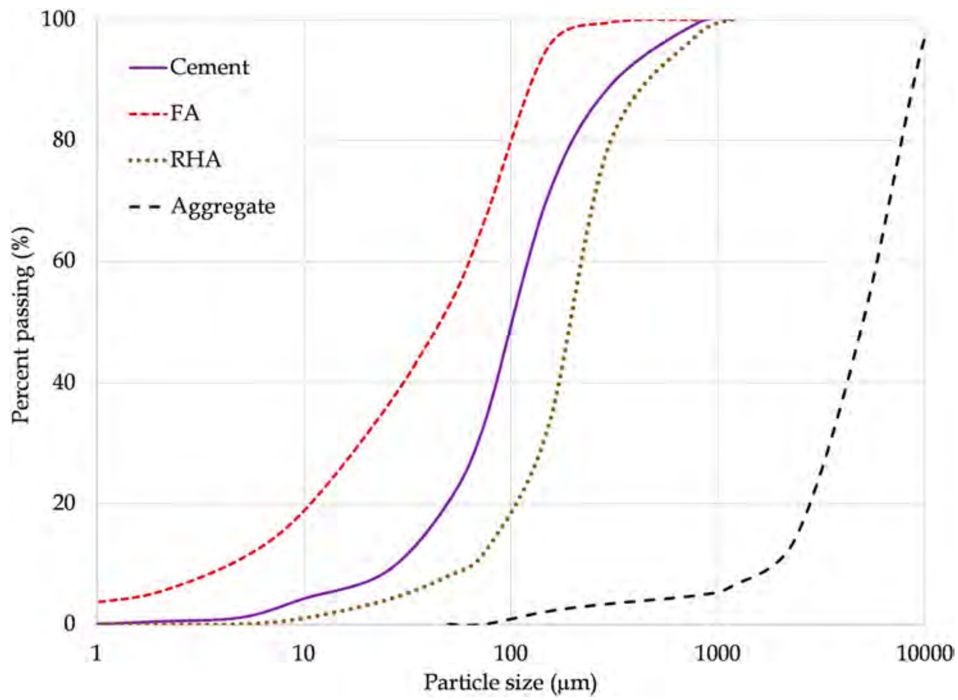

Figure 2. Particle size distribution of raw materials.

mechanical parameter (compressive strength). To evaluate the sustainability of FA and RHA used in pervious concrete, cost analysis, embodied energy requirement and carbon emission analysis were calculated and compared with control mortar.

2. Materials and methods

2.1. Material used

Figure 1 illustrates raw materials used for casting of pervious concrete mix. Ordinary Portland Cement (OPC) as the primary binding material was used. Fly ash (FA) was received from Nuraicholai Coal Power Plant in Puttalam, Sri Lanka and it was sieved through 300-micron before being used for the casting of fresh mortar. Rice husk ash (RHA) was obtained from Ampara, Sri Lanka and it was sieved through 800-micron sieves.

Table 4. Composition of chemical component and physical characteristic of cement, FA and RHA.

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

The aggregates used in this study are natural granite-gneisses rock of igneous origin from Western Province of Sri Lanka. The aggregate was sieved thoroughly and the size of aggregates between 5 and 10 mm was used in casting pervious concrete. The tests for loose bulk density, specific gravity, moisture content, water absorption, aggregate crushing value (ACV), aggregate impact value (AIV), elongation index and flakiness index were conducted on aggregates according to BS standards (BS-EN-933 2017, BS-EN-1097 2020). Table 3 summarises the tested properties and corresponding standards used. The test results indicate that the aggregates are of adequate quality to be used as coarse aggregates in pervious concrete production.

The particle size distribution of the material used is given in Figure 2. Table 4 summarised the physical properties and chemical composition of cement, fly ash and rice husk ash used in the present experimental program. The main components of FA are SiO_2 and Al_2O_3 and on the other hand, for RHA, it is SiO_2. For both FA and RHA, the percentage of CaO is less than 10%.

2.2. Mix design

The mixed proportion of materials used for pervious concrete mortar is detailed in Table 5. Aggregate to binder ratio equals 2.5 used for all mixes. Cement was partially substituted by supplementary cementitious materials, FA and RHA in 5, 10, 15 and 20% increments individually and in combinations. Binder with 100% cement was used as a control mix to compare the effect of the FA and RHA in the mortar mix. All replacement levels, water to binder ratio varying from 0.3 to 0.45 with 0.05 increments were applied to check the impact of water to binder ratio on properties of pervious concrete. Based on recommendation provide for permeable pavements by Permeable

Table 5. Mix design for experiment program.

Mix ID	Variables (%) Cement	FA	RHA	Quantities (kg/m^3) Cement	FA	RHA	Aggregate	Water to Binder ratio
Control	100	–	–	544.0			1360	0.30, 0.35, 0.40, 0.45
FA05	95	5	–	516.8	27.2		1360	
FA10	90	10	–	489.6	54.4		1360	
FA15	85	15	–	462.4	81.6		1360	
FA20	80	20	–	435.2	108.8		1360	
RHA5	95	–	5	516.8		27.2	1360	
RHA10	90	–	10	489.6		54.4	1360	
RHA15	85	–	15	462.4		81.6	1360	
RHA20	80	–	20	435.2		108.8	1360	

Pavements Task Committee (Eisenberg *et al.* 2015), target porosity in the present study set as 18–22%.

Cubes with the size of 150×150×150 mm were used to measure the density, porosity and compressive strength. For permeability measurement, cylindrical specimen of 100 mm diameter and 150 mm height was used. The compaction was done in three layers and five blows from standard protector hammer was delivered for each layer. To make an even surface on the sample, a wooden board was placed on the top of the mould and struck lightly with a tamping rod.

2.3. Testing

The slump of the fresh concrete mixture was measured according to ASTM-C143/C143M (2020) with a total cone height of 300 mm as shown in Figure 3(a). The slump of pervious concrete fresh mix is conventionally expected to be zero, so as to ensure the passage of fluid through the entire vertical profile. Higher slump contrives sinking of binder material to the bottom of the casting mold and seal the bottom face, objecting transfer of fluids. In this study, slump test is done to ensure that the slump was zero in the mix adopted for subsequent experiments. Mass of concrete mixture in a cube was measured and the wet density was computed by dividing it by the volume of the cube according to ASTM-C1688/C1688M (2014). The compressive strength of hardened concrete was measured according to ASTM-C109 (2020). For each mortar mix composition, six cubes were tested at curing age of 7 and 28 days for compressive strength using a Universal Testing Machine (UTM). The axial load was applied at a rate of displacement of 1 mm/min as shown in Figure 3(b).

Figure 3(c) illustrates the test set-up employed to quantify the permeability of pervious concrete samples. A cylinder specimen of 100 mm diameter and 150 mm height was placed

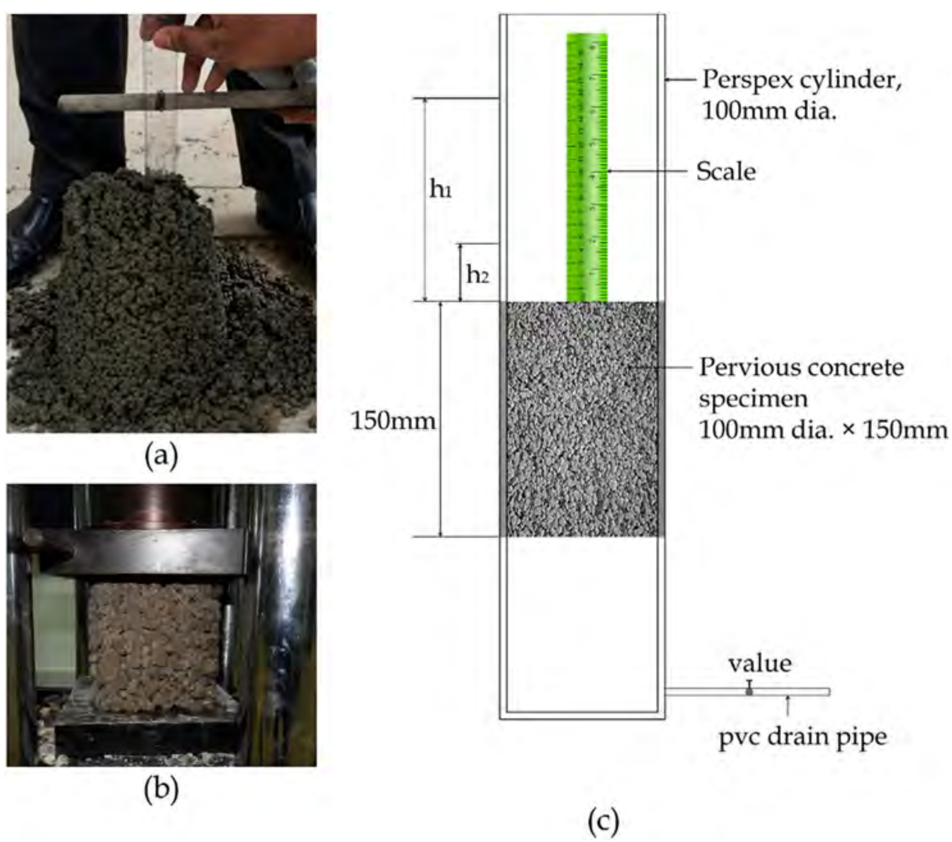

Figure 3. Testing for (a) slump, (b) compression and (c) permeability.

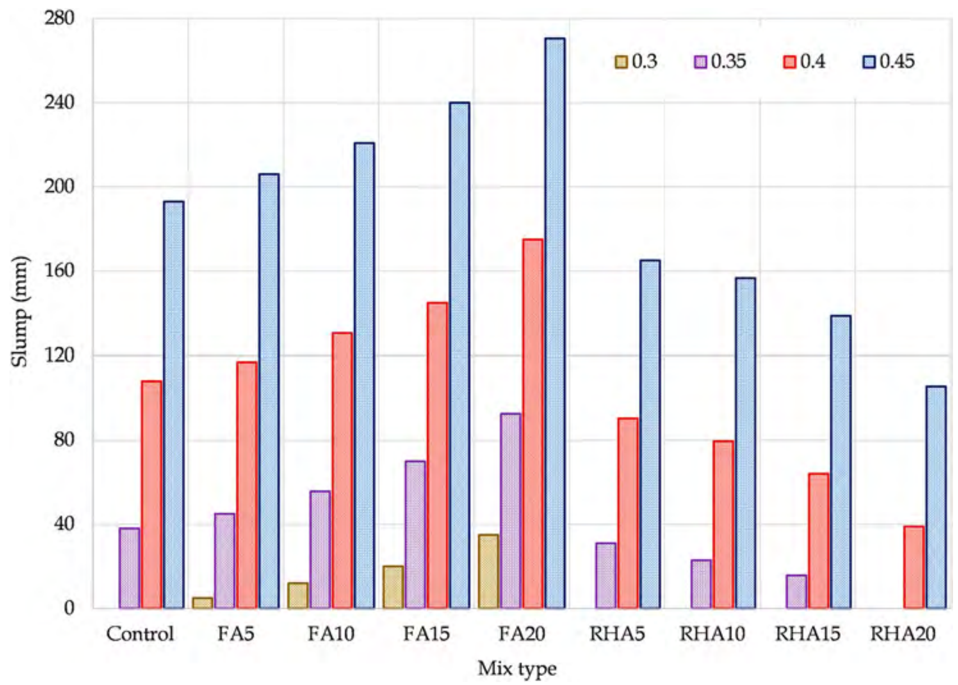

Figure 4. Slump variation of fresh mortar mix.

in between two Perspex tubes. With pvc drain pipe valve is closed, the top Perspex tube is filled with water. Then the valve is opened and time (t) taken for water falling from head h_1 to h_2 was measured. The test was repeated three times and the average value was calculated. The permeability coefficient was calculated using Equation (1)

$$K = \log(h_1/h_2) \times (A_1 \times l)/(A_2 \times t) \quad (1)$$

where A_1 and A_2 are the cross-sectional area of the specimen and drain pipe, respectively. In addition, the porosity of the pervious concrete cubes was measured by water replacement method. The cube sample was dipped into a tank of known dimensions that was partially filled with water and the displacement of the level of water upon dipping the sample was measured. The volume of water displaced indicated the volume of solids, where the remaining volume indicated porosity. In this method, however, the pores that are not connected to the surface would be included as the solid volume

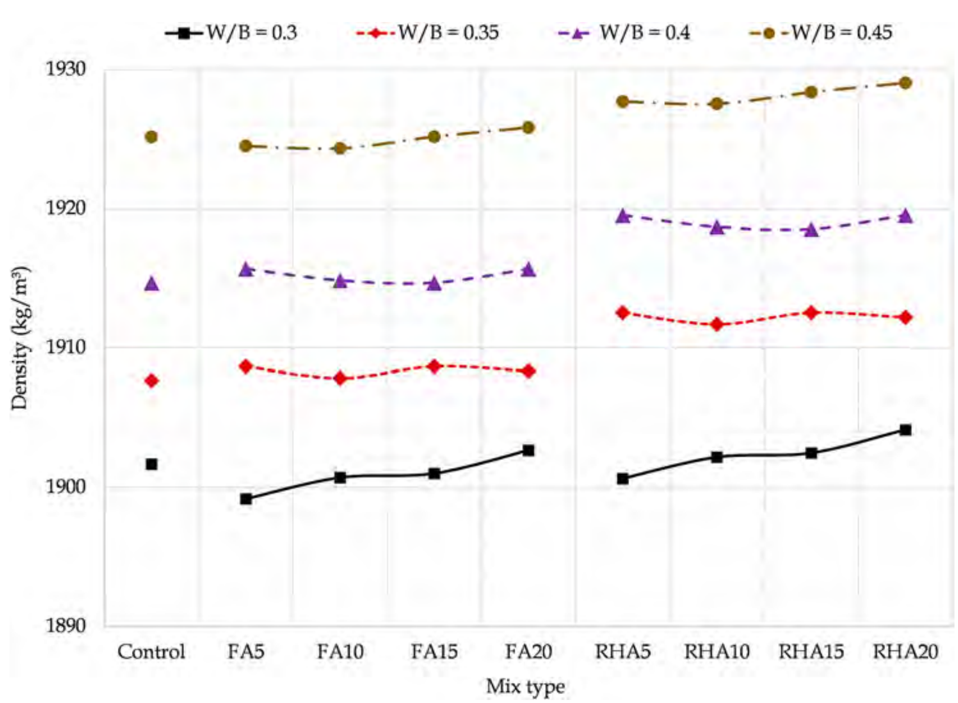

Figure 5. Density variation of hardened pervious concrete.

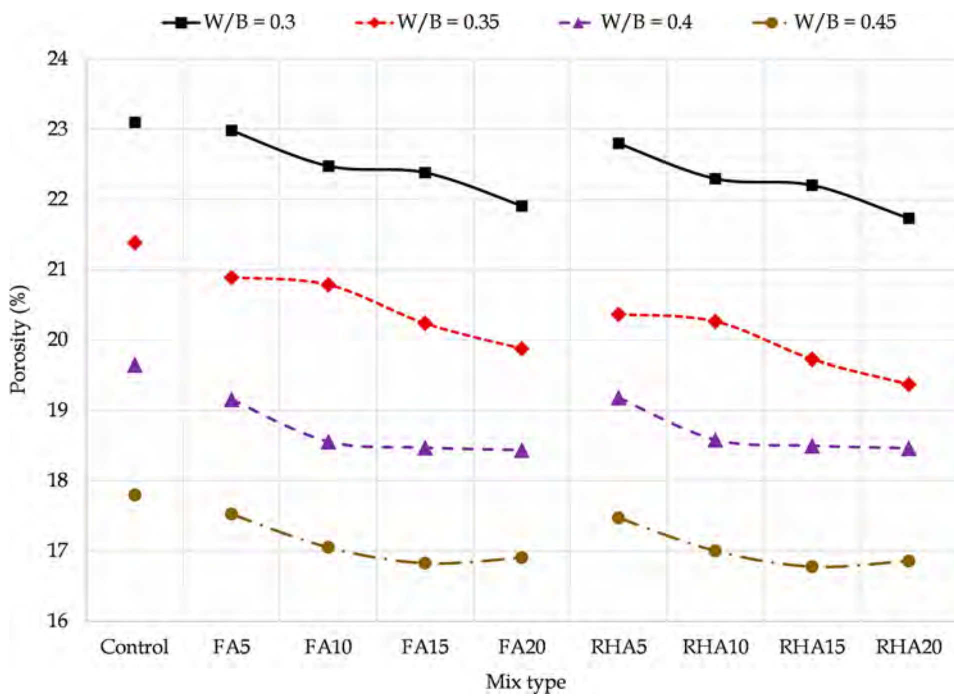

Figure 6. Porosity variation of hardened pervious concrete.

(Anburuvel and Subramaniam 2022, Sajeevan *et al.* 2022, Subramaniam *et al.* 2022).

3. Results and discussion

3.1. Effect FA and RHA on properties of pervious concrete

3.1.1. Slump

Workability of the mortar mix mainly depends on particle size, specific surface area, the shape and texture of particles and water absorption characteristics of raw material used for the fresh mix. The slump for various FA and RHA content as well as water to binder ratio (w/b) is presented in Figure 4. The overall trend was that the slump increased with water to binder ratio and increased with higher FA content, but reduced with higher RHA content.

The slump value is equal to zero for the control mixture with a w/b of 0.3. For the same w/b ratio, the slump was increased to 5, 12, 20 and 35 mm for mixtures with 5, 10, 15 and 20% of FA replacement. Fresh mortar of pervious concrete conventionally has a lower slump, normally less than 20 mm,

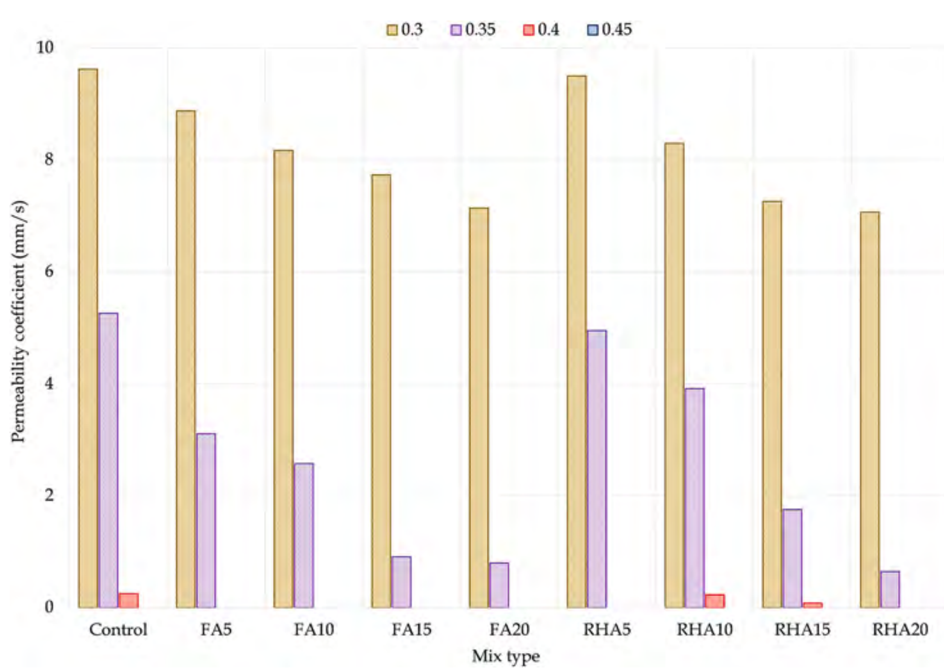

Figure 7. Permeability coefficient variation of hardened pervious concrete.

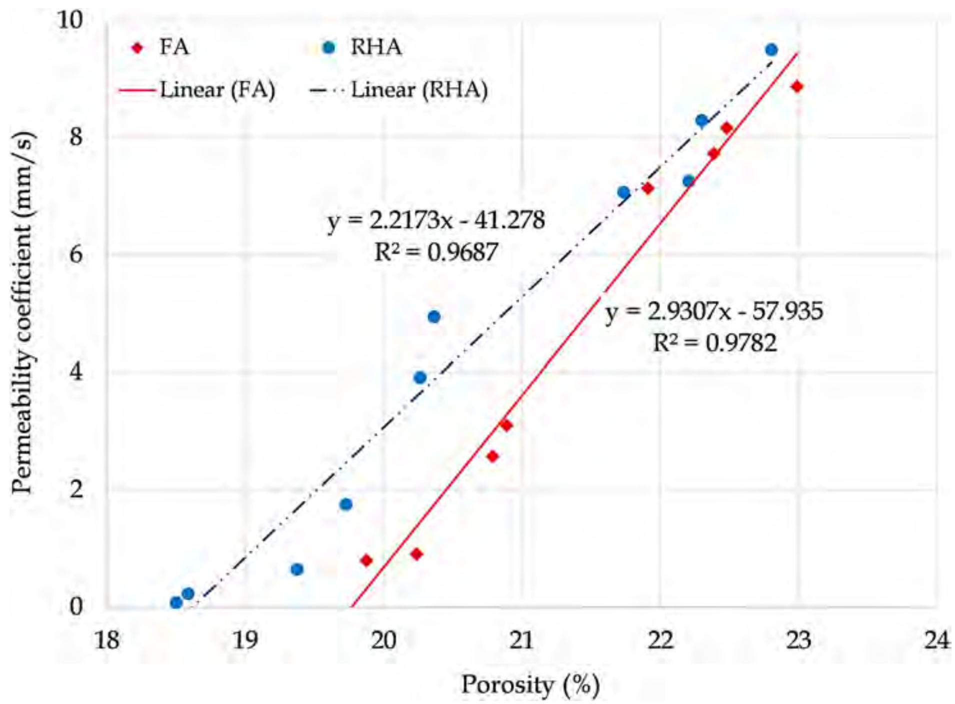

Figure 8. Correlation between permeability and porosity.

while slumps as high as 50 mm have been occasionally used (Nguyen *et al.* 2014, Obla and Sabnis 2015). Therefore, it is shown that even for higher FA replacement (20%) with w/b of 0.3, an acceptable slump was observed. However, for w/b of 0.35, only for control and 5% FA replacement had slump less than 50 mm and for higher FA replacement, the slump was more than 50 mm. For w/b of 0.4 and 0.45, the slump was higher than 100 mm for control and all FA replacement levels. When FA is added to the mixture, its spherical-shaped particles have an effect similar to miniature ball bearings within the cement-aggregates mix, which act as a lubricant and therefore with less amount of water, the mixture gets the desirable workability.

On the other hand, the replacement of RHA in the fresh mortar has reduced the slump. For w/b of 0.3, all RHA replacement, the slump was zero. Even for w/b of 0.35, the slump was less than 50 mm and the values are shown as 31, 23, 16 and 0 mm for mixtures with 5, 10, 15 and 20% of RHA

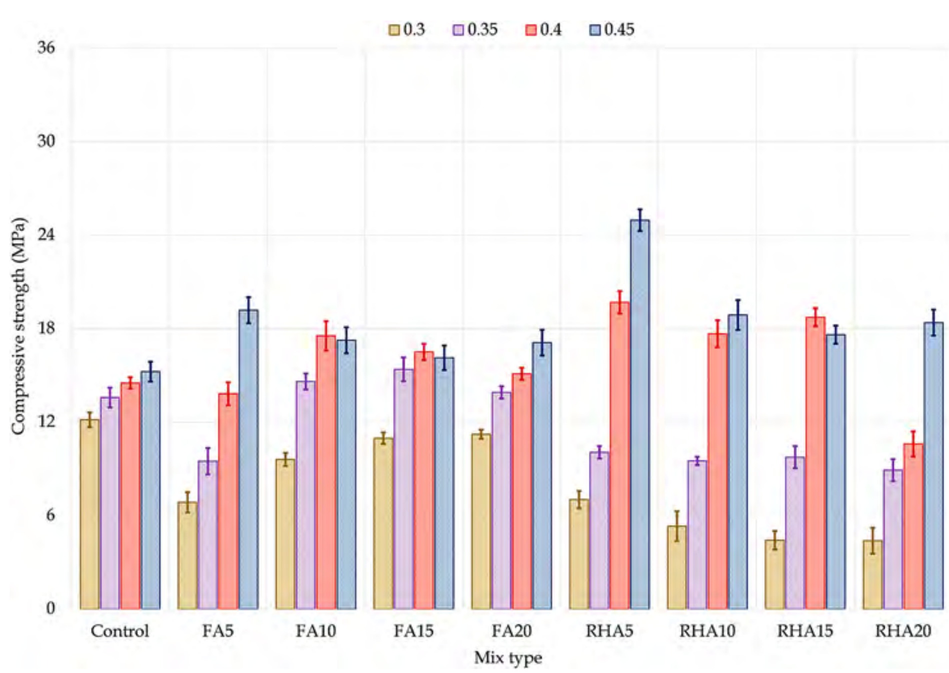

Figure 9. Compressive strength variation of the pervious concrete after 7 days.

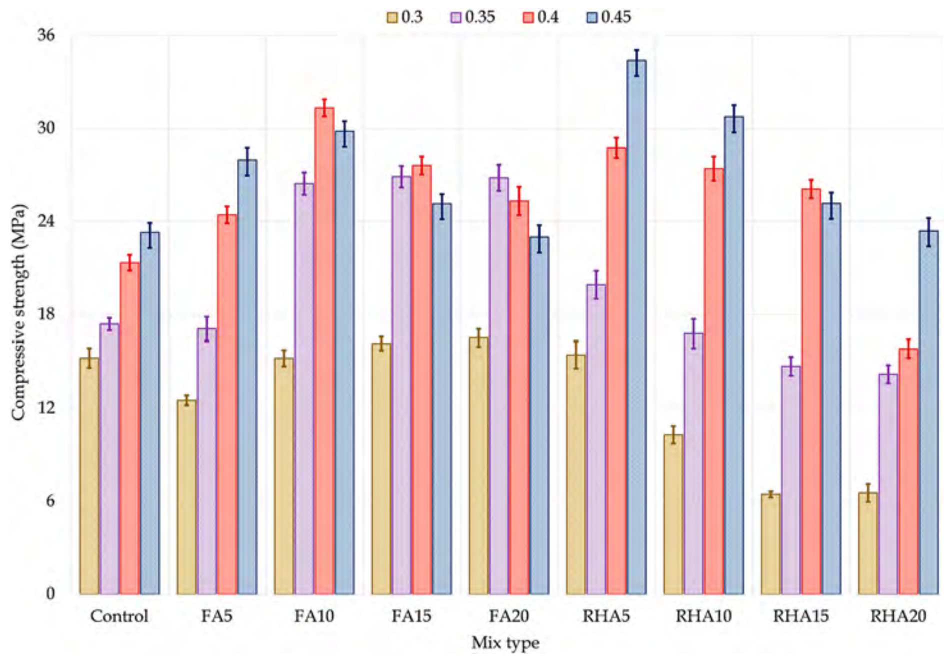

Figure 10. Compressive strength variation of the pervious concrete after 28 days.

replacement. However, for a higher w/b ratio, except for the mixture with 20% RHA replacement and w/b of 0.4, all other mixes showed slump of more than 50 mm. When RHA replaced cement in the mixture, the volume of RHA increased due to its lower density. Therefore, mixtures required more water to get the desired workability.

3.1.2. Density and porosity

Figure 5 illustrates the effect of FA and RHA replacements as well as the w/b ratio on the density of the hardened pervious concrete. The density value for 0.3, 0.35, 0.40 and 0.45 water to cement of control mixes were 1902, 1908, 1915 and 1925 kg/m^3. The results showed that even though FA and RHA have lesser specific gravity than cement, their replacement does not significantly affect the density of pervious concrete.

Substitution of 20% of cement by an alternative filler would alter the density by approximately 1% (according to calculations). In addition, the increase in the volume of binder due to replacement of cement by lighter fillers such as FA

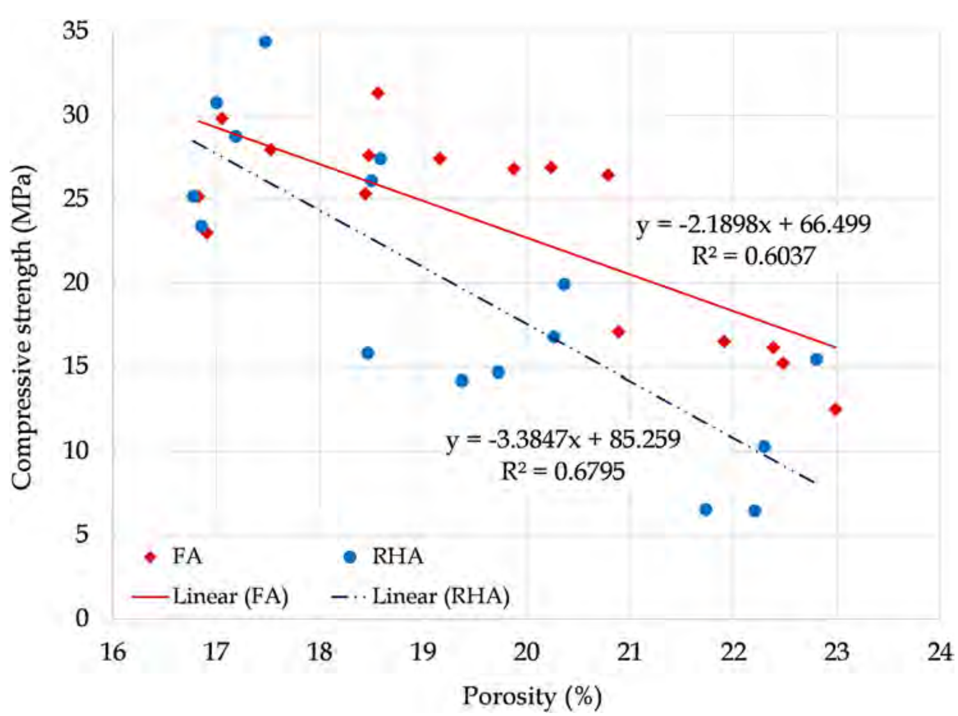

Figure 11. Correlation between compressive strength and porosity.

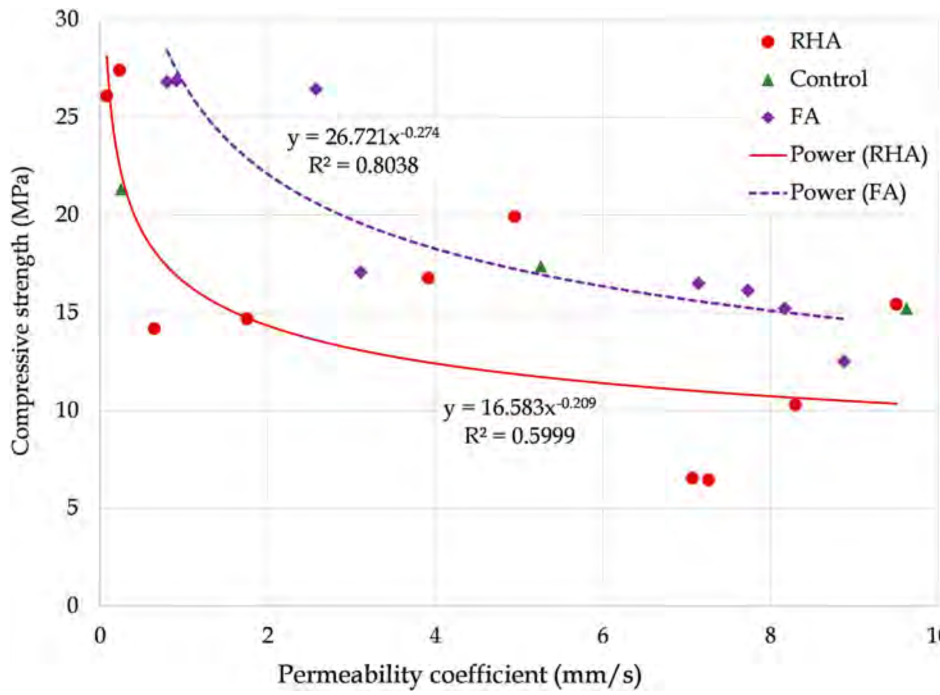

Figure 12. Correlation between compressive strength and permeability coefficient.

and RHA may also lead to filling of pores, which does not contribute to an increase in the volume of the cube. Hence, an increase in the density maybe even more compromised that is insignificant.

Figure 6 illustrates the effect of FA and RHA replacement as well as the w/b ratio on the porosity of the hardened pervious concrete. The average porosity is around 20%, while a slight variation in porosity was recorded with an increase in FA and RHA content. It is evident that porosity is significantly affected by the w/b ratio, while there is a slight reduction in porosity due to FA or RHA replacement for cement. The rheology of the binder would have an impact from the inclusion of fillers, reducing the viscous effect of the concrete mix. Reduction in viscosity increases the ease with which the binder and aggregate mix rearrange during application of compaction energy. This would in turn assist movement of binder around the aggregates and to fill the pores, when compaction is applied. This eventually reduces the porosity of the pervious concrete. The increase in the RHA content resulted in a decrease of slump, specifically in higher W/C ratios (0.4 and 0.45). Simultaneously, this does not have any significant impact on the density (a change of approximately 1 kg/m^3). However, the porosity does decrease by approximately 1.5%, primarily due to replacement of cement with less dense RHA, by mass. Replacing cement with less density RHA by mass increases the volume of material included, that in turn increases the binder volume. This will lead to filling of pores with the excessive binder available. This will result in reduction of porosity. The bulge in volume due to replacement of cement with less dense fillers would in turn effect a thicker coating, which is also less viscous. Upon compaction, the binder would move to fill the pores to a higher degree compared

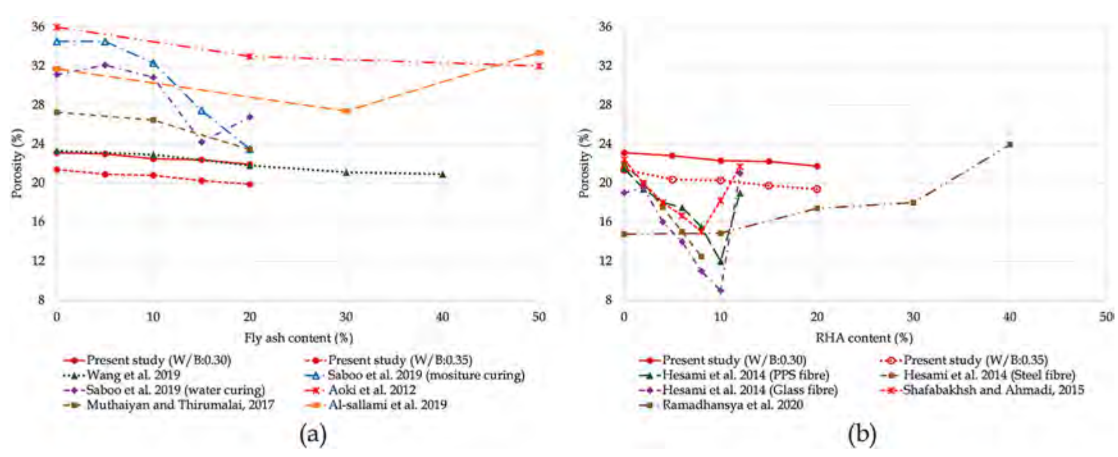

Figure 13. Porosity variation with (a) fly ash and (b) RHA replacement, data extracted from present study and published literature (Aoki *et al.* 2012, Hesami *et al.* 2014, Shafabakhsh and Ahmadi 2015, Muthaiyan and Thirumalai 2017, Saboo *et al.* 2019, Wang *et al.* 2019, Al-sallami *et al.* 2020, Ramadhansyah *et al.* 2020).

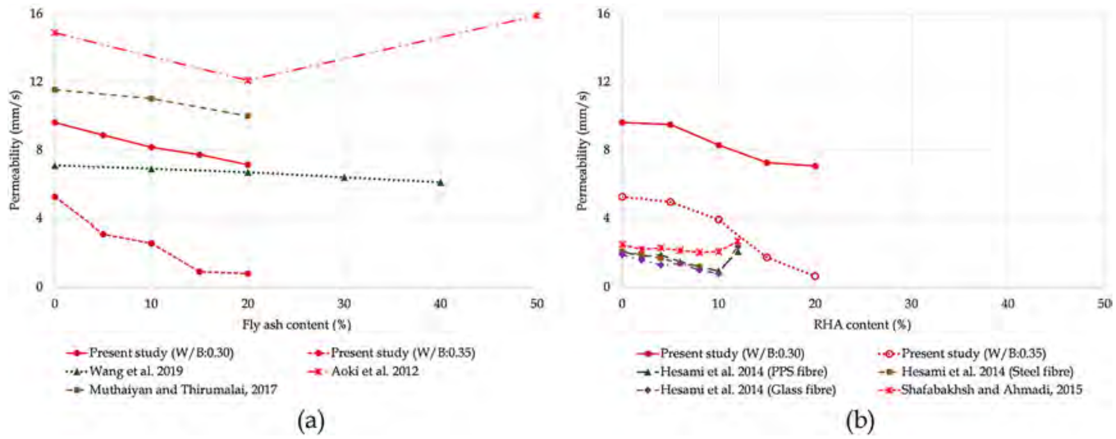

Figure 14. Permeability variation with (a) fly ash and (b) RHA replacement, data extracted from present study and published literature (Aoki *et al*. 2012, Hesami *et al*. 2014, Shafabakhsh and Ahmadi 2015, Muthaiyan and Thirumalai 2017, Wang *et al*. 2019).

to the binder with cement and water alone. This may have caused a slight reduction in porosity of pervious concrete.

3.1.3. Permeability

The most important property of pervious concrete is its capability to allow water to permeate through the voids. The permeability coefficient of pervious concrete mainly depends on the porosity and pore structure. Figure 7 illustrates the permeability coefficient of pervious concrete with FA and RHA replacement. The permeability coefficient for control samples of pervious concrete was 9.61, 5.26 and 0.25 mm/s for w/b ratio of 0.3, 0.35 and 0.4, respectively. For w/b of 0.45, it had been observed to be zero.

Permeability is the measure of transmissibility of pervious concrete to fluids percolation. This essentially requires connection of pores, specifically in the vertical profile of the sample. Therefore, increase in porosity would essentially mean increase in porosity. As seen from Figure 8, it is clear that the increase in porosity, effected an increase in permeability. The trend is congruent to the trend that of the porosity, discussed above. With an increase in FA and RHA content (substitution of cement), the porosity decreases due to the increase in the volume of binder. The decrease in porosity reduces the ability of the sample in transmitting fluids, as observed as a reduction in permeability of the sample. Increase in W/C ratio increase the slump of mix design, that eventually reduced the porosity of samples. This observation is reflected as rapid decrease in permeability, as shown in the figure. Although the permeability would increase with an increase in porosity, the relationship would not be linear as porosity permeability gets affected by capillary effect, that again depends on the pore shape and size. When the porosity reduces, the pore size and the shape of pores also change significantly, affecting the permeability to a higher extent. This results in a rapid decrease in porosity for incremental decrease in porosity.

In Figure 8, it can also be noted that, the fitted trendline shows that permeability becomes zero when porosity is less 18.6 and 19.7% for RHA and FA replaced mortar. Permeability would generally not be linearly correlated to porosity, as the reduction in pore sizes will increase the capillary effect which restraints water percolation. However, within a short range of porosity variation, the relationship could be considered linear, as indicated by very high coefficient of correlation in Figure 8. On such occasions, extrapolation of the relationship over long-range may not be advisable. Yet in this case, it could be observed that the permeability reaches a point, where the percolation of water could be considered insignificant, which occurs within the range.

3.1.4. Compressive strength

When supplementary cementitious materials replace cement, there are both benefits and adverse effects on compressive strength. On the beneficial side, amorphous silica in FA or RHA can react with calcium hydroxide ($Ca(OH)_2$), which is a product of cement hydration, to form calcium silicate hydrate (C–S–H) gel. This is called pozzolanic reaction, and it is much slower than the cement hydration process. The cement hydration and pozzolanic reaction are given by Equations (2) and (3)

$$Ca_3SiO_5 + H_2O \rightarrow C - S - H + Ca(OH)_2 \tag{2}$$

$$Ca(OH)_2 + SiO_2 + H_2O \rightarrow C - S - H \tag{3}$$

However, the additional C–S–H gel is formed only for a limited amount of FA or RHA. For a higher amount of FA or RHA, due to decrease of calcium hydroxide (due to a decrease in cement content in the mix) and an excessive amount of silica in the mix, there would not be enough $Ca(OH)_2$ to react with the silica to form C–S–H gel. Therefore, the replacement of supplementary cementitious materials is beneficial only up to an optimum level of replacement.

Figures 9 and 10 illustrate the 7th and 28th days compressive strength of pervious concrete with FA and RHA replacement. In the case of FA, the optimum strength lies between 10% and 15% replacement level. On other hand, for RHA replacement, optimum strength occur around 5% replacement level.

The results also reveal that cubes with FA and RHA replacement have lesser early strength (7 days) compared with 28th-day compressive strength. This is due to the hydration process, which requires Ca^{2+} for the formation of C–S–H in the mix to reach saturation. When FA or RHA replaced cement in the

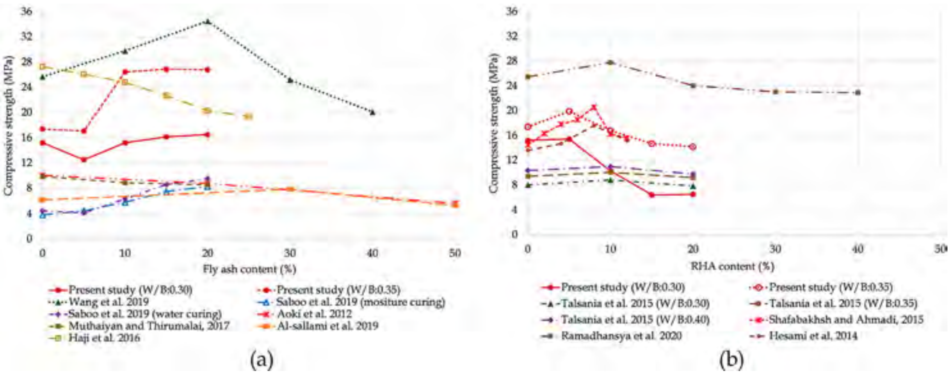

Figure 15. Compressive strength variation with (a) fly ash and (b) RHA replacement, data extracted from present study and published literature (Aoki *et al.* 2012, Hesami *et al.* 2014, Talsania *et al.* 2015, Haji *et al.* 2016, Shafabakhsh and Ahmadi 2016, Muthaiyan and Thirumalai 2017, Saboo *et al.* 2019, Wang *et al.* 2019, Al-sallami *et al.* 2020, Ramadhansyah *et al.* 2020).

mix, Ca^{2+} was observed on the surface of the FA and RHA particles. Therefore, the time it takes for the amount of Ca^{2+} concentration in the mix to reach saturation was delayed. Therefore, it delayed the early age hydration process and affected the early age strength too. However, when comparing FA and RHA, the particle size of FA is smaller than that of RHA, and therefore FA acted as nucleation and contributed to the hydration process. When w/b of 0.3 is considered, the 28th to 7th day compressive strength ratio for control was 1.25. The ratio was varied between 1.47–1.83 for FA and 1.49–2.20 for RHA, respectively. A similar trend was observed for higher w/b as well.

The 28th compressive strength of control pervious concrete ranged from 15.23 to 23.3 MPa. Generally, pervious concrete with porosity of more than 20% and concrete with a compressive strength of more than 13 MPa can be used for paving parking lots (Khankhaje *et al.* 2016, Sherwani *et al.* 2021). Therefore, w/b of more than 0.35, would not be suitable for control samples of pervious concrete. The compressive strength of the pervious concrete with FA ranging from 12.52 to 16.51 MPa and 17.09 to 26.89 MPa were achieved at w/b of 0.3 and 0.35, respectively. However, pervious concrete with 20% FA replacement and w/b of 0.35 showed lower than 20% of porosity. Therefore, optimum compressive strength for pervious concrete with FA was 26.89 MPa and was achieved at 15% FA replacement level with a w/b of 0.35. On the other hand, the compressive strength of the pervious concrete with RHA ranging from 6.54 to 15.44 MPa and 14.19 to 19.92 MPa were achieved at w/b of 0.3 and 0.35, respectively. However, for pervious concrete with 15 and 20% RHA replacement and w/b of 0.35 showed lower than 20% of porosity. Therefore, optimum compressive strength for pervious concrete with RHA was 19.92 MPa and was achieved at 5% RHA replacement level with w/b of 0.35. Also, all levels of FA and RHA replacement with w/b of 0.4 and 0.45 showed less than 20% porosity.

Table 6. Statistical analysis of the studied parameters of the pervious concrete.

Dependent variables	Independent variables	Sequential sum of squares	*F*-value	*P*-value	Significance[a]	Contribution (%)
Slump	w/b	165,316.81	371.31	0.000	✓	85.1
	FA	9387.26	21.08	0.000	✓	4.8
	RHA	5250.58	11.79	0.002	✓	2.7
	Error	14,247.15				7.3
	Total	194,201.80				
Density	w/b	3042.22	1731.65	0.000	✓	96.8
	FA	0.03	0.02	0.899	✓	0.0
	RHA	43.35	24.68	0.000	✓	1.4
	Error	56.22				1.8
	Total	3141.82				
Porosity	w/b	140.36	810.81	0.000	✓	91.6
	FA	2.68	15.45	0.000	✓	1.7
	RHA	4.71	27.21	0.000	✓	3.1
	Error	5.54				3.6
	Total	153.29				
Compressive strength	w/b	1058.76	66.49	0.000	✓	62.8
	FA	4.72	0.30	0.590	×	0.3
	RHA	113.08	7.10	0.012	✓	6.7
	Error	509.54				30.2
	Total	1686.10				
Permeability coefficient	w/b	315.77	122.35	0.000	✓	75.0
	FA	13.34	5.17	0.030	✓	3.2
	RHA	9.23	3.58	0.068	×	2.2
	Error	82.59				19.6
	Total	420.94				

[a]Significance: statistically significance of the effects due to independent parameters.

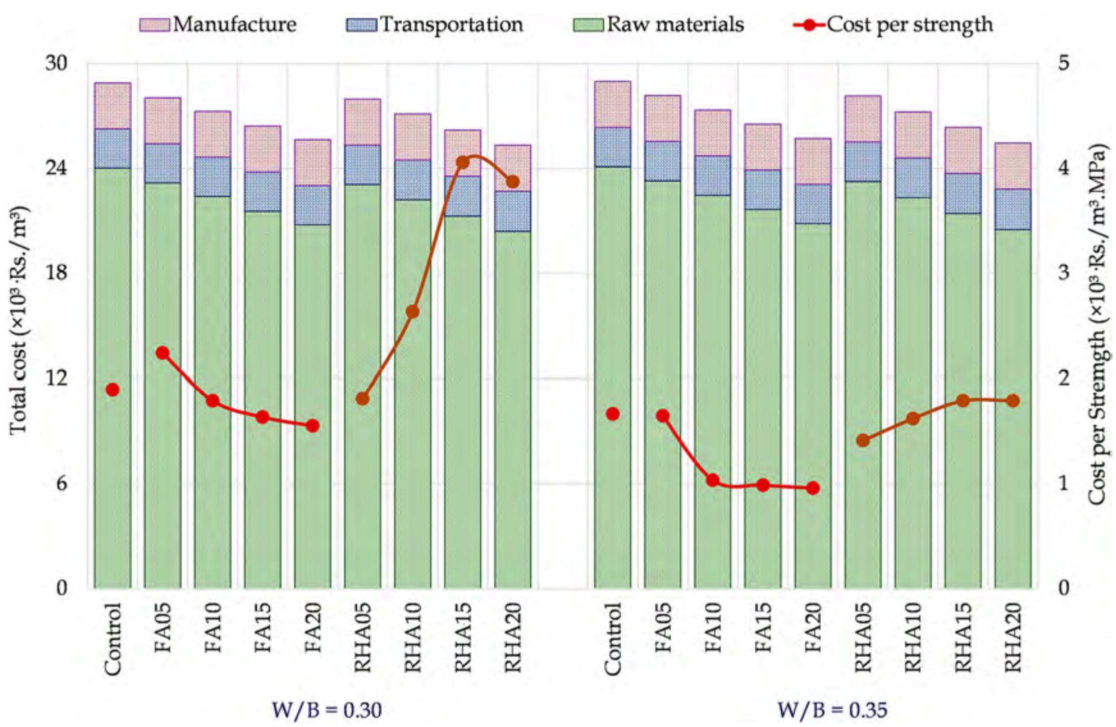

Figure 16. Cost analysis for various mixes of pervious concrete.

The scatter plots are presented in Figures 11 and 12 for identifying the relationship and understanding the goodness of fit of compressive strength with porosity and permeability coefficient, respectively. As evident from Figure 12, it can be seen that compressive strength reduced with an increase in porosity. However, the goodness of fit between compressive strength and porosity was relatively lower, which may be due to compressive strength being affected by extraneous factors such as the bond between binding material and aggregates, the surface texture of the materials used, to name a few.

Similar to porosity, compressive strength reduced with an increase in permeability coefficient and followed the power law to describe the goodness of fit. Compared with RHA, FA incorporated pervious concrete showed higher goodness of fit between compressive strength and permeability coefficient.

3.1.5. Comparison with previous studies

Figure 13(a) and (b) illustrates the variation of porosity with fly ash and RHA replacement level, from the data extracted from present study and published literature. For FA replacement, published findings except Saboo *et al.* (2019), agree with the trend observed from present study. In that case, Saboo *et al.* (2019), the specimens used were kept in the wet curing (water kept under water) for 28 days. On the other hand, experimental program conducted by Al-sallami *et al.* (2020) showed that, the porosity decreased with increase in FA replacement up to 30%, but for higher FA replacement (50%), it shows an increasing trend in porosity. For RHA replacement, the trend observed in the present study agrees with published literature for only low-level RHA replacement (less 10%). However, for the replacement level more than 10%, it showed an increasing trend in the porosity.

Figure 14(a) and (b) illustrates the variation of permeability with fly ash and RHA replacement level, from the data extracted from present study and published literature. For FA replacement, both present study and published literature showed similar trends up to 20% FA, where permeability had decreased with increasing FA content. The experimental program conducted by Aoki *et al.* (2012) showed that, the permeability decreased for FA replacement up to 20%, but for higher FA replacement (50%), it shows an increasing trend in permeability. For RHA replacement, the trend observed in the present study agrees with published literature for only low-level RHA replacement (less 10%). However, for the replacement of 12% RHA shown higher permeability than those of 10% RHA replacement.

Figure 15(a) and (b) illustrates the variation of compressive strength with fly ash and RHA replacement level, from the data extracted from present study and published literature. The results of present study agrees with the trend reported by Wang *et al.* (2019) and Saboo *et al.* (2019), where optimum FA replacement was 20% for enhanced compressive strength. However, other studies (Aoki *et al.* 2012, Haji *et al.* 2016, Muthaiyan and Thirumalai 2017, Al-sallami *et al.* 2020) showed a decreasing trend in permeability with increasing fly ash replacement content. For RHA replacement, both present study and published literatures showed similar trends as compressive strength increased with RHA replacement content and reach the optimum at 5–10% RHA replacement. Then the compressive strength decreased with increasing RHA replacement.

3.2. Statistical analysis

Analysis of Variance (ANOVA) was employed to check the impact of independent variables (water to binder ratio, FA

Table 7. Equivalent energy embodied and CO_2 emission for each material (per kg).

Material	Raw material production		Transportation			Ref.
	Embodied energy (MJ/kg)	CO_2 emission (CO_2.kg/kg)	Distance (km)	Embodied energy[a] (MJ/kg)	CO_2 emission [a] (CO_2.kg/kg)	
Cement	4.5	0.73	200	0.48	0.03	(ICE 2011)
FA	0.1	0.008	200	0.48	0.03	(ICE 2011)
RHA	0.0083	0.0048	20	0.048	0.003	(Pode 2016)
Aggregates	0.01	0.001	250	0.6	0.0375	(ICE 2011)
Water		0.000196	–	–	–	(Kelechi *et al.* 2022)

[a]The Bath Inventory of Carbon and Energy (ICE 2011) recommends embodied energy of 2.4 MJ/ton.km and CO_2 emission of 0.15 kg/ton.km for road transport.

content and RHA content) on dependent variables slump, density, porosity, 28th-day compressive strength and permeability coefficient. SPSS software was used for this analysis. The statistical analysis was done using a general linear model (GLM-ANOVA) and the significant level of 0.05 was used to determine the important parameter, which affects the physical and mechanical characteristics of the pervious concrete. The significance of the independent variable on the outcome of the dependent variables was decided by $P < 0.05$. The impact of each independent variable was analysed by dividing the sequential sum of squares of a particular variable by the total value. As shown in Table 6, the results indicated that the w/b ratio had a significant impact on all properties of pervious concrete as P-value was observed to be approximately zero. Also, RHA content showed significant influence on all the properties except permeability coefficient, and on the other hand, FA content significantly influenced slump, porosity and permeability coefficient. When the contribution of the independent variables on properties was considered, the w/b ratio had a greater impact compared with FA and RHA replacement levels. Regarding comparing the contribution of FA and RHA, FA had a better impact on slump and permeability; and RHA had a better impact on density, porosity and compressive strength.

3.3. Cost analysis

To evaluate the cost benefits of FA and RHA as alternative cementitious materials in pervious concrete, the total cost for raw material consumption transportation of raw material and manufacturing for each mix composition with w/b of 0.3 and 0.35, was computed. The raw material consumption was calculated in terms of cement, FA, RHA and aggregate required for one ton of pervious concrete production. The price of cement and FA obtained from the local market as SLR 1375 and SLR 400 per 50 kg bag, respectively. The price of cement and FA obtained from the local market as SLR 1375 and SLR 400 per 50 kg bag, respectively. Although RHA is a waste material, preparation of RHA for pervious concrete production required direct costs such as transportation and grinding. The cost of coarse aggregates, based on the local market is SLR 3700 per 1-m^3. The cost of water is SLR 45.67 per meter cube, based on charge proposed by Sri Lankan water board (Dharmaratna and Parasnis 2012). Based on these,

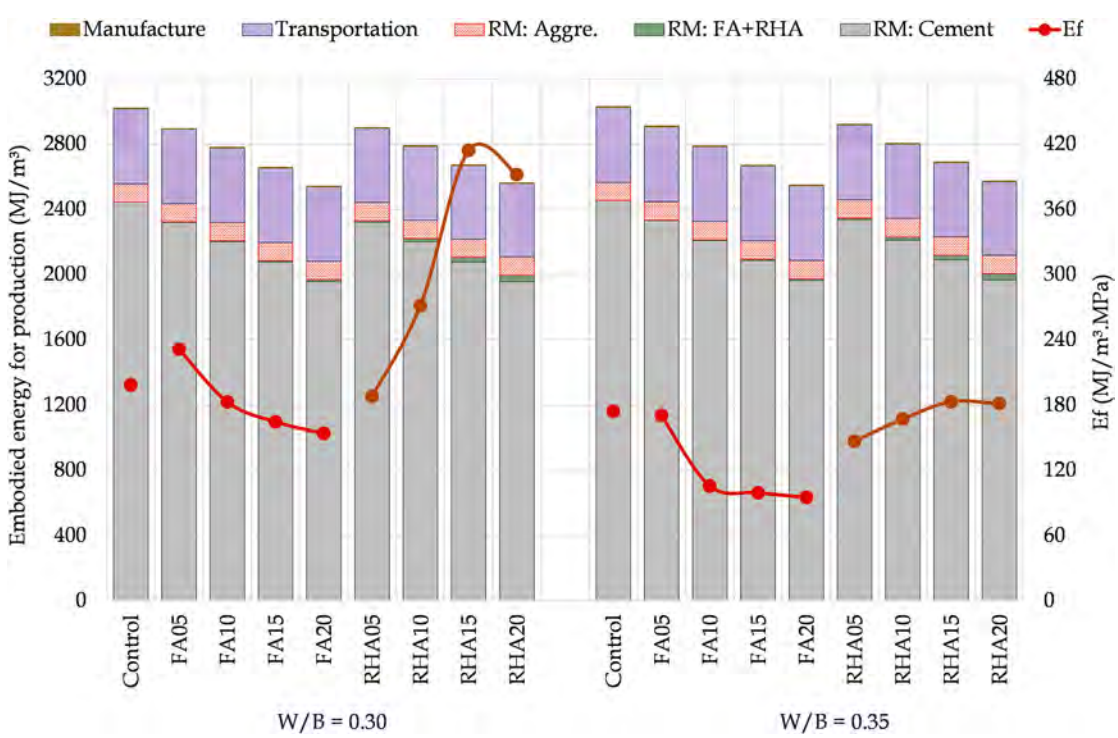

Figure 17. Embodied energy analysis for various mixes of pervious concrete.

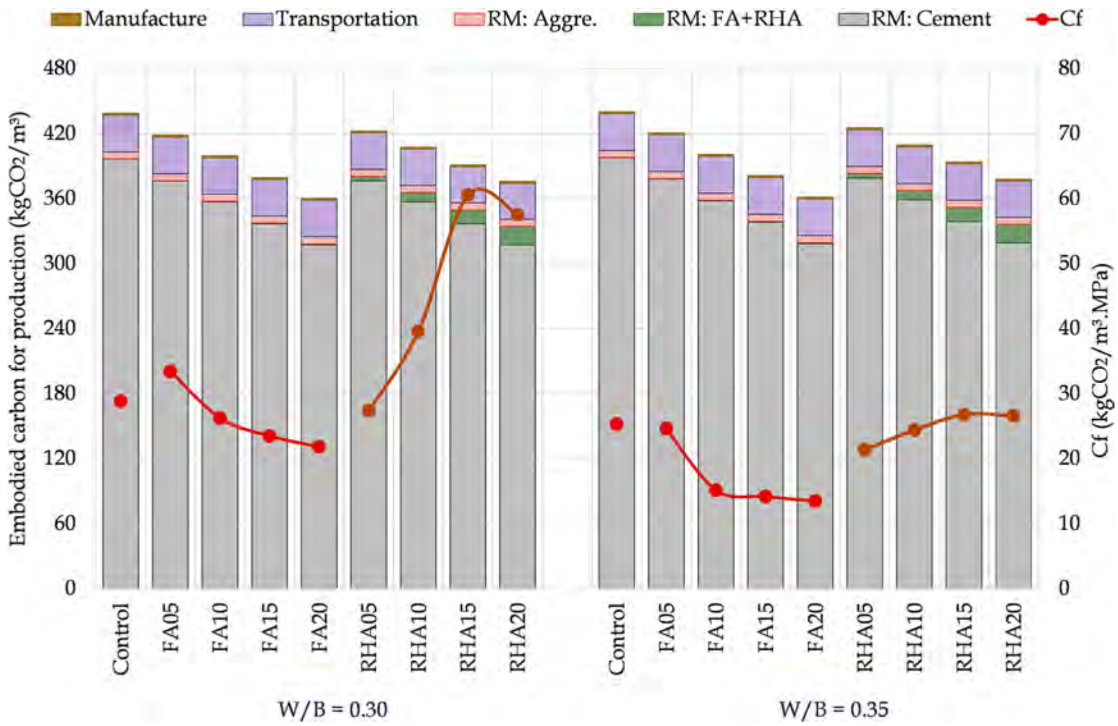

Figure 18. Carbon emission analysis for various mixes of pervious concrete.

the cost of 1 kg of cement, FA, RHA coarse aggregates and water is SLR were 27.50, 8.00, 7.58 2.48 and 0.05, respectively. For transportation of raw materials, SLR 157 (US$ 1.02) per 1-m^3 /1 km is used according to the building schedule of rates of Sri Lanka (BSR 2019). Manufacturing cost include the machine cost and labour cost and labour unit rates for construction works was for the calculation (BSR 2019).

Figure 16 illustrates the total production cost for 1 m^3 of pervious concrete and the cost per m^3 to strength ratio. Compared to the control mortar, total cost was reduced as FA and RHA content percentage increased in the mix. However, when the cost to strength ratio was considered, for w/b of 0.3, FA content of 10, 15 and 20%, and RHA content of 5% was observed to be cost-effective than the control mortar. In the case of w/b ratio of 0.35, in addition to above-mentioned ratio, FA content of 5% and RHA content of 10% also showed cost-effectiveness. Both w/b ratios, FA content of 20% are observed to be most cost-effective compared with control blocks, where the reduction in cost per strength is equal to 18.1% and 42.4% for w/b of 0.3 and 0.35, respectively.

3.4. Benefit analysis of environmental ecology

Energy consumption and carbon dioxide emissions are two factors that contribute to environmental issues in any

Table 8. Summary of the results.

w/b	Mix	Den Kg/m^3	Perm. mm/s	fc MPa	cost Rs./m^3.MPa	Ef MJ/m^3.MPa	Cf Kg.CO_2/m^3.MPa
0.30	Control	1,901.7	9.6	15.2	1,897.2	198.5	28.8
	FA05	1,899.2	8.9	12.5▼	2,240.7▲	231.4▲	33.4▲
	FA10	1,902.3	8.2	15.2	1,792.0▼	182.9▼	26.3▼
	FA15	1,899.8	7.7	16.2▲	1,635.9▼	164.7▼	23.5▼
	FA20	1,902.7	7.1	16.5▲	1,553.0▼	154.0▼	21.8▼
	RHA05	1,899.0	9.5	15.4▲	1,811.8▼	188.1▼	27.4▼
	RHA10	1,902.2	8.3	10.3▼	2,634.1▲	271.3▲	39.6▲
	RHA15	1,899.7	7.3	6.5▼	4,056.9▲	414.3▲	60.6▲
	RHA20	1,902.5	7.1	6.5▼	3,873.1▲	391.9▲	57.5▲
0.35	Control	1,907.7	5.3	17.4	1,666.4	174.4	25.3
	FA05	1,908.7	3.1	17.1▼	1,648.8▼	170.5▼	24.6▼
	FA10	1,907.8	2.6	26.4▲	1,034.1▼	105.6▼	15.2▼
	FA15	1,908.7	0.9	26.9▲	987.0▼	99.4▼	14.2▼
	FA20	1,908.3	0.8	26.8▲	959.1▼	95.2▼	13.5▼
	RHA05	1,912.5	4.9	19.9▲	1,413.2▼	146.8▼	21.4▼
	RHA10	1,911.7	3.9	16.8▼	1,623.0▼	167.3▼	24.4▼
	RHA15	1,912.5	1.8	14.7▼	1,792.2▲	183.1▲	26.8▲
	RHA20	1,912.2	0.6	14.2▼	1,792.8▲	181.5▲	26.6▲

▲- value greater than control mortar, ▼- value lower than control mortar
Color code: Green – positive effect and Red – negative effect

cementitious material production. In the present study, energy resource requirement and carbon emissions during the production stage of pervious concrete are determined and two parameters E_f and C_f were calculated using Equations (4) and (5) (Hu *et al.* 2020).

$$E_f = \frac{E \cdot \text{energy (MJ/ton)}}{f_c} \tag{4}$$

$$C_f = \frac{E \cdot CO_2 \text{ (kg } CO_2\text{J/ton)}}{f_c} \tag{5}$$

where E·energy and E·CO_2 are embodied energy and CO_2 emission during the production stage for one tom of pervious concrete, respectively. E_f and C_f are parameters concerned with embodied energy in MJ/ton·MPa and CO_2 emission in kgCO_2/ton·MPa, respectively. fc denotes the compressive strength of mortar.

The production stage is divided into three as follows; acquisition of raw materials, transportation and manufacturing (ISO-13315-2 2014). At the raw material stage, the embodied energy and CO_2 emission due to the raw material used for pervious concrete: cement, FA, RHA, aggregates and water were considered for calculations. The embodied energy and CO_2 emissions were obtained from the Bath Inventory of Carbon and Energy (ICE 2011), which is widely used in Europe and developing countries (Hugo *et al.* 2012).

Table 7 presents the equivalent energy embodied and CO_2 emission for each material for production and transportation. For the transportation stage, the energy embodied and CO_2 emission are considered during the process of transporting raw material to the production plant. In the manufacturing stage, the energy embodied and CO_2 emissions come from energy materials used in concrete plants. When the mortar is prepared using the mixer on site, the energy required is 0.0025 MJ/kg (Gonzalez Stumpf *et al.* 2014) and generally, electricity is used as energy source. Each Kwh (3.6 MJ) of delivered electricity emits roughly 0.59 kg of CO_2 (ICE 2011). The equivalent energy embodied and CO_2 of the mortar mixes from cradle to gate was determined from the data provided in Table 7 and mix proportion in Table 5 using Equations (6) and (7), respectively (Kelechi *et al.* 2022)

$$E_{\text{energy}} = \sum_{i=1}^{n} (M_i \times \text{Energy}_{(i,J)}) \tag{6}$$

$$CO_{2,\text{ emission}} = \sum_{i=1}^{n} (M_i \times CO_{2,(i,J)}) \tag{7}$$

where i is the individual material, n is the number of raw materials used for production of pervious concrete, Mi is the quantity of the raw material, $CO_{2,(i,J)}$ is the equivalent CO_2 emission of materials i during material production, transportation and manufacturing of pervious concrete, $\text{Energy}_{(i,J)}$ is the equivalent embodied energy of materials i during material production, transportation and manufacturing of pervious concrete, and E_{energy} and $CO_{2,\text{emission}}$ are total embodied energy and CO_2 emission for the production of pervious concrete.

The environmental friendliness of FA and RHA with varied replacement ratios in pervious concrete was evaluated and the embodied energy and CO_2 emission of FA and RHA utilisation is presented in Figures 17 and 18, respectively. The addition of FA and RHA into pervious concrete revealed a declined trend of embodied energy and carbon emission compared with control mortar. For both w/b ratios, the trend is almost similar. However, when E_f and C_f were compared, FA incorporated pervious concrete revealed more energy-efficient and lesser carbon emission per strength compared RHA incorporated pervious concrete. Both w/b ratios, FA content of 20% showed most energy-efficient and lowest carbon emission. Compared with control mortar, mortar with 20% FA as cement replacement showed E_f and C_f values were 22.4 and 24.3% lesser, respectively, for w/b of 0.3, and 45.4% and 46.7% lesser, respectively, for w/b of 0.35.

3.5. Summary of the results

Table 8 presents the summary of pervious concrete characteristics and sustainability analyses obtained from the present study. It can be observed that pervious concrete with 10, 15 and 20% of FA and 5% of RHA provided a positive contribution to compressive strength, cost-effectiveness and eco-friendly production without compromising permeability. Overall, pervious concrete with FA replacement performs better and is more sustainable compared to pervious concrete with RHA replacement.

4. Conclusion

The present study assessed permeability and compressive strength of pervious concrete as well as sustainability analysis of pervious concrete production with FA and RHA as partial cement replacement. The effect of FA content, RHA content and water to binder ratio was investigated. Based on the study outcomes, the following findings have been drawn:

- Mortar mix with w/b more than 0.35 was not suitable for pervious concrete as permeability is too low or zero.
- Permeability of pervious concrete decreased with an increase in FA content, RHA content and w/b ratio. Permeability reduction trend was similar for concrete with both FA and RHA replacement.
- Compressive strength increased with FA replacement but decreased with RHA replacement.
- Sustainability analysis including embodied energy and carbon emission confirmed the eco-friendliness of FA and RHA utilisation. When embodied energy and carbon emission per strength were compared, pervious concrete with FA as cement replacement revealed more energy efficiency and lesser carbon emission compared to pervious concrete with RA as cement replacement.

The study shows that FA and RHA can be used efficiently to produce more economical and sustainable pervious concrete. The utilisation of FA and RHA for pervious concrete prevents environmental pollution and reduces CO_2 emissions from cement production.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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