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RESEARCH ARTICLE

Influence of aggregate gradation and compaction on compressive strength and porosity characteristics of pervious concrete

Arulanantham Anburuvel and Daniel Niruban Subramaniam

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

ABSTRACT
This study examined the influence of aggregate gradation on compressive strength and porosity in Pervious Concrete (PC) subjected to various compaction efforts. Two aggregate gradations 12–18 and 18–25 mm were recombined in different proportions in the range of 10–50% to obtain five different gradations. PC specimens were cast with these five aggregate gradations by applying standard Proctor compaction, varying efforts from 0 to 75 blows. Test results indicated that wet density and compressive strength increased with compaction effort at higher rate for specimens casted with Aggregate-to-Cement (A/C) ratio 2.5 than 5.0, but porosity reduced at almost the same rate for both A/C ratios. Compressive strength reduced when aggregate gradation with larger size particles increased, however porosity increased. Altering aggregate gradation or compaction effort yielded no significant change in PC properties for A/C ratio of 5.0 than it did for 2.5. The developed mathematical models predicted compressive strength and porosity of PC mixes in terms of aggregate gradation and compaction effort. The highest mean deviation and relative error of model prediction were 1.377 MPa and 10.4% for compressive strength, and 1.414% and 5.8% for porosity, respectively.

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KEYWORDS
Pervious concrete; porosity; compressive strength; aggregate gradation; aggregate-to-cement ratio

Introduction

Pervious Concrete (PC) has been extensively deployed in flood control applications, as it has the ability to transport water effectively, as opposed to conventional concrete (Neithalath *et al.*, 2010, Haselbach *et al.*, 2011, Zhong *et al.*, 2018). In addition to flood control, PC contributes to thermal insulation, acoustic noise control and building partitions (Haselbach *et al.*, 2011, Chu *et al.*, 2017). The presence of abundant pores in PC as opposed to conventional concrete, makes PC suitable for the above-said applications. Pores are the void spaces lie between aggregates coated with cement paste, which contributes to porosity. Porosity is the ratio between volume of voids and total volume of mix (Ibrahim *et al.*, 2014, Debnath and Sarkar, 2020). Porosity could be considered as the connecting parameter for all the above applications. Large amount of pores present in PC mix, however, weakens its strength characteristics and thus limiting its potential applications (AlShareedah and Nassiri, 2021, Li *et al.*, 2021). Strength and pore characteristics of PC is dictated by its constituents such as coarse aggregates and cementitious material, and associated parameters such as aggregate gradation, Water-to-Cement (W/C) ratio, Aggregate-to-Cement (A/C) ratio and compaction (Yang and Jiang, 2003, Neithalath *et al.*, 2010, Ibrahim *et al.*, 2014, Debnath and Sarkar, 2020, Rao *et al.*, 2020). Among all these, aggregate gradation is identified as one of the key players in controlling PC properties (Deo and Neithalath, 2010, Xu *et al.*, 2018). The aggregate gradation is one of the decisive parameters that governs cement paste thickness around each aggregate, and hence influence pore size and strength properties of PC (Jimma and Rangaraju, 2014, Torres *et al.*, 2015, Li *et al.*, 2022).

Typical range of aggregate gradation for PC reported in the literature is 9.5–19 mm, which could be further extended up to 2.36 mm to enhance strength properties (ACI 522R, 2010, Deo and Neithalath, 2010, Kevern *et al.*, 2010, Chandrappa and Biligiri, 2016). The presence of large-sized aggregates in PC mix results in increased porosity and reduced strength, on the contrary small-sized aggregates lead to loss in porosity but increase in strength (Kevern *et al.*, 2010, Cui *et al.*, 2017). Figure 1 illustrates a schematic representation of various aggregate gradations. When all aggregates are small (Figure 1(a)), the binding area becomes larger that provides more window for contact between aggregate and cementitious material, resulting in improved binding, and hence enhance strength characteristics, as opposed to large aggregates (Figure 1(b)) (Yang and Jiang, 2003, Kant Sahdeo *et al.*, 2020). As briefed earlier, some PC mixtures add small amount of fine aggregates to enhance strength properties. Smaller aggregates, however, tend to reduce effective pore interconnection since they are closely packed and that contributes to the reduction in porosity. Ghafoori and Dutta reported that, compressive strength of PC was dictated by the size of the aggregate while porosity was dependent on aggregate gradation Ghafoori and Dutta (1995). Combination of smaller and larger-sized aggregates (Figure 1(c)) is therefore envisaged to moderate strength and porosity characteristics in PC, yet exploring it before applications is vital.

Researchers have explored the effect of aggregate gradation on the performance of PC under various contexts. Table 1 summarises the details of previous works done on PC mix

CONTACT Arulanantham Anburuvel aanbu007@eng.jfn.ac.lk

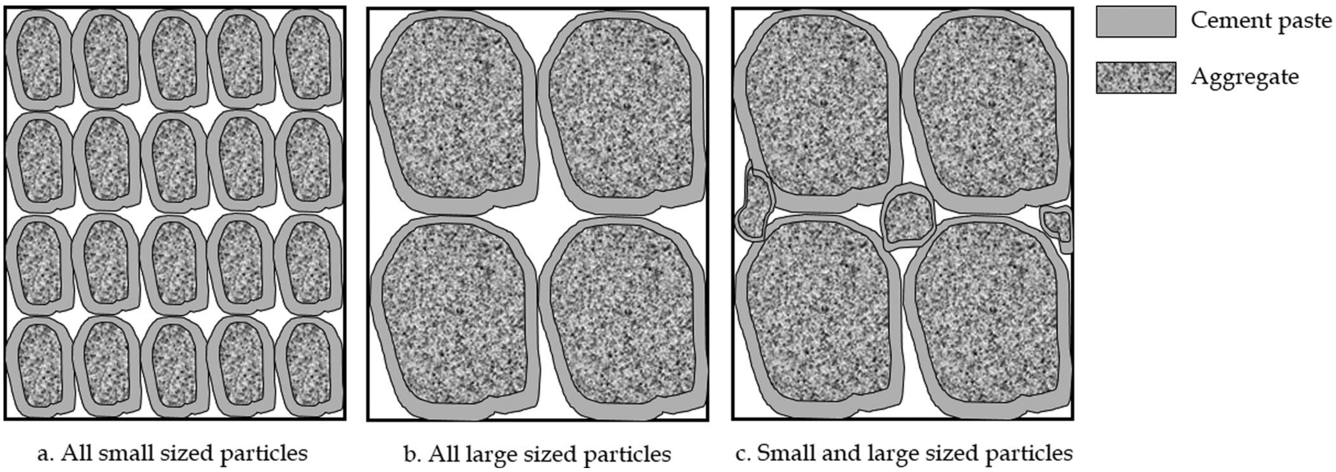

Figure 1. Schematic diagram of different types of aggregate gradations.

Table 1. Details of aggregate gradations used in previous studies.

Reference	Aggregate size (mm)	W/C ratio	Compressive strength (MPa)	Porosity (%)
Chindaprasirt *et al.* (2009)	2.5–5.0, 5.0–3.0, 13.0–20.0	0.225	5–40	15–30
Maguesvari and Narasimha (2013)	4.75–9.0, 9.0–12.5, 12.5–16.0, 16.0–19.5	0.34	9.6–26.2	0.40–1.26*
Fu *et al.* (2014)	2.4–4.8, 4.8–6.4, 6.4–9.5, 9.5–12.7	0.25–0.45	7.5–25.7	0.03–0.14*
Joshaghani *et al.* (2015)	4.75–9.5, 9.5–12.5, 12.5–19.0	0.25–0.35	5.5–9.4	13.5–33.1
Ćosić *et al.* (2015)	0–4, 4–8, 8–16	0.33	20.2–69.5**	14.2–22.2
Yu *et al.* (2019)	2.36–4.75, 4.75–6.0, 6.0–8.0, 8.0–9.5, 4.75–9.5, 10.0–12.5, 12.5–15.0, 10.0–15.0	0.31	19.9–32.0	20.5–21.3
Sahdeo *et al.* (2021)	1.18–12.5, 4.75–6.7, 10.0–12.5, 12.5–19.0, 10–12.5 + Fine (5%), 10–12.5 + Fine (10%)	0.30–0.38	13.0–24.0	8–27
Dai *et al.* (2020)	2.36–4.75, 4.75–9.5, 9.5–13.2	0.31	24.5–31.6	17.3–25.6

*Permeability in cm/s.
**with superplasticiser.

design by changing aggregate sizes and W/C ratios. These studies have reported 28-day compressive strength and porosity in the range of 5–40 MPa and 8–33%, respectively. Researchers claimed that typical values for compressive strength and porosity of PC lie between 1–28 MPa and 15–30%, respectively (Tennis *et al.*, 2004b, ACI 522R-06, 2006, Deo and Neithalath, 2010, Ćosić *et al.*, 2015, Chandrappa *et al.*, 2018, Debnath and Sarkar, 2020). Other mechanical properties such as splitting tensile strength and flexural strength also have been assessed in some works depending on the application (Joshaghani *et al.*, 2015, Kant Sahdeo *et al.*, 2020). As per Joshaghani *et al.* (2015), paste content and size of aggregate influence compressive strength, and tensile and flexural strength, respectively. Similarly, reduction in static elastic modulus has been observed with the increase in aggregate size due to insufficient cement paste coating Crouch *et al.* (2007).

Larger aggregates lead to reduced workability while small aggregates contribute to improved workability Schaefer and Wang (2006). To retain workability characteristics without compromising mechanical and permeability properties and to meet slump requirements, admixtures have been deployed (ACI 522R, 2010, Dai *et al.*, 2020). PC with aggregate gradation of 0–16 mm used superplasticiser to enhance compressive strength up to 69.5 MPa which resulted in a connected porosity of 0.7% Ćosić *et al.* (2015). Yang and Jiang (2003) found that compressive and tensile strength could be improved up to 50.0 and 6.0 MPa, respectively, by including admixtures. Another study by Dai *et al.* (2020) found that adding more than one admixture was more productive in improving mechanical properties than altering A/C ratio. The use of admixtures, however, increases the production cost of PC significantly.

Another important parameter besides aggregate gradation that alters the performance of PC is compaction. Applying compaction in PC mix preparation contributes to pack aggregates in a homogenous manner and also helps cement paste to coat around aggregate Kevern *et al.*, 2009, Lian and Zhuge, 2010). Excess compaction, however, results in clogging pores. Studies, therefore emphasised the need of moderating compaction process in PC mix preparation (Kevern *et al.*, 2009, Lian and Zhuge, 2010, Pieralisi *et al.*, 2016). Compaction is characterised by its type, energy supplied and configuration. Various types of compaction methods including static loading, vibration, rodding, standard Proctor rammer and Marshall rammer have been deployed (Zhuge, 2008, Lian and Zhuge, 2010, Putman and Neptune, 2011, Sahdeo *et al.*, 2021). Among all the methods, standard Proctor compaction produced the least variability of parameters including infiltration, density and porosity Putman and Neptune (2011). As per Zhuge (2008), rammer compaction is suitable for strong aggregate types to achieve dense packing, and hence to achieve high strengths. While vibration method resulted in choking of cement paste at the bottom layer for mixes with higher cement paste, static loading method of compaction produced higher degree of compaction at top layers and lower at the bottom Rao *et al.* (2020). Furthermore, researches have indicated that porosity and density of PC mixes, produced with standard Proctor rammer, were similar to that of field placed PC (Zhuge, 2008, Singh *et al.*, 2020).

Contemporary studies have reported enough aspects of aggregate grading with little or no attention to compaction effort. The authors feel that both factors are inextricably intertwined in influencing compressive strength and porosity of PC. Moreover, a mathematical relationship to describe the dynamics of aggregate gradation in PC mix design is the need of the hour. To the best of author's knowledge, the development of such models is in primitive stage. Depicting the variations between compressive strength and porosity with compaction effort for various gradations and generating frequency distribution charts for strength and porosity could provide practitioners and researchers more insights on PC mix design parameters and their interrelationships. Moreover, developing mathematical models would help to grasp the dynamics of comprehensive strength or porosity with aggregate gradation and compaction effort. This would enable choosing relatively better input parameters during PC mix design for a wide range of PC applications.

Research objective and scope

The ultimate goal of the presented work was to examine the influence of aggregate gradation on PC mix properties, subjected to various compaction efforts. Two objectives were thus set; one was to evaluate the changes in compressive strength and porosity characteristics under varying compaction efforts, second was to formulate a mathematical relationship between compressive strength or porosity in terms of aggregate gradation and compaction effort.

By keeping aggregate type, A/C ratio and W/C ratio constant, PC specimens were prepared by varying aggregate gradations and compaction efforts. The prepared specimens were subjected to standard laboratory tests to determine compressive strength, porosity and density.

Materials and methods

Study framework

Figure 2 shows the detailed framework of this study, which comprises experimental work and analysis of results. To examine the performance of PC mixes under varying aggregate gradations and compaction efforts, a comprehensive laboratory experimental programme was designed and conducted. Experimental programme was performed in two phases; in phase I, constituents of PC were characterised by determining their physical properties and in phase II, performance parameters of various PC mixes were evaluated. To be in compliance with contemporary construction practices, the constituents of PC chosen for laboratory investigation were of similar type to what had been widely deployed in industrial applications. The PC properties obtained from experiments were analysed to comprehend the correlation between aggregate gradation and compaction effort, and PC properties. Eventually, relationship between these parameters was devised to formulate a mathematical model.

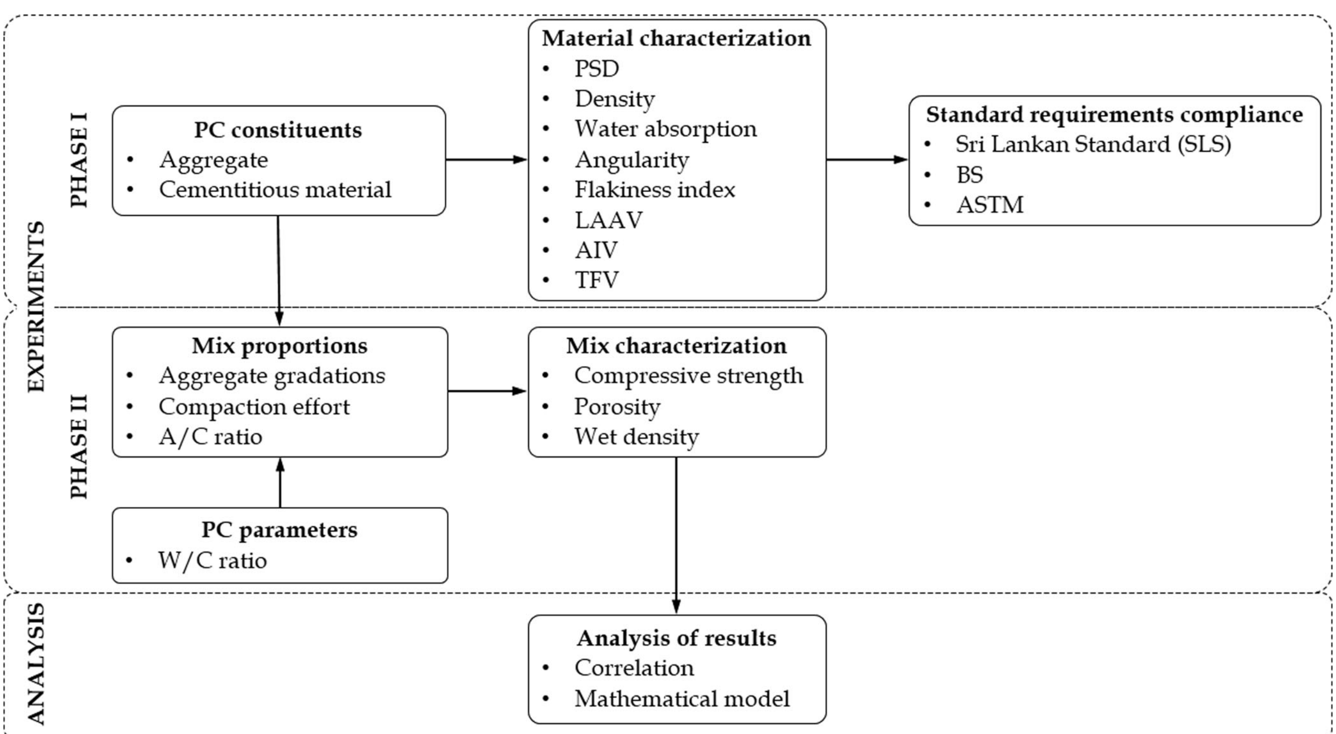

Figure 2. Framework of the study.

Material characterisation

In phase I of the experimental programme, individual PC constituents; aggregates of different gradations and cementitious material were characterised using standard laboratory experiments.

The aggregate type used in the study was of gneiss rock origin, extracted from natural mineral deposits of the central highlands of Sri Lanka. Extracted aggregates were crushed in a jaw crusher to produce coarse aggregates. From aggregate stockpile, two primary sets of aggregate gradations were devised for further experiments as follows; gradations G12 and G18, comprised of particle sizes ranging between 12–18 mm and 18–25 mm, respectively. The grain size distributions of G12, G18 and their combinations detailed in Table 2 are shown in Figure 2. Uniformity coefficient (Cu) and coefficient of curvature (Cc) of G12 and G18 are close to unity, which implies that both gradations are gap-graded and thus highly recommended to be used in PC (Neithalath *et al.*, 2010, Debnath and Sarkar, 2020). G18 was added to G12 from 10% to 50% in 10% increments as summarised in Table 2, to obtain different gradations for each PC mix. Figure 3.

The cementitious material generally used for PC is Ordinary Portland Cement (OPC) conforming to BS–12–1996 BS 12 (1996). According to literature, OPC provides sufficient paste thickness to coat around aggregates that improves strength and durability characteristics of PCs (Li *et al.*, 2017, Debnath and Sarkar, 2020). Considering the benefits of OPC, this study deployed OPC as cementitious material.

Table 2. Summary of aggregate mixture proportions.

Mix ID	Proportion of G18 (%)	Proportion of G12 (%)
G18 – 10	10	90
G18 – 20	20	80
G18 – 30	30	70
G18 – 40	40	60
G18 - 50	50	50

Table 3 and 4 summarises properties of aggregate and cement, which were determined according to BS and ASTM standards (BS 812-105.1, 1989, BS 812: 112, 1990a, BS 812: 111, 1990b, BS 812 1995, ASTM C131 / C131M, 2014). In all mixes, aggregate showed considerable resistance to impact, abrasive and static forces as indicated by higher Aggregate Impact Value (AIV), Los Angeles Abrasion Value (LAAV) and Ten percent Fines Value (TFV), respectively. In addition, used aggregate comprised of significantly low internal pores as designated by water absorption. Also, the determined properties were found to be well in compliance with standard requirements for aggregates used in construction (ORN31, 1993, SCA/5, 2009). Low angularity number contributes to increase in strength with reduction in permeability; however total porosity of PC was observed to be in the range of 29–38% (Jain and Chouhan, 2011, Maguesvari and Narasimha, 2013, Chandrappa and Biligiri, 2016).

Parameters

Choice of W/C ratio is crucial as it is directly correlated to strength and workability of PC mix (Yang and Jiang, 2003, Debnath and Sarkar, 2020). Higher W/C ratios generate excess cement paste, which may choke pores, and thus disturb interconnectivity of pores (Chindaprasirt *et al.*, 2008, Nguyen *et al.*, 2014, Xie *et al.*, 2018, Debnath and Sarkar, 2020). A study by Li *et al.* (2021) emphasised the impact of W/C ratio and cement paste on pore connectivity. The literature demonstrate that typical range of W/C ratio lies between 0.27 and 0.44 (Tennis *et al.*, 2004a, Chindaprasirt *et al.*, 2008, Deo and Neithalath, 2011, Debnath and Sarkar, 2020). This study settled to use W/C ratio by weight as 0.3 for all PC mixes, to incorporate the requirement of zero slump in the absence of admixtures.

Another indispensable parameter in PC mix design is A/C ratio, which influences strength and pore characteristics Debnath and Sarkar (2020). Aggregate constitutes to 50–65% and 60–75% by volume in traditional concrete and PC, respectively

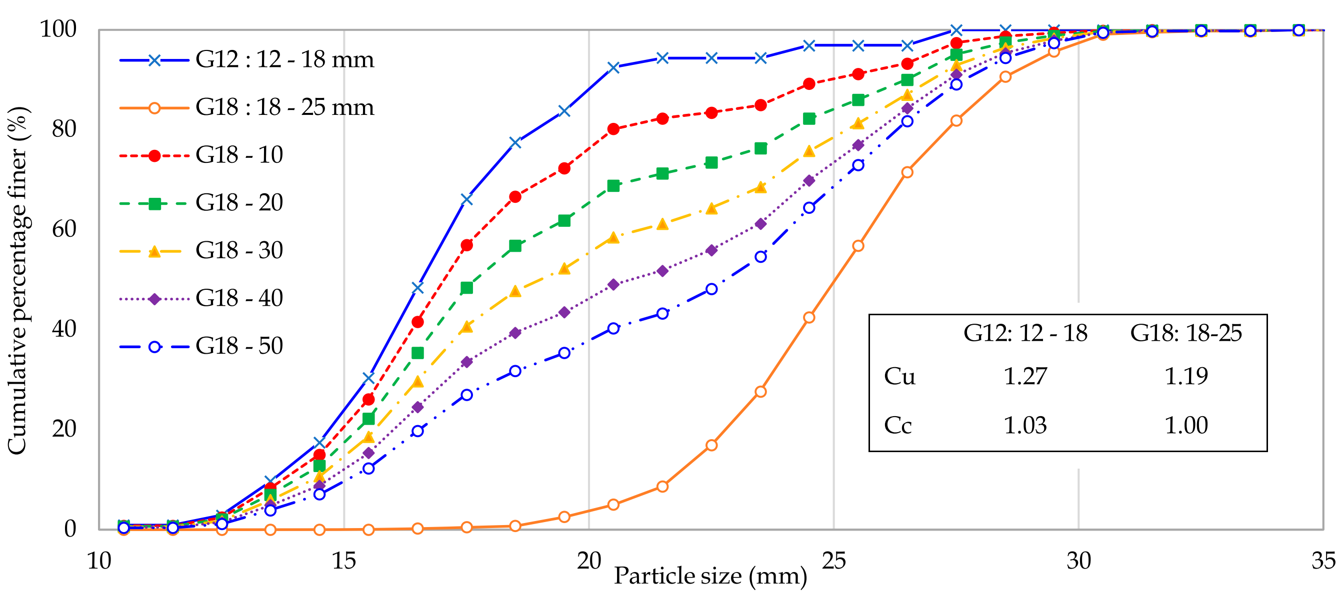

Figure 3. Particle size distribution of primary aggregate gradations and their combinations used in this study.

Table 3. Summary of aggregate properties.

Property description	Mix ID of aggregate gradation					Standard
	G18 - 10	G18 - 20	G18 - 30	G18 - 40	G18 - 50	
Compacted density, Mg/m^3	1.899	1.876	1.952	1.893	1.902	BS 812: Part 2:1995
Uncompacted density, Mg/m^3	1.720	1.780	1.752	1.637	1.821	BS 812: Part 2:1995
Apparent specific gravity	2.828	2.828	2.828	2.828	2.828	BS 812: Part 2:1995
Angularity number	12.90	13.26	14.92	12.41	11.41	BS 812-105.1: 1989
Water absorption, %	0.22	0.26	0.23	0.22	0.24	BS 812: Part 2:1995
Los Angeles Abrasion Value (LAAV), %	28	28	28	28	28	ASTM C131/ C131M
Aggregate Impact Value (AIV), %	22	22	22	22	22	BS 812: 112: 1990
Ten percent Fines Value (TFV), kN	114	114	114	114	114	BS 812: 111: 1990

Table 4. Summary of cement properties.

Property description	Value	Standard
Specific gravity	3.15	BS 812: Part 2:1995
Density, Mg/m^3	1.362	BS 812: Part 2:1995

Chandrappa and Biligiri (2016). According to literature, A/C ratios in PC studies have been traditionally varied in the range of 2.0–10.0 (Deo and Neithalath, 2011, Maguesvari and Narasimha, 2013, Chandrappa and Biligiri, 2016, Mohammed *et al.*, 2016, Zhong *et al.*, 2018). In PC mixes, increase in A/C ratio improves porosity but retards strength Debnath and Sarkar (2020). To prepare PC mixes, this study deployed 2 different A/C ratios; 2.5 and 5.0.

In order to focus on the aggregate gradation and compaction effort, other extraneous variables such as aggregate type, chemical admixtures and supplementary cementitious material, were kept maintained as much constant as possible.

Mix design

Phase II of the experimental programme consisted of casting and testing of various PC specimens with alternative aggregate gradations and compaction efforts. Table 5 summarises the details of PC specimens casted under different categories. Aggregates with five different gradations as summarised in Table 2 were subjected to eight different compaction efforts to cast PC mixes. Casting was done for two different A/C ratios; 2.5 and 5.0. Twelve PC specimens from each category were casted and tested in order to minimise the occurrence of random noise in test observations. Accordingly, 960 samples were casted in total, of which half of them were used for compressive strength measurements and the remaining were for porosity. Compaction was given by standard Proctor compaction rammer stipulated in BS 1377-4:1990 BS 1377–4 (1990), given the superior performance pointed out in literature (Putman and Neptune, 2011, Sahdeo *et al.*, 2021). Rammer compaction was viable owing to strong characteristics of constituent aggregates as described above Zhuge (2008). All sample preparation and experiments were carried out by well-trained personnel under exactly the same laboratory conditions to minimise the occurrence of random error in observations. Test results were recorded at recommended precision in accordance with standards. Recording of test results was periodically monitored by supervisors to eliminate blunders.

Table 5. Number of PC specimens cast for different A/C ratios, aggregate gradations and compaction effort.

A/C ratio	Aggregate gradation	Compaction effort (no. of blows)								W/C ratio
		00	10	15	25	30	40	50	75	
2.5	G18 – 10	12	12	12	12	12	12	12	12	0.3
	G18 – 20	12	12	12	12	12	12	12	12	0.3
	G18 – 30	12	12	12	12	12	12	12	12	0.3
	G18 – 40	12	12	12	12	12	12	12	12	0.3
	G18 - 50	12	12	12	12	12	12	12	12	0.3
5.0	G18 – 10	12	12	12	12	12	12	12	12	0.3
	G18 – 20	12	12	12	12	12	12	12	12	0.3
	G18 – 30	12	12	12	12	12	12	12	12	0.3
	G18 – 40	12	12	12	12	12	12	12	12	0.3
	G18 - 50	12	12	12	12	12	12	12	12	0.3

Mix preparation and characterisation

The required amount of coarse aggregate, cement and water were estimated using respective A/C ratio and W/C ratio. The estimated quantities of constituents were weighed separately using an electronic balance with least count of 0.1 mg and were fed into an electrically operated concrete mixer with a capacity of 120 L. The constituents were thoroughly mixed by following the timeline of events illustrated in Figure 4. The whole mixing process was done for about 20 min until a homogenous mix was ready.

Slump of the prepared fresh mixes was measured according to standard BS 1881–102 (1983), which found to be little (less than 15 mm) to no slump adhering to PC mix design requirements. The fresh mix was, thereafter placed into 150 × 150 × 150 mm^3 concrete moulds and given a compaction using standard proctor compaction rammer stipulated in BS 1377-4 (1990). The rammer is of 2.5 kg with a 5.08 cm diameter face, freely dropped from a height of 300 mm for every blow. The blows were given uniformly across the face of the cube as prescribed in BS 1377-4:1990. The compaction effort was varied from 0 to 75 number of blows. 0 number of blows refers to no compaction state (a few tampings with the tamping rod). Having performed the designated compaction, the excess mix was levelled and removed using an iron rod. The casted PC cubes were left in the mould for one day at room temperature. On the next day, cubes were removed from the moulds and fully submerged into clean water bath for curing for a period of 28 days.

Density measurement

One set of PC specimens was subjected to density measurements using simple mass-volume relationship stipulated in British Standard 812: Part 2:1995 BS 812 (1995). Mass of compacted PC mix with mould and mass of mould were separately

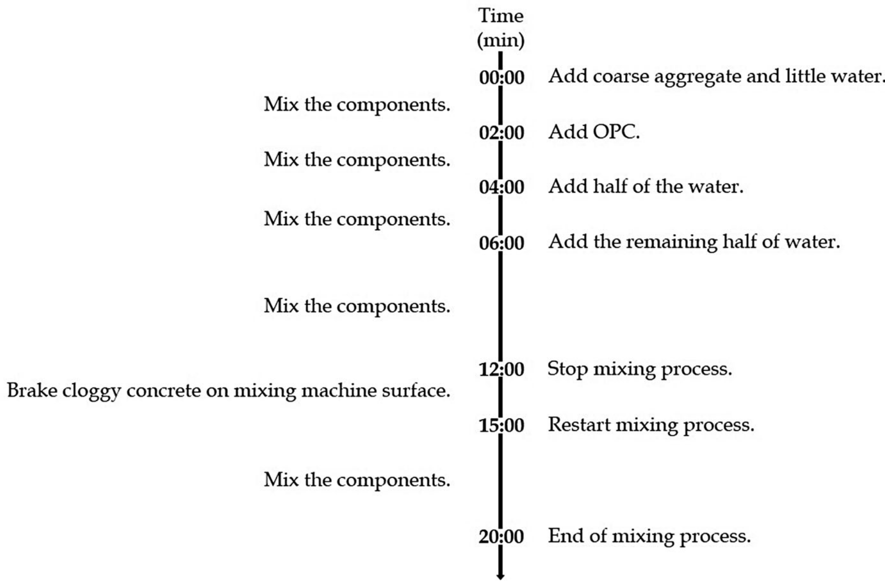

Figure 4. Timeline of pervious concrete mixing process.

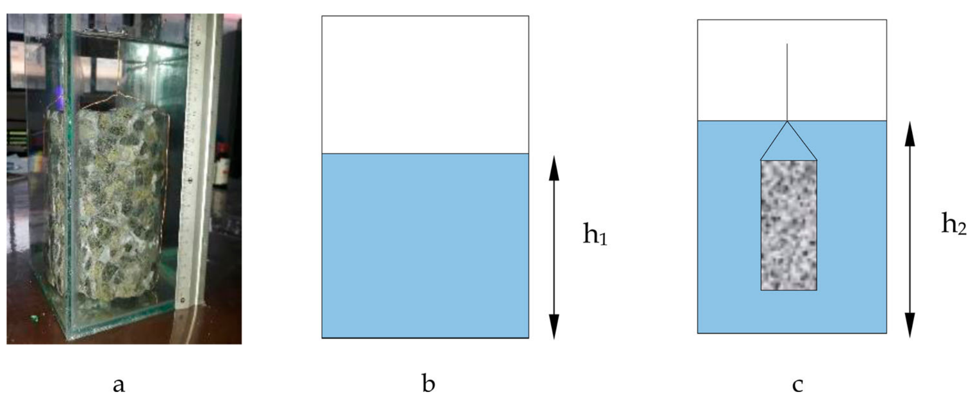

Figure 5. Porosity measurement with water displacement method.

measured using a digital balance with least count 0.1 g. Fresh density of PC mix (ρ) was estimated as follows.

$$\rho = \frac{\text{Mass of compacted PC with mould} - \text{Mass of mould}}{\text{Volume of mould}} \qquad (1)$$

Strength measurement

After 28 days of curing, PC cubes were removed from the curing tank and wiped with a clean cloth to remove excess surface water and make it Surface Saturated Dry (SSD). Compressive strength of cubes was then tested using a state-of-the-art, calibrated, compression testing machine. Obtained readings were recorded with recommended precision according to the standard. Subsequently, similar measurements were grouped together and averaged out to estimate the mean compressive strength.

Porosity measurement

Cylindrical core samples of 100 mm diameter from the middle of the cubes excluding vertical face boundary zones were extracted using core-cutter after 28 days of curing. Boundary zones were avoided to reduce the impact of porosity reduction at vertical faces of concrete mould due to cement paste accumulation. Cylindrical specimens were subjected to porosity measurements using simple water displacement technique (Montes *et al.*, 2005, Rao *et al.*, 2020). Water displacement method directly estimates porosity by measuring the volume of water added and the change in the height of water level Montes *et al.* (2005).

Water displacement method used a tank with cross sectional area 140 × 140 mm and height of 250 mm, which was attached with a Vernier scale with 0.1 mm least count to record heights of water level measurements. Figure 5(a) shows the complete setup used for porosity measurements. Water tank was partially filled with water and positioned on a horizontal bed.

The cylindrical core samples were fully immersed into the water tank while recording initial and final heights of water levels before and after the submergence of cylindrical samples (Figures 5(b,c)). When recording heights of water levels, appropriate precautions were taken to

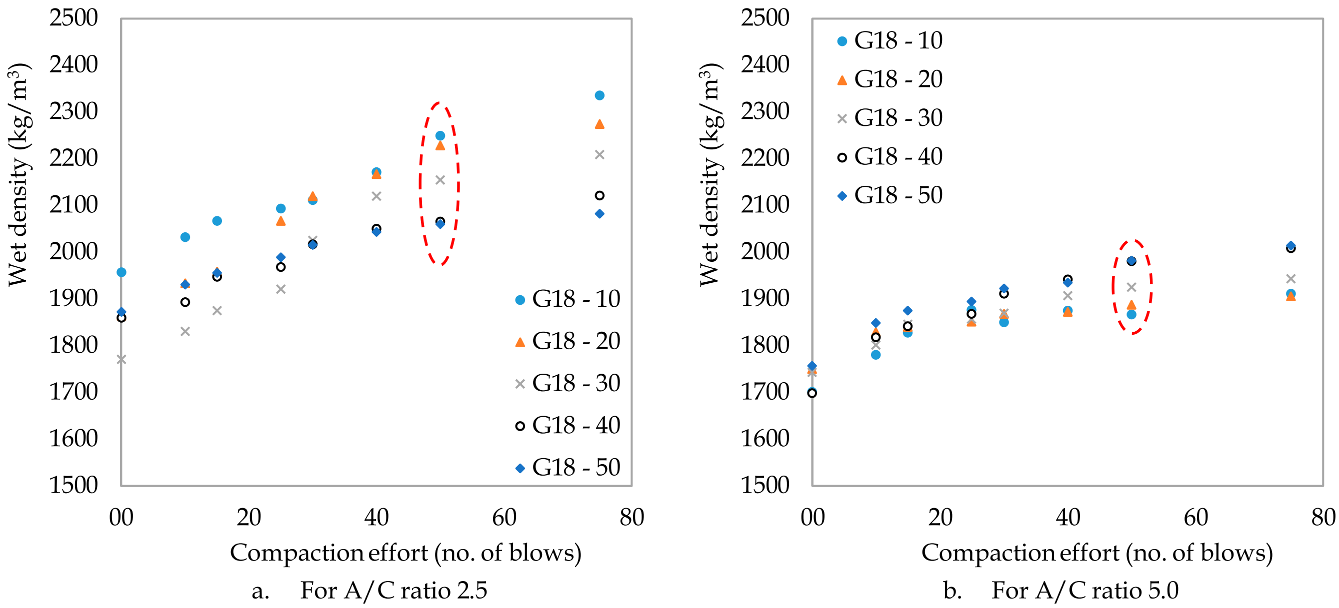

Figure 6. Wet density variation against compaction effort among different aggregate gradations for A/C ratios 2.5 & 5.0.

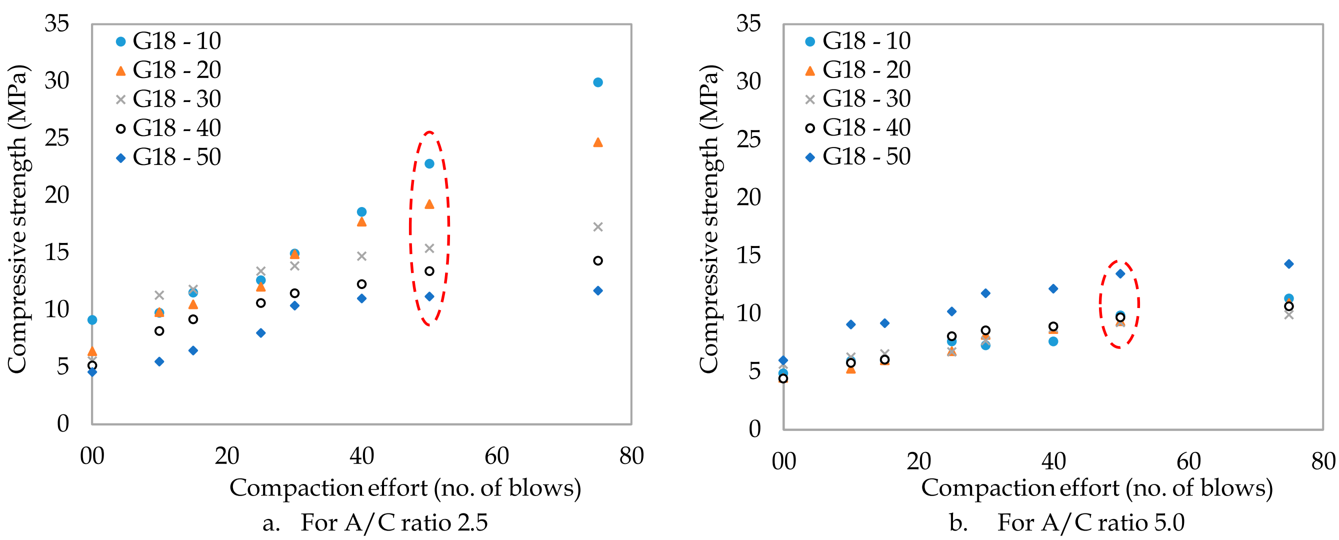

Figure 7. Compressive strength variation against compaction effort among different aggregate gradations for A/C ratios 2.5 & 5.0.

minimise meniscus effect and parallax error. The porosity (Φ) of PC cylindrical samples measured using water displacement method was estimated using the following equation.

$$\Phi = \frac{[V - A(h_2 - h_1)]}{V} \times 100\% \qquad (2)$$

where V and A refer to the volume of pervious concrete cylindrical core and cross-sectional area of the tank, respectively; h_1 and h_2 refer to initial and final height of water level before and after submergence of cylindrical core, respectively.

Results and discussions

Effect of aggregate gradation on compressive strength and porosity

The results for wet density and compressive strength with various compaction efforts are shown in Figures 6 and 7. Wet density and compressive strength improved with compaction effort for both A/C ratios. The rate of improvement was significantly high in A/C ratio 2.5 than that of in 5.0. This may be due to the fact that low A/C ratio had adequate cement paste, which not only filled pores but also coated around aggregates well, and this may have resulted in higher densities and compressive strengths. Furthermore, increase in compaction

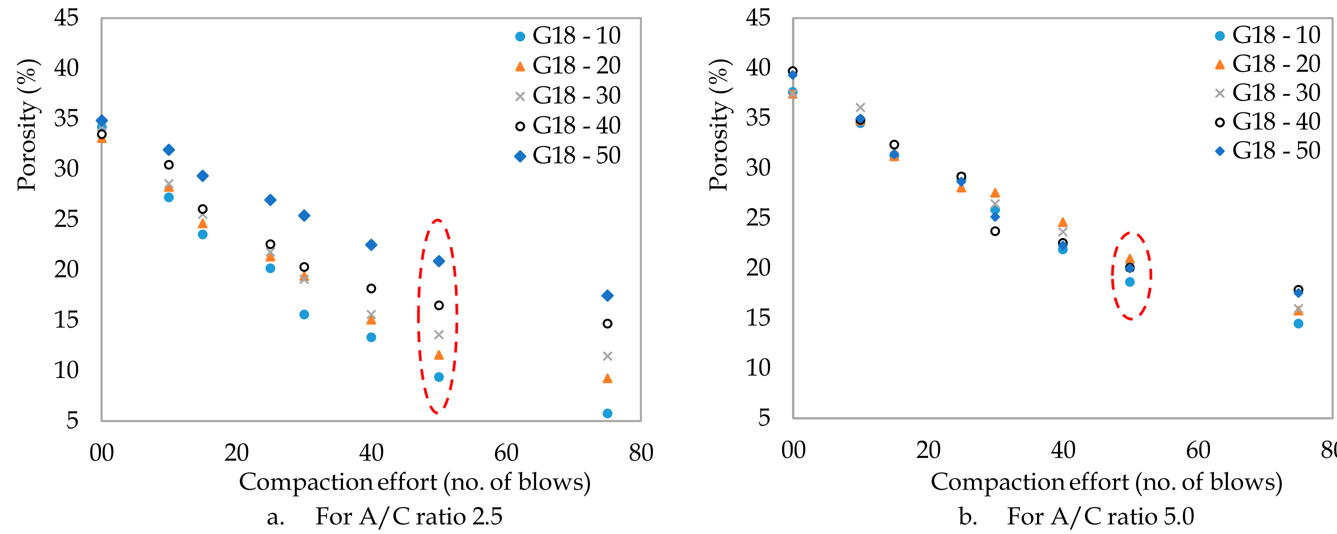

Figure 8. Porosity variation against compaction effort among different aggregate gradations for A/C ratios 2.5 & 5.0.

effort contributed for dense and homogenous packing of aggregates that improved strength in both A/C ratios.

For A/C ratio of 2.5, given a constant compaction effort, wet densities or compressive strengths obtained for different aggregate gradations were observed to span in relatively large interval. On the contrary, both wet densities or compressive strengths spanned in a small interval for mixes with A/C ratio 5.0. This may be attributed to available cement paste and aggregate gradation with higher proportion of smaller aggregates which had relatively higher surface area, i.e. surface area in G18–10 was higher than G18–50. Higher surface area enabled adequate coating with cement paste comparatively well in A/C ratio of 2.5 that contributed to higher density and compressive strengths. Surface area reduction with the increase in larger aggregates, however resulted in low level of coating and hence strength. On the other hand, available cement paste in A/C ratio 5.0 was significantly small compared to 2.5, which was inadequate to cause impact on density and compressive strength across varying aggregate gradations. Similar observations were also made on compressive strength and density by previous researchers (Ćosić *et al.*, 2015, Joshaghani *et al.*, 2015).

The effect of different gradation on porosity with varying compaction efforts are shown in Figure 8. As expected, porosities were reduced with increasing compaction effort. The obtained porosities ranged between 5.8–34.8% and 14.5–39.4% for A/C ratios 2.5 and 5.0, respectively. In low A/C ratios, excessive amounts of cement paste were present that may have filled considerable amount of pores, thereby clogged the passage for water transport. Furthermore, compaction contributed to dense packing of aggregates. And hence, porosity of the PC specimen reduced. Gradations with higher proportion of larger aggregates had more voids; i.e. voids in G18–50 were higher than that of in G18–10, thereby contributed to increase porosity. Literature has reported similar trend in porosity (Neithalath *et al.*, 2010, Deo and Neithalath, 2011, Ćosić *et al.*, 2015).

Figure 9 shows the plots of compressive strength versus porosity for A/C ratios 2.5 and 5.0. From Figure 9, it can be

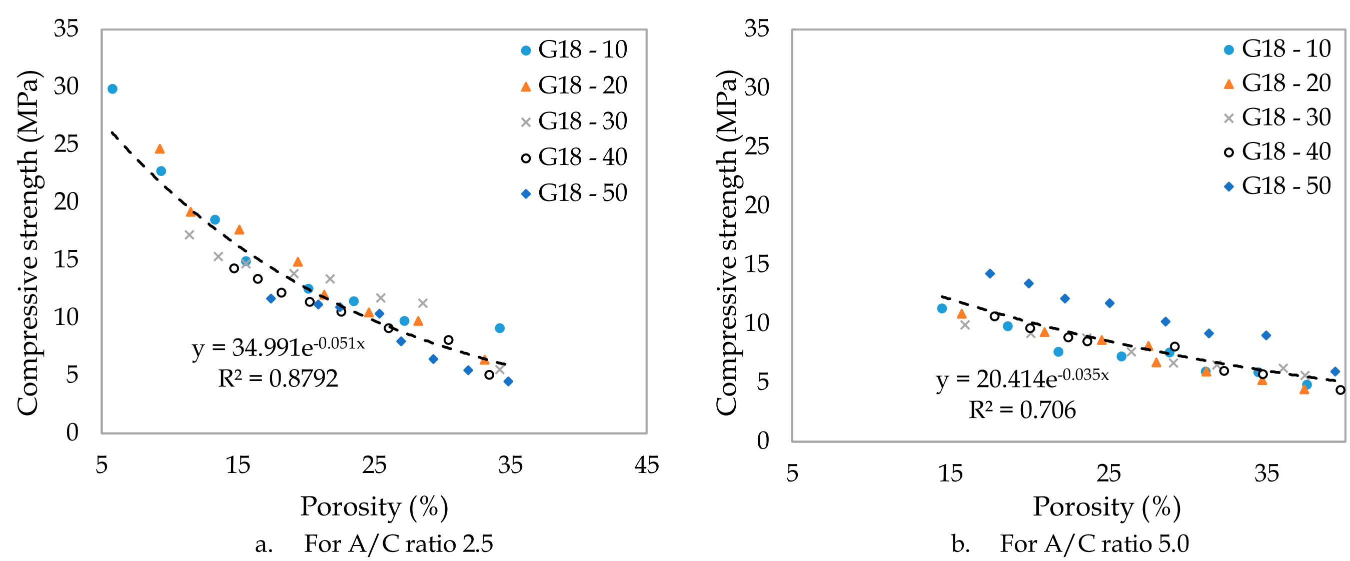

Figure 9. Compressive strength variation against porosity among different aggregate gradations for A/C ratios 2.5 & 5.0. (*y* – compressive strength and *x* – porosity).

observed that compressive strength and porosity follow a non-linear relationship. This exponential decay type of relationship between compressive strength and porosity has been reported in published literature (Maguesvari and Narasimha, 2013, Ibrahim *et al*., 2014, Li *et al*., 2017). The relationship was relatively perfect in A/C ratio 2.5 compared to that of 5.0.

The frequency distribution of compressive strength obtained from the experiments is shown in Figure 10. For A/C ratio 2.5 and gradations with higher proportion of small aggregates (G18-10 and G18-20), frequency concentrated to the right, which implied that produced PC specimens of this specification were of high compressive strength. Noticeably, higher compaction efforts yielded higher compressive strengths, exhibiting a strong correlation, which was reported by other researchers Sahdeo *et al.* (2021). With the reduction in proportion of small aggregates in the composition (from G18-10 to G18-50), the frequency gradually moved to the left. This pattern was, however not observed in A/C ratio 5.0. This was mainly because adequate cement paste and large surface area were present in mixes with low A/C ratios and small aggregates, which contributed to compressive strength development. For large A/C ratios, even though large surface area was present for gradations with higher proportion of small aggregates (G18-10 and G18-20), low amount of available cement paste might not be sufficient enough to contribute to compressive strength development. This is in agreement with the findings of Fu *et al.* (2014).

Similarly, Figure 11 shows frequency distribution of porosity. Frequency distribution gradually moved from left to right with the increase in proportion of larger particles in aggregate gradation for both A/C ratios. This may be attributed to the creation of voids and straight paths of water flow in aggregate gradation with larger particles that enhanced water transport and hence porosity. However, the frequency distribution of porosity was almost uniform, and not much significant deference was observed between compaction efforts. This may be attributed to a compromised relationship between the amount of cement paste and voids in different aggregate gradations.

Model development

Relationship between compressive strength, aggregate gradation and compaction effort

From Figure 7, it can be concluded that the rate of change in compressive strength with respect to compaction effort showed an increasing trend at the beginning and gradually attained an asymptotic relation with compaction effort. Hence the variation between compressive strength of PC and compaction effort for a particular A/C ratio could be represented through a saturation curve as follows

$$\sigma = \frac{\mathrm{a}}{1 + \mathrm{b}\ \mathrm{e}^{(-\mathrm{c}\ \mathrm{y})}} \tag{3}$$

where σ refers to compressive strength (in MPa) and y denotes compaction effort (in no. of blows). a, b and c are model parameters corresponding to the range of compressive strength variation between compaction efforts, impact of initial compaction and the rate of change of compressive strength, respectively.

For the same compaction effort, compressive strength varied in response to the change in aggregate gradation. By incorporating the effect of aggregate gradation in parameters a, b and c simultaneously, a general model could be developed. By fitting Equation (3) for compressive strength and compaction effort for each aggregate gradation, the parameters a, b and c were determined. The estimated parameters a, b and c were thereafter mapped with corresponding aggregate gradation to derive a common relationship in terms of aggregate gradation for each A/C ratio. Given that, x refers to the proportion of G18 in fraction, derived parameters; a, b and c, and equations are given in Table 6.

Relationship between porosity, aggregate gradation and compaction effort

Similarly, in Figure 8, an exponential decay type of change was observed between porosity and compaction effort. For a particular A/C ratio, such relationship could be represented through a mathematical equation as follows

$$\Phi = \mathrm{a}\ \mathrm{e}^{(\mathrm{b}\ \mathrm{y})} \tag{4}$$

where Φ and y denote porosity (in %) and compaction effort (in no. of blows), respectively. a and b are model parameters.

Porosity model also was fitted in the same way, similar to how compressive strength model was set up. Incorporating aggregate gradation as a variable, parameters a, b and c were determined and are summarised in Table 7. x refers to the proportion of G18 in fraction.

Model performance

Performance of the proposed model was assessed by computing indices such as Root Mean Square Error (RMSE) and Mean Absolute Relative Error (MARE) of the estimates. The RMSE and MARE were computed using Equations (5) and (6).

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(m_i - z_i)^2}{n}} \tag{5}$$

$$\mathrm{MARE} = \frac{\sum_{i=1}^{n}\left|\frac{m_i - z_i}{m_i}\right|}{n} \tag{6}$$

where m_i and z_i refer to measured and estimated values of ith sample design mix; n is the number of entities compared.

Table 8 summarises RMSE and MARE values of proposed model for A/C ratios 2.5 and 5.0. The maximum estimation uncertainty in compressive strength was approximately 1.377 MPa (approximately 10%) which obviously characterises the superior performance of the proposed model. Similarly, the maximum uncertainty in porosity estimation was 1.414%, which was approximately 6% of the mean value of porosity.

During PC mix design, aggregate gradation and compaction effort could be optimised with the proposed model to enhance compressive strength or porosity.

Conclusions

The influence of aggregate gradation on PC mix design was investigated in this study. Five aggregate gradations (G18-10,

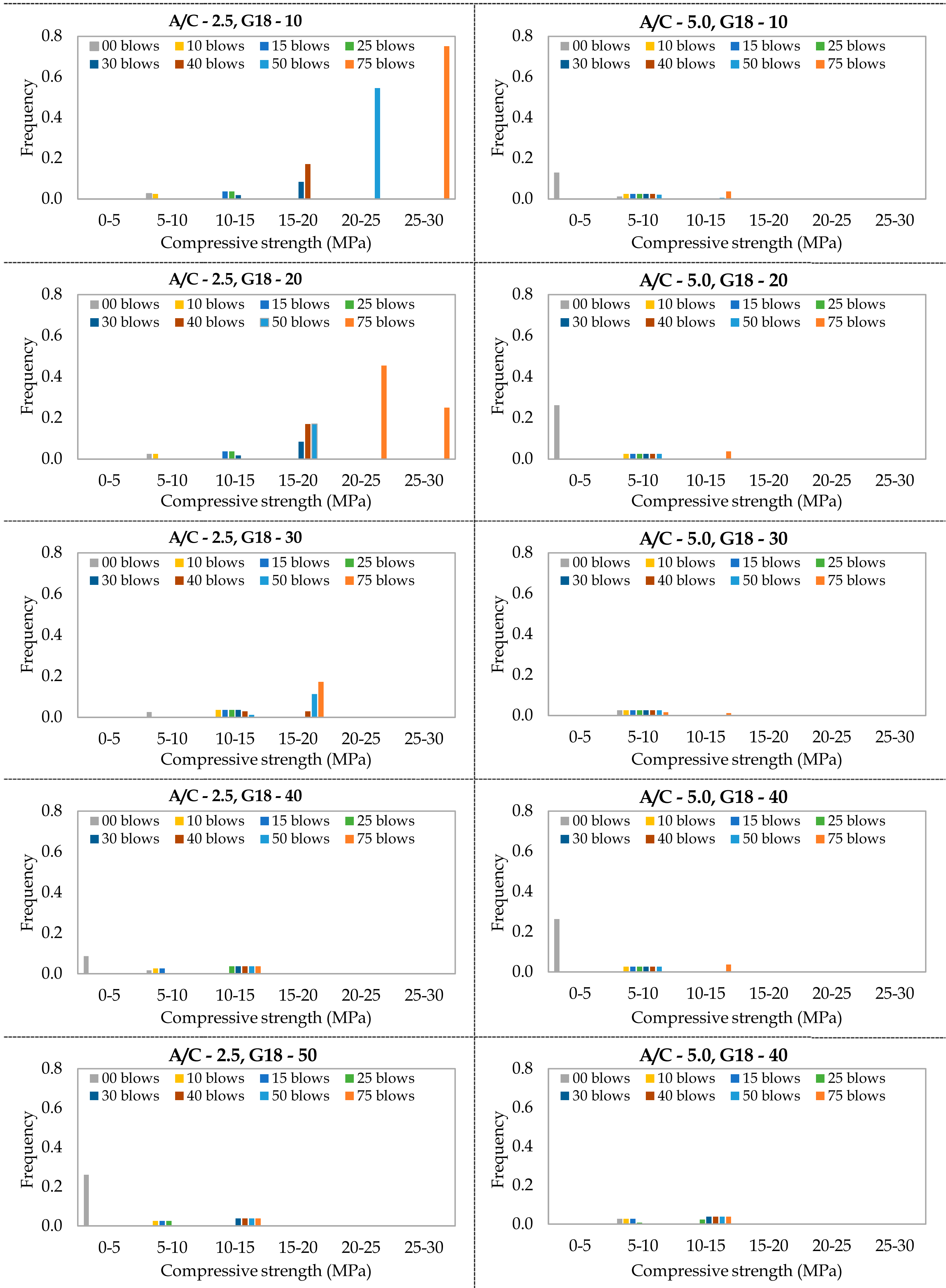

Figure 10. Distribution of compressive strength with various aggregate gradation and compaction efforts for A/C ratios 2.5 and 5.0.

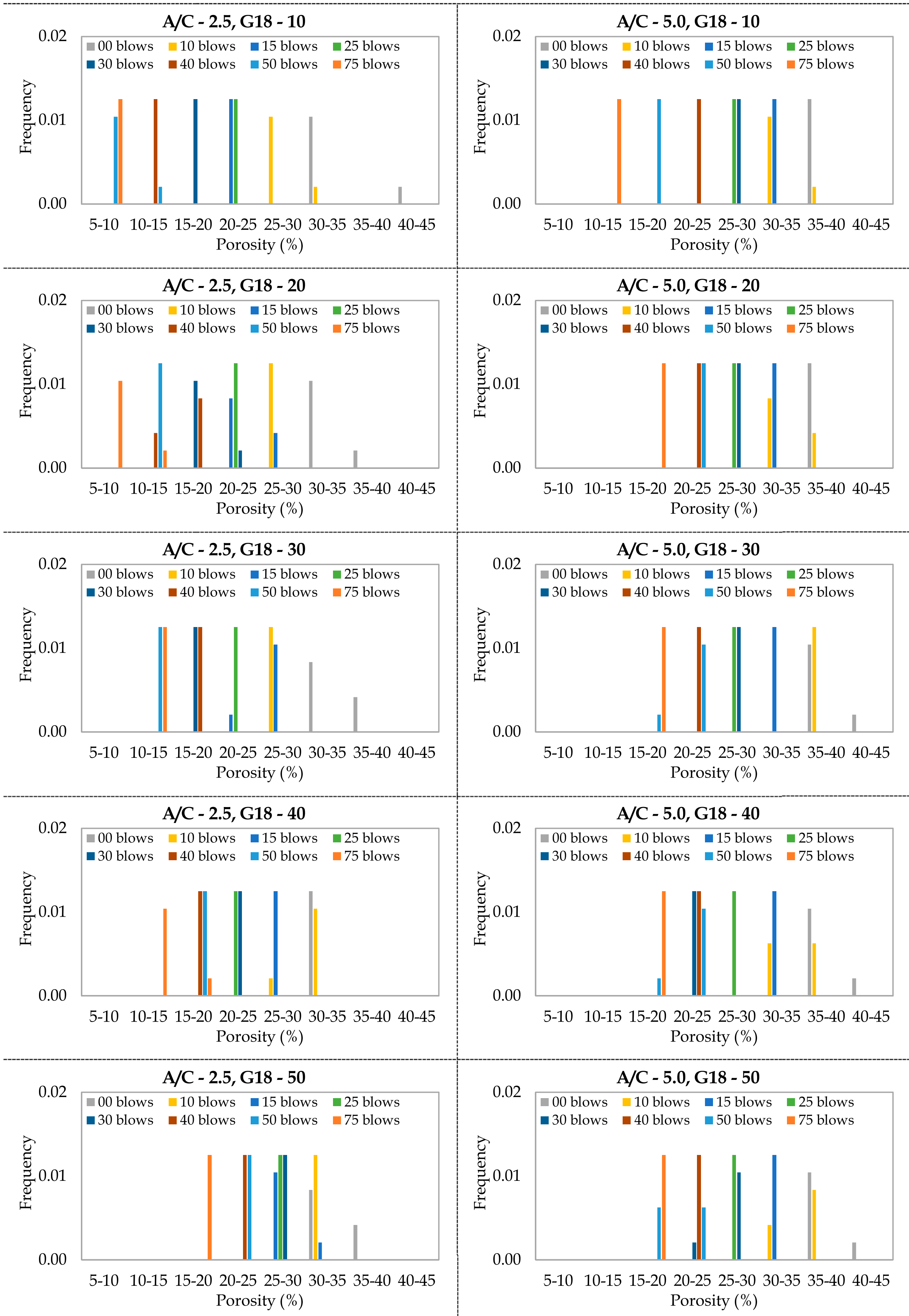

Figure 11. Distribution of porosity with various aggregate gradation and compaction efforts for A/C ratios 2.5 and 5.0.

Table 6. Compressive strength in terms of aggregate gradation and compaction effort.

	A/C ratio	
Parameters	2.5	5.0
a	$344.86x^2–297.95x + 75.80$	$116.93x^2–76.59x + 23.33$
b	$47.86x^2 –36.50x + 8.38$	$13.86x^2–10.99x + 3.42$
c	$0.11x + 0.02$	$0.09x + 0.01$
Equation	$\sigma = \frac{344.86x^2 - 297.95x + 75.802}{1 + (47.86x^2 - 36.50x + 8.38)\, e^{-(0.11x + 0.02)y}}$	$\sigma = \frac{116.93x^2 - 76.59x + 23.33}{1 + (13.86x^2 - 10.99x + 3.42)\, e^{-(0.09x + 0.01)y}}$

Table 7. Porosity in terms of aggregate gradation and compaction effort.

	A/C ratio	
Parameters	2.5	5.0
a	$3.37x + 32.92$	$1.4x + 38.2$
b	$0.032x − 0.03$	$−0.013$
Equation	$\Phi = (3.37x + 32.92)\, e^{(0.032x - 0.03)y}$	$\Phi = (1.4x + 38.2)\, e^{(-0.013)y}$

Table 8. Performance indices of the proposed model.

Performance index	A/C ratio	Performance indicator	Value
Compressive strength (MPa)	2.5	RMSE (MPa)	1.377
		MARE (%)	10.396
	5.0	RMSE (MPa)	0.603
		MARE (%)	6.299
Porosity (%)	2.5	RMSE (MPa)	1.414
		MARE (%)	5.831
	5.0	RMSE (MPa)	1.284
		MARE (%)	4.183

G18-20, G18-30, G18-40 and G18-50) were prepared by binary blending of two sets of aggregates (G12 and G18) in proportions of 10%, 20%, 30%, 40% and 50%. Two sets of A/C ratios 2.5 and 5.0 were deployed in this study, while keeping W/C ratio by weight as 0.3 and other extraneous variables as much a constant as possible. PC mixes were casted using the prepared aggregate gradations and tested for compressive strength and porosity. Test results were analysed and eventually mathematical relationships were formulated between compressive strength or porosity in terms of aggregate gradation and compaction effort.

Based on the results of this study, the following conclusions can be drawn for PC:

- Wet density and compressive strength increased with compaction effort in both A/C ratios 2.5 and 5.0. The rate of improvement in A/C ratio was significantly higher than that of 5.0. Porosity reduced with compaction effort in both cases at almost the same rate.
- Compressive strength reduced when aggregate gradation with larger size particles increased, but porosity increased.
- For A/C ratio 2.5, compressive strength and porosity values of the same compaction effort tended to scatter more when aggregate gradations varied but not in A/C ratio 5.0.
- For larger A/C ratio 5.0, altering aggregate gradation or compaction effort yielded no significant change in PC properties than it did for smaller A/C ratio 2.5.
- For lower A/C ratio 2.5, aggregate gradation with higher share of smaller particles (G18 – 10 and G18 – 20) has higher probability of producing specimens with higher compressive strengths, when subjected to large compaction efforts.
- The following models were developed to predict compressive strength (σ) and porosity (Φ) in terms of aggregate gradation (x) and compaction effort (y).

A/C ratio	Compressive strength	Porosity
2.5	$\sigma = \frac{344.86x^2 - 297.95x + 75.802}{1 + (47.86x^2 - 36.50x + 8.38)\, e^{-(0.11x + 0.02)y}}$	$\Phi = (3.37x + 32.92)\, e^{(0.032x - 0.03)y}$
5.0	$\sigma = \frac{116.93x^2 - 76.59x + 23.33}{1 + (13.86x^2 - 10.99x + 3.42)\, e^{-(0.09x + 0.01)y}}$	$\Phi = (1.4x + 38.2)\, e^{(-0.013)y}$

- The developed models predicted compressive strength and porosity of PC mixes with A/C ratio 2.5 and 5.0 at uncertainties 10% and 6% of the mean values, respectively.

The presented plots of compressive strength or porosity or wet density versus compaction effort for various aggregate gradation aid practitioners and researchers to comprehend the distinct nature of variations between the said parameters. Furthermore, the developed models precisely depict compressive strength or porosity in terms of aggregate gradation and compaction effort. Practitioners and researchers would be benefited by these models while configuring PC mix design parameters for a variety of PC applications.

The presented research could be further extended to study the impact of A/C ratios on compressive strength and porosity as the next step. This extension would help to formulate a single relationship for compressive strength or porosity in terms of A/C ratio, aggregate gradation and compaction effort. With the basis established in this study, further assessment on the influence of aggregate type, grading type and W/C ratio could be possible. From hydraulic perspectives of PC, porosity could be further projected to permeability to characterise the hydraulic conductivity of PC.

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Authors' contributions

Anburuvel A: Data Analysis, Drafting original manuscript and Writing – review & editing.

Subramaniam D N: Conceptualisation, Formal analysis and Writing – review & editing.

Availability of data and materials

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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ORCID

Arulanantham Anburuvel http://orcid.org/0000-0001-5357-4137
Daniel Niruban Subramaniam http://orcid.org/0000-0002-1023-1617

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