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To cite this article: Emmanuel Ejiofor Anike, Karl S. Williams, Leila Khajenoori & Nkiru Ifeanyichukwu Ibeakuzie (2026) Investigating the mechanical and hydraulic properties of permeable concrete with binary combination of waste cockle, scallop and whelk shells, International Journal of Pavement Engineering, 27:1, 2732148, DOI: [10.1080/10298436.2026.2732148](https://doi.org/10.1080/10298436.2026.2732148)

To link to this article: <https://doi.org/10.1080/10298436.2026.2732148>



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Published online: 25 Sep 2026.



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RESEARCH ARTICLE



Investigating the mechanical and hydraulic properties of permeable concrete with binary combination of waste cockle, scallop and whelk shells

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ABSTRACT

The adoption of permeable concrete (PC) for pavement applications can mitigate the risk of flood events in urban areas, and the use of waste materials as a partial substitute for aggregate in concrete will play a significant role in decarbonising the construction sector. This paper presents an investigation conducted on PC incorporating crushed seashells as a substitute for natural aggregate. The experiments involved seven formulations, including a control mix, mixes with 20% aggregate replacement using crushed cockle, scallop, or whelk shells individually, and mixes containing binary combinations of the shells. The results show that the presence of seashells affects the mechanical properties of concrete, but the degree of influence depends on the type of seashell. The lowest compressive strength obtained in this investigation was 8.33 MPa, which is more than the minimum required for PC uses. The addition of seashells enhanced the void content and permeability performances of PC by up to 13% and 31%, respectively. This study presents the first investigation of binary combinations of seashells in PC production, demonstrating their potential to mitigate the limitations of individual shell types while enhancing permeability and reducing the environmental and climate impacts associated with natural aggregate exploitation and indiscriminate shellfish by-product disposal.

ARTICLE HISTORY

Received 11 June 2025

Accepted 4 September 2026

KEYWORDS

Permeable concrete; natural aggregate; seashells; permeability; seashell combination

1. Introduction

Most natural aggregates are derived from a quarrying process involving extraction and crushing operations, thereby leading to energy consumption and carbon (iv) oxide emissions. Additionally, non-renewable natural aggregate (NA) reserves are depleted because of the increasing global demand for construction aggregate. These concerns have compelled the construction sector to look into using waste materials as a substitute for aggregate in concrete production. To this end, different studies have been conducted using waste materials including, but are not limited to, construction and demolition waste (Anike et al., 2020a, 2020b, 2020c, 2022; Fathifazl et al., 2011), palm kernel shell (Ibrahim & Abdul Razak, 2016; Khankhaje et al., 2016), incineration bottom ash (Wu et al., 2016; Zaetang et al., 2015), waste tire rubber (Gesoğlu et al., 2014), polypropylene fibres (Reyad and ElTair, 2024) and seashells (Khankhaje et al., 2017; Kuo et al., 2013; Panda et al., 2020; Williams et al., 2022). Among these industrial by-products, seashells contain a high calcium carbonate content, which has the ability to improve both the mechanical and physical properties of concrete (Mo et al., 2018). In fact, seashells contain over 90% calcium carbonate (Martínez-García and González-Fontebao, 2017, 2020; Richardson & Fuller, 2013; Wang et al., 2019). Although seashells possess offensive smell due to the decay of the animal flesh and/or the decomposition of salts contained in the shells (Tayeh et al., 2020), recycling them into aggregates to be used in concrete production remains an attractive option and can reduce the pressure on depleting NA as well as help to manage our waste arisings responsibly.

Several investigations involving the use of seashells as a replacement for fine aggregate, coarse aggregate, cement or as a filler material in concrete production have been published (Chen et al., 2019; Ez-zaki et al., 2018; Kuo et al., 2013; Martínez-García et al., 2019; Nguyen et al., 2017; Richardson & Fuller, 2013; Soltanzadeh et al.,

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2018; Tayeh et al., 2020; Varhen et al., 2017; Wang et al., 2019; Yang et al., 2010). In most studies, the mechanical properties of concrete were negatively affected when crushed seashell was used to replace normal aggregate. Experiments have revealed that there exists weak bonding between crushed shells and cement paste due to the large surface area of the seashell, resulting in thin cement coating (Martínez-García et al., 2019; Panda et al., 2020). Hence, Varhen et al. (2017) maintained that the effective bonding between crushed shells and cement paste should determine the replacement level of aggregate with seashell in concrete. Another limiting factor is the salt and chloride contents of seashells, which can be harmful to concrete. As a result, it is recommended to employ economical process (such as proper washing with water) and regulate the content of seashell in concrete to minimise the impact of these substances to the least. Also, studies have found that the inclusion of oyster and mussel shells has workability and long-term durability effects on concrete (Ez-zaki et al., 2018; Kuo et al., 2013; Panda et al., 2020; Yang et al., 2010). It should be noted that the ability of seashell to decrease the slump value of fresh concrete is useful in the production of pervious concrete, which requires a zero-slump value.

However, most investigations conducted using waste seashell as a substitute for aggregate by early researchers focused on normal-strength concrete. But seashell particles are flaky, as such, they are more suitable for replacing coarse aggregate in lightweight and low-strength concrete (Nguyen et al., 2013; Varhen et al., 2017). Permeable concrete (PC), otherwise referred to as pervious concrete, no fines concrete, porous concrete, or draining concrete, is a lightweight as well as low-strength concrete that provides the optimal solution in stormwater management for developing sustainable urban drainage systems. PC is designed to have sufficient interconnected voids that produce highly permeable material that allows the passage of water. To achieve these objectives of PC for pavement applications, the properties to be specified for acceptance of the concrete are void content and density, and the idea of adding fine aggregate to the concrete mix remains optional.

In this study, common cockle (*Cerastoderma Edule*), king scallop (*Pecten Maximus*) and common whelk (*Buccinum Undatum*) shells were individually used to replace 20% by weight of aggregate in the production of PC. Also, binary combination of the three shell types was investigated, to study the mechanical, hydraulic and durability performances of the resulting concrete. The idea of binary combinations of shells is to create a more reliable and consistent product by blending locally available shell types, mitigating the variability in properties that can come from relying on a single shell type. In addition, the environmental impact of the PC with seashell compared with conventional PC was investigated using the life cycle assessment (LCA) approach. This work is affiliated to Interreg CIRCLE project aimed at limiting both carbon and climate impacts by using a recycled waste product in PC to be used for cycle paths, car parks and footpaths. It is important to note that 20% by weight of aggregate replacement level was adopted following the preliminary study conducted by the Lead Partner on 10%, 15%, 20% and 25% replacements with seashell. Additionally, the three types of seashells investigated were chosen because they are among the several species of bivalve shellfish that are found in French and UK coastal waters, as the CIRCLE project was undertaken by 6 French and British partners. To the best of the authors' knowledge, no previous study has been conducted using crushed whelk seashells or a binary combination of seashells as a substitute for aggregates in concrete, especially PC.

2. Background

In connection with the climate change that we are currently experiencing, Europe is now facing more extreme weather conditions, with increased precipitation over shorter periods. To tackle this problem, the drainage of road structures is highly recommended. Hence, CIRCLE project was funded by the European Regional Development Fund (ERDF), to develop new commercially viable solutions for permeable surfaces from new concrete formulations with a lower environmental impact, incorporating abundant shellfish co-products in substitution for NA.

It was important to understand the regional availability of waste shell quantities, so as to minimise distances required to transport material to plants and sites. To discover the annual stocks of shellfish waste in the UK, data was gathered over a 12-month period through private communication with the Shellfish Association of Great Britain and its members. It was found that there were large seashell sources in the UK, with yearly availabilities of 14,500 tonnes of cockle shell (CS), 6330 tonnes of scallop shell (SS) and 11,250 tonnes of whelk shell (WS) as shown in Table 1.

Table 1. UK annual regional availability of cockle, scallop and whelk shells.

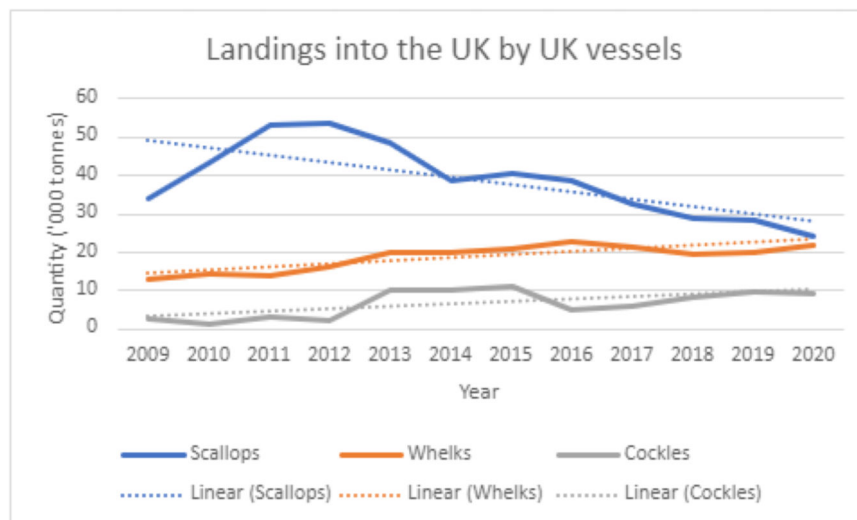
Region	CS (tons)	SS (tons)	WS (tons)
North-East England	—	500	—
North-East Scotland	—	500	2000
South-East England	5500	1500	—
South-West England	—	2680	4100
Wales & North-West England	4000	400	4400
Wash	5000	750	750
Total	14,500	6330	11,250

Figure 1 provides an overview of the UK shellfish industry over an 11-year period between 2009 and 2020. The figures for each species are the total live weight. This is the sum of the live weight of shellfish when caught and before processing occurs, such as shelling. The data shows that both cockle and whelk landings have gradually increased year-on-year over the last decade, doubling their numbers from 2009. Meanwhile, scallops have decreased, at almost half of their peak in 2012, although still the largest industry of the 3 species.

It should be noted that the statistics use data exclusively from fishing vessels. Boats under 10 m in length are not required to report on landing numbers, therefore data may be incomplete. Furthermore, most cockles are hand caught in shallow waters and therefore are not recorded in the graph, somewhat skewing the data. Landings into the UK by non-UK vessels were deemed too small to be included in the analysis.

Currently, waste shells are deemed to be an expensive by-product by shellfish processors. Depending on the species, they have varying levels of utilisation, although these come at a cost to processors. It is estimated that around 90% of shellfish waste is sent to landfill. To dispose of waste shells at landfill sites in the UK, processors are charged £98.60 per tonne (HM Revenue & Customs, 2022), with an additional gate fee of an average of £24 per tonne (WRAP, 2021). This is excluding transportation costs and time spent preparing the waste for landfill. For a business producing hundreds of tonnes of such waste per year, this can be significant. Figure 2 shows the map of the material flows of waste shells from the regions of source in the UK. Over 30,000 tonnes of waste shells go to landfill nationally, each year, costing shellfish processors over £3.5 million per year.

Diverting this waste to the concrete industry presents an economic advantage to shellfish processors and shows the potential of shellfish waste as a sustainable material, particularly in the coastal areas where they are harvested. However, owing to the shellfish distribution in the UK, binary combination of seashells was deemed appropriate and was investigated in this study. This would provide local solutions using locally sourced waste shells, thereby providing a low-carbon sustainable product on a regional basis. Various combinations investigated include cockle with scallop, cockle with whelk, and scallop with whelk.

**Figure 1.** The UK annual shellfish landings by UK vessels (Seifeddine et al., 2021).

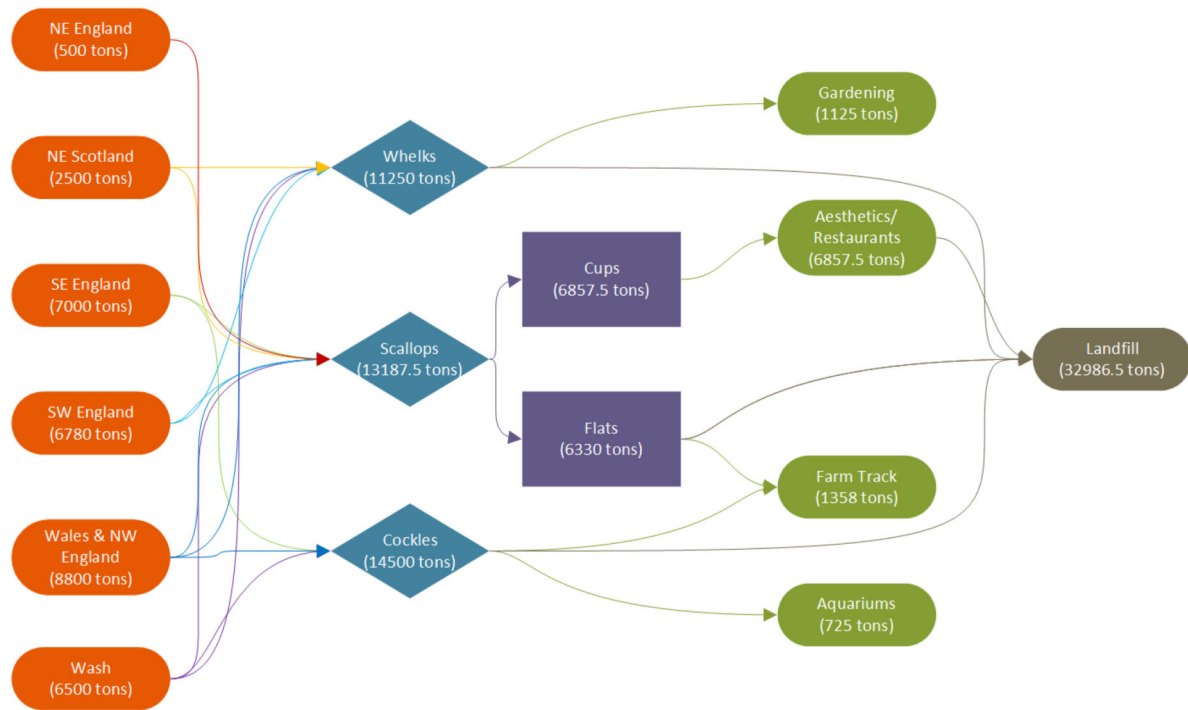


Figure 2. UK waste shell flow analysis.

3. Materials and characterisation

3.1. Water

Clean tap water obtained from the laboratory was used.

3.2. Cement

Rugby brand Portland-limestone cement, CEM II/A-L 32.5R conforming to BS EN 197-1, was used.

3.3. Aggregates

Both natural and crushed seashell aggregates of size range 4–10 mm were used in this study. The NA was supplied by Buildbase company in Preston, United Kingdom, while the seashells were crushed and delivered unsorted by AM Seafoods, Fleetwood, Lancashire. The seashells were crushed using a Christy Turner hammer mill.

3.3.1. Natural aggregate

Limestone of maximum size 10 mm was used. The NA was used as delivered with no further sieving. The properties of the NA were determined and are presented in Table 2.

3.3.2. Seashell aggregate

Three types of seashells shown in Figure 3, namely, cockle, scallop and whelk, were investigated in this study. The crushed shells were supplied in bags, uncleaned and ungraded. The bagged shells were left outside for about 6 months before taken to the laboratory for processing (washing, drying, sieving and grading). The seashells were fairly washed by the supplier and the rain for the period they were kept outside. However, additional washing of the seashells was done as shown in Figure 3(b), (d) and (f), before using them in concrete production. It was ensured that the floating lightweight materials in the shells were removed prior to use. The washed shells were then air-dried, passed through a set of sieves of sizes 10 mm and 4 mm, and the shells retained between the two sieves were characterised and used in PC mixes. The XRF analysis of the seashells

Table 2. Properties of the natural and seashell aggregates.

Properties	Limestone	CS	SS	WS
Specific gravity				
Oven dry	2.56	2.53	2.43	2.24
Saturated surface-dry	2.59	2.62	2.48	2.33
Water absorption (%)	1.2	3.8	1.7	4.1
Bulk density (kg/m ³)				
Loose	1464	786	964	1089
Compacted	1570	946	1089	1232
Void content (%)				
Loose	43	69	60	51
Compacted	38	63	55	45

Note: CS; cockle shell, SS; scallop shell, WS; whelk shell.

are shown in Figure 4, and the results show that all three seashells are composed of more than 90% calcium carbonate.

The properties of the shells are presented in Table 2. The specific gravity and water absorption of the aggregates were determined according to ASTM C127 (2015), while bulk density and voids in the aggregates were obtained according to ASTM C29 (2009). The seashells characterisation showed they are of lightweight aggregates class, with a loose bulk density below 1200 kg/m³. The CS demonstrated higher specific gravity and void content than the corresponding SS and WS. In terms of water absorption capacity, the SS showed a significantly lower value than both CS and WS. In fact, the absorption of SS was comparable to that of NA used. The sieve analyses of both NA and seashell-aggregates used were done and presented in Figure 5. The result shows that all the aggregates are well-graded, however, the particles size distribution of CS and SS are almost the same.

4. Formulation of permeable concrete and characterisation

4.1. Mix design

The mix proportioning guideline for pervious concrete provided in American Concrete Institute ACI 522R-10 (2010) was adopted in this study. Seven mixes were formulated, as shown in Table 3, using a target void content between 20% and 30%. The formulation labelled F1 was composed entirely of NA, while the formulations designated F2, F3 and F4 were made of 20% (by weight of aggregate) of CS, SS and WS respectively, as replacements for conventional aggregate. The F5, F6 and F7 formulations consist of binary combinations of seashells at different ratios (as explained in the note given in Table 3). To maintain both the water absorption of the aggregates and the water-to-cement ratio, all the aggregates used were in saturated surface-dry condition. The quantity of aggregate required for each mix was determined by weight. Trial mixes were conducted, and necessary adjustments in the effective water-to-cement ratio were made until a satisfactory workability with zero slump value was obtained. However, it should be noted that the use of seashells enhanced the workability of the concrete.

In the design of the mixes containing seashells, the overall specific gravity, water absorption capacity and compacted bulk density of the crushed seashells and NA were adjusted accordingly, depending on the replacement level (with seashells) under consideration. This was to ensure that the characteristics of the shell-aggregates were adapted to in the mix design. To account for the differing properties of the shell-aggregates in the mix design, the specific gravity, water absorption and compacted bulk density for the combined aggregate blend were calculated as a weighted average, as shown in Equations (1) to (6). For mixes containing a single shell type, Equations (1)–(3) were used as follows:

$$\text{Specific gravity} = 0.8x_1 + 0.2y_1, \quad (1)$$

$$\text{Water absorption capacity} = 0.8x_2 + 0.2y_2, \quad (2)$$

$$\text{Compacted bulk density} = 0.8x_3 + 0.2y_3. \quad (3)$$

Similarly, the specific gravity, water absorption and compacted bulk density for mixes containing a binary combination of seashells were calculated using the following Equations (4)–(6):



(a)



(b)



(c)



(d)

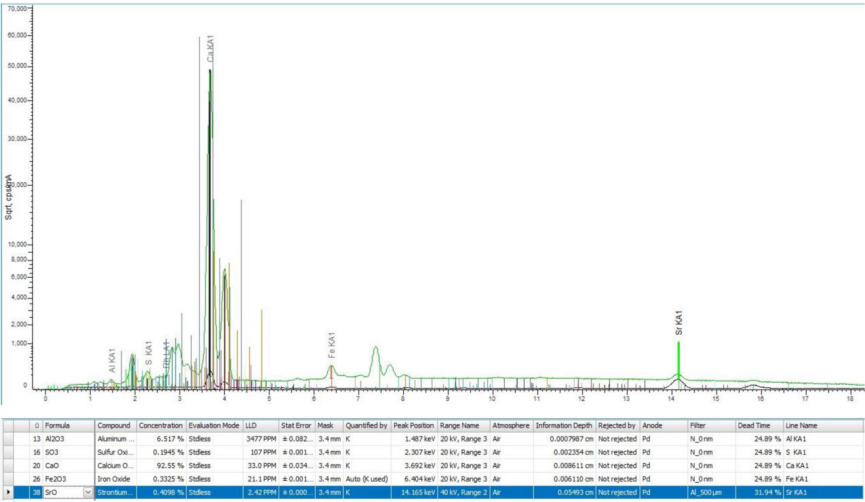


(e)

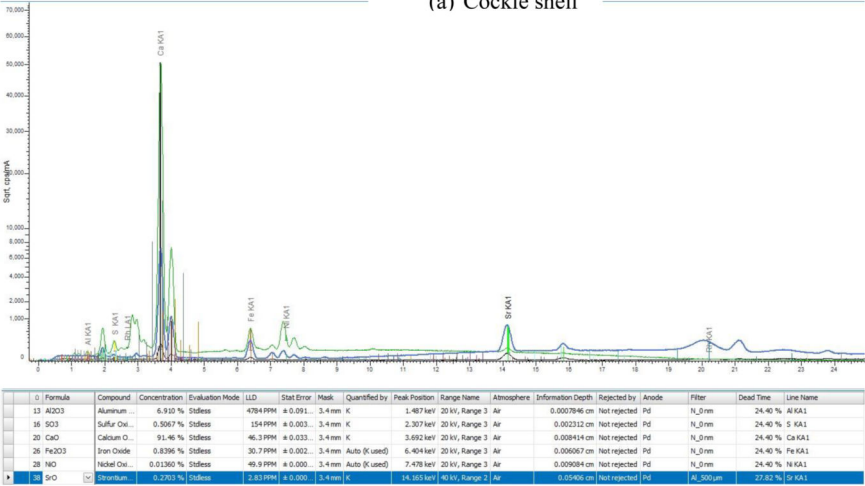


(f)

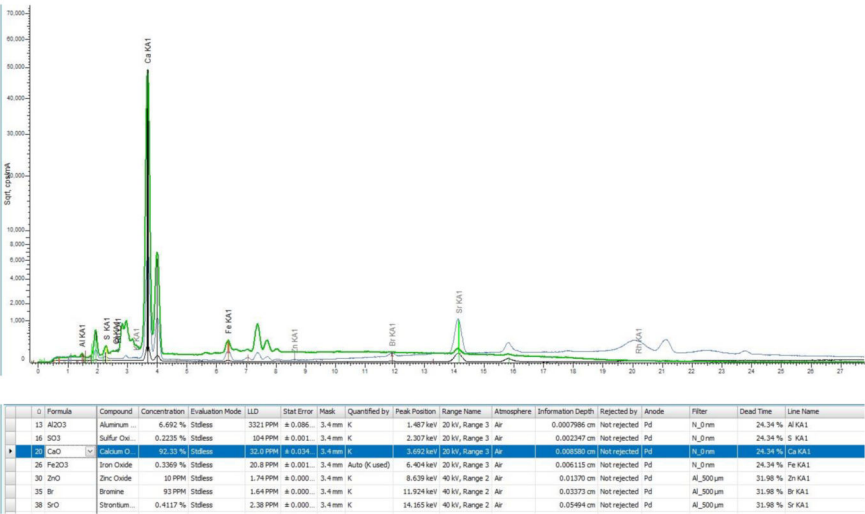
Figure 3. Waste seashells (a) uncrushed cockle shells, (b) crushed, washed and graded cockle shells, (c) uncrushed scallop shells, (d) crushed, washed and graded scallop shells, (e) uncrushed whelk shells and (f) crushed, washed and graded whelk shells.



(a) Cockle shell



(b) Scallop shell



(c) Whelk shell

Figure 4. XRF analysis of seashell.

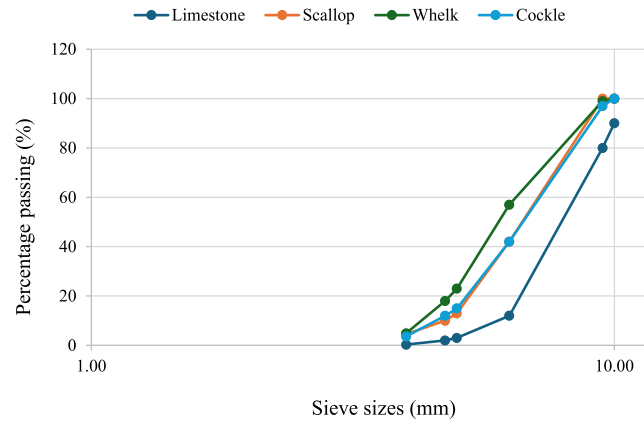


Figure 5. Particles size distribution.

Table 3. Mix proportions of various PC formulations investigated (in kg/m³).

Formulations	Cement (kg)	Limestone (kg)	Water (kg)	Seashells (kg)			w/c
				Cockle	Scallop	Whelk	
F1 (Control)	229	1574.39	78	0	0	0	0.34
F2 (20% CS)	229	1165.28	78	291.32	0	0	0.34
F3 (20% SS)	229	1183.38	78	0	295.85	0	0.34
F4 (20% WS)	229	1212.02	78	0	0	303.01	0.34
F5 (20% CS & SS)	229	1170.71	78	203.92	88.76	0	0.34
F6 (20% CS & WS)	229	1188.65	78	145.66	0	151.51	0.34
F7 (20% SS & WS)	229	1203.43	78	0	88.76	212.11	0.34

Note: cockle and scallop shells are combined in the ratio 7:3, cockle and whelk shells are combined in the ratio 1:1, scallop and whelk shells are combined in the ratio 3:7.

$$\text{Specific gravity} = 0.8x_1 + 0.2(ay_{11} + by_{12}), \quad (4)$$

$$\text{Water absorption capacity} = 0.8x_2 + 0.2(ay_{21} + by_{22}), \quad (5)$$

$$\text{Compacted bulk density} = 0.8x_3 + 0.2(ay_{31} + by_{32}), \quad (6)$$

where x_1 is the specific gravity of conventional aggregate (limestone).

x_2 is the water absorption capacity of limestone.

x_3 is the compacted bulk density of limestone.

y_1 is the specific gravity of the shell type under consideration (SS, CS or WS).

y_2 is the water absorption capacity of the shell type under consideration.

y_3 is the compacted bulk density of the shell type under consideration.

y_{11} is the specific gravity of one of the two combining shell types in F5, F6 and F7.

y_{12} is the specific gravity of the second combining shell type in F5, F6 and F7.

y_{21} is the water absorption capacity of one of the two combining shell types in F5, F6 and F7.

y_{22} is the water absorption capacity of the second combining shell type in F5, F6 and F7.

y_{31} is the compacted bulk density of one of the two combining shell types in F5, F6 and F7.

y_{32} is the compacted bulk density of the second combining shell type in F5, F6 and F7.

a and b are the percentage replacement associated with each of the combining shell types in formulations F5, F6 and F7. The percentage replacement of the combining shell types are as explained in Table 3.

The result obtained from Equations (1)–(6) are shown in Table 4 and used in the design of the PC mixes.

4.2. Production of concrete and preparation of specimens

PC constituents were batched and mixed in a concrete mixer until a consistent mixture was obtained. Immediately, the mix was discharged into a wheelbarrow and then placed in oiled moulds (using a scoop)

where it was compacted and left to harden. After approximately 24 h, the specimens were demoulded and kept in the curing tank until the day of testing. The sequence of activities and details of operation for the concrete production and preparation of the specimens are explained in the following headings.

4.2.1. Batching

Concrete constituents were batched by weight using a weighing balance of 60 kg capacity.

4.2.2. Mixing

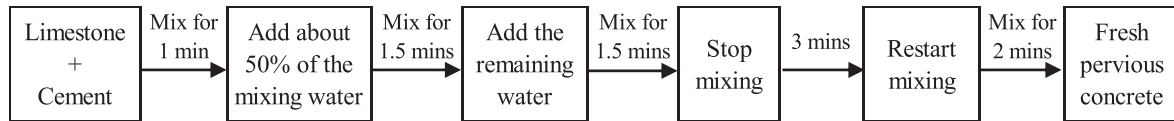
This operation was done in a 70-L capacity concrete mixer. The mixing procedures adopted are illustrated in Figure 6.

4.2.3. Compaction

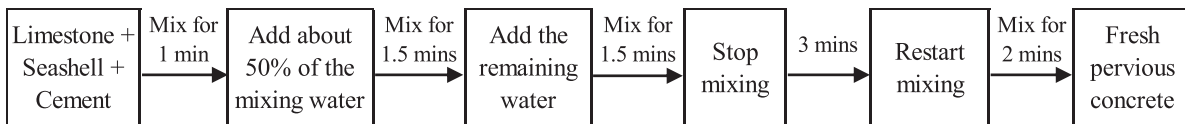
PC was compacted in plastic moulds corresponding to the specimen type and size given in Table 5. Compaction was done in two layers by applying 20 blows (for cubical and cylindrical specimens) and 30 blows (for prismatic specimens) per layer, using a standard proctor hammer shown in Figure 7. In addition, a 5-s vibration using a vibrating table was applied to harmonise the two layers according to Kevern et al. (2008). Finally, the surface of the specimens was finished using a trowel.

Table 4. Adjusted specific gravity, water absorption and bulk density due to inclusion of seashells.

Formulation	Specific gravity	Water absorption (%)	Bulk density (kg/m ³)
F1 (control)	2.56	1.20	1574.39
F2 (20% CS)	2.55	1.72	1259.81
F3 (20% SS)	2.53	1.30	1477.31
F4 (20% WS)	2.50	1.78	1505.91
F5 (20% CS & SS)	2.55	1.59	1457.29
F6 (20% CS & WS)	2.53	1.75	1477.31
F7 (20% SS & WS)	2.51	1.64	1497.33



(a) The control mix (F1 formulation)



(b) Seashells incorporated mixes (F2 to F7 formulations)

Figure 6. Adopted mixing process for PC mixes.

Table 5. Properties of PC investigated with the standards used.

Property of PC	Standard	Specimen		
		Type	Size (mm)	Age (days)
Compressive strength	BS EN 12390-3	Cube	100 × 100 × 100	7 & 28
Splitting tensile strength	BS EN 12390-6 [37]	Cylinder	150 × 300	28
Flexural strength	BS EN 12390-5 [38]	Prism	100 × 100 × 350	28
Freeze and thaw resistance	Nguyen et al. [25]	Prism	100 × 100 × 220	28
Density & void content of hardened concrete	ASTM C1754 [39]	Cylinder	100 × 200	28
Permeability	Falling-head method [36]	Cylinder	100 × 150	28

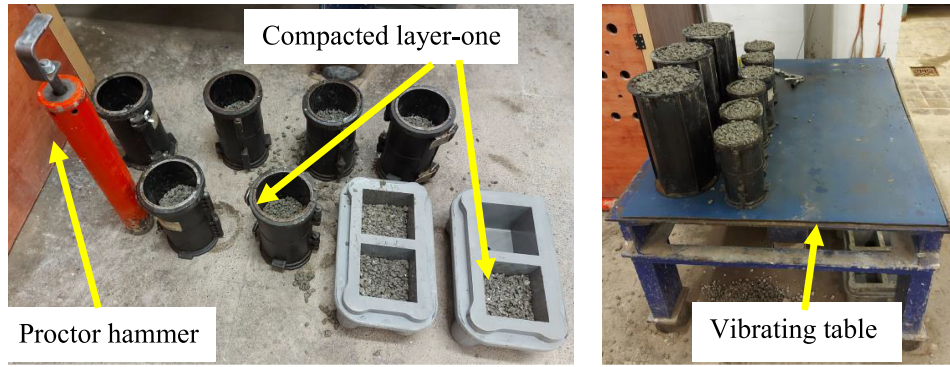


Figure 7. Compaction of specimens.



Figure 8. Curing of specimens: (a) initial curing (b) final curing by water immersion.

4.2.4. Curing

The specimens were initially cured by covering them with plastic sheets, as shown in Figure 8(a), for about 24 h. This method was adopted to avoid rapid evaporation of water in the concrete mix required for the hydration process. Subsequently, the specimens were demoulded and transferred into a curing tank where they were cured by immersion in water at 17 °C (Figure 8(b)) until the day of testing.

4.3. Testing

The investigated properties of PC with the standards employed for testing are presented in Table 5. Because there are no existing test standards for the compressive, splitting tensile and flexural strengths of PC, the recommended loading rates for conventional concrete were adjusted. This is to compensate for the lower strength of PC and to reach a reasonable test duration for each specimen. Thus, the modified loading rates for the compressive, splitting tensile and flexural strength tests in this study are 0.069 MPa/s, 0.05 MPa/s and 0.125 kN/s, respectively. These loading rates gave satisfactory results.

The falling head permeability test apparatus shown in Figure 9 was used to determine the permeability of the PC. In this test method, saturated cylindrical specimens of dimension 100 mm diameter by 150 mm long were confined in a latex membrane and sealed in a rubber collar sleeve with four adjustable hose clips. The test was performed using acrylic tube of external diameter 100 mm, graduated to represent heights of the water. The time taken for water height to change from h_1 (initial level) to h_2 (final level) was recorded and inputted into Equation (7) with other parameters to determine the coefficient of permeability, k , assuming a laminar flow. The value of k is given by:

$$k = \frac{A_1 L}{A_2 t} \ln \frac{h_1}{h_2}, \quad (7)$$

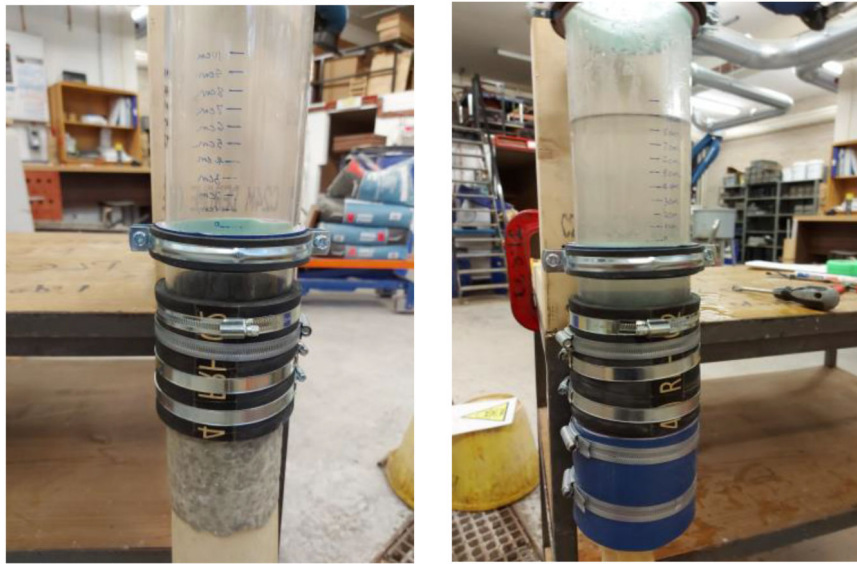


Figure 9. Permeability test setup.

where k is the coefficient of permeability (cm/s), A_1 is the cross-sectional area of the acrylic tube (cm²), A_2 is the cross-sectional area of the specimen (cm²), L is the length of specimen (cm), h_1 is the initial level of water in the tube, h_2 is the final level of water in the tube and t is the time as defined above.

The freeze and thaw resistance of all the concrete formulations was determined according to Nguyen et al. (2017). For this test, the temperature was varied from $-18\text{ }^{\circ}\text{C}$ to $+20\text{ }^{\circ}\text{C}$ for 24 h, and the specimens were fully saturated. After 300 cycles, the deterioration of PC due to freeze and thaw was evaluated based on weight loss and visual inspection.

5. Results and discussion

All the properties of PC investigated are presented in Table 6 and Figures 10–16. The values reported represent the average of three test specimens. In this study, the void content and coefficient of permeability (k) values ranged from 29.0% to 33.2% and 4.6 cm/s to 6.9 cm/s, respectively. The hardened density of the concrete ranged from 1733 kg/m³ to 1825 kg/m³, which meets the requirement for pervious concrete uses. The 28-day compressive strength was found to vary from 8.3 MPa to 11.9 MPa, while splitting tensile strength and flexural strength ranged from 0.60 MPa to 0.73 MPa and 1.50 MPa to 3.0 MPa, respectively. These values obtained meet the requirement for the use of PC for pavement applications.

5.1. Mechanical properties of permeable concrete

5.1.1. Compressive strength

The downside of PC when compared to conventional concrete is its low mechanical strength. Apparently, this is due to the presence of pores in PC and the thin layer of cement paste bonding the aggregates together (Joung & Grasley, 2008). The compressive strength of all the concrete formulations investigated in this study

Table 6. Mechanical and hydraulic properties of PC.

Formulations	Tensile strength (MPa)	Stdev ^γ (MPa)	Flexural strength (MPa)	Stdev ^β (MPa)	Hardened density (kg/m ³)	Void content (%)	k (cm/s)
F1 (Control)	0.68	0.14	3.00	0.07	1825	29.0	4.6
F2 (20% CS)	0.64	0.08	2.30	0.53	1745	30.1	4.9
F3 (20% SS)	0.60	0.17	2.35	0.14	1733	33.2	6.7
F4 (20% WS)	0.73	0.06	2.35	0.26	1813	29.6	5.4
F5 (20% CS&SS)	0.73	0.01	1.50	0.16	1758	31.6	5.6
F6 (20% CS&WS)	0.70	0.02	1.50	0.12	1775	29.4	5.3
F7 (20% SS&WS)	0.62	0.09	1.85	0.49	1748	32.2	5.6

Note: ^γStandard deviation of tensile strength values for 3 specimens, ^βStandard deviation of flexural strength values for 3 specimens.

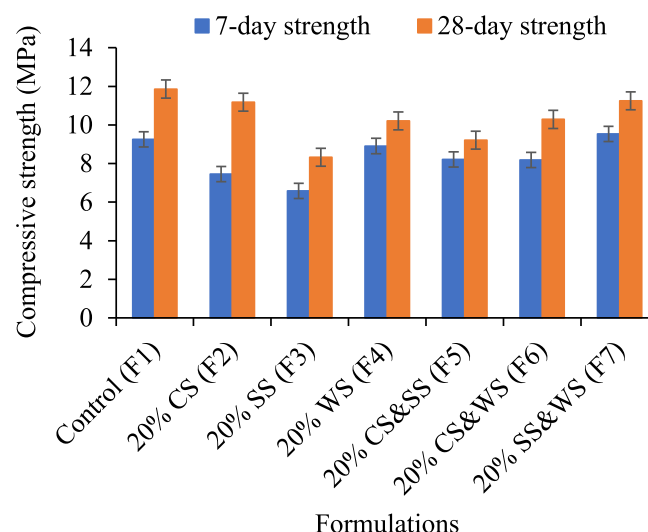


Figure 10. Compressive strength of PC mixes with and without crushed seashells.

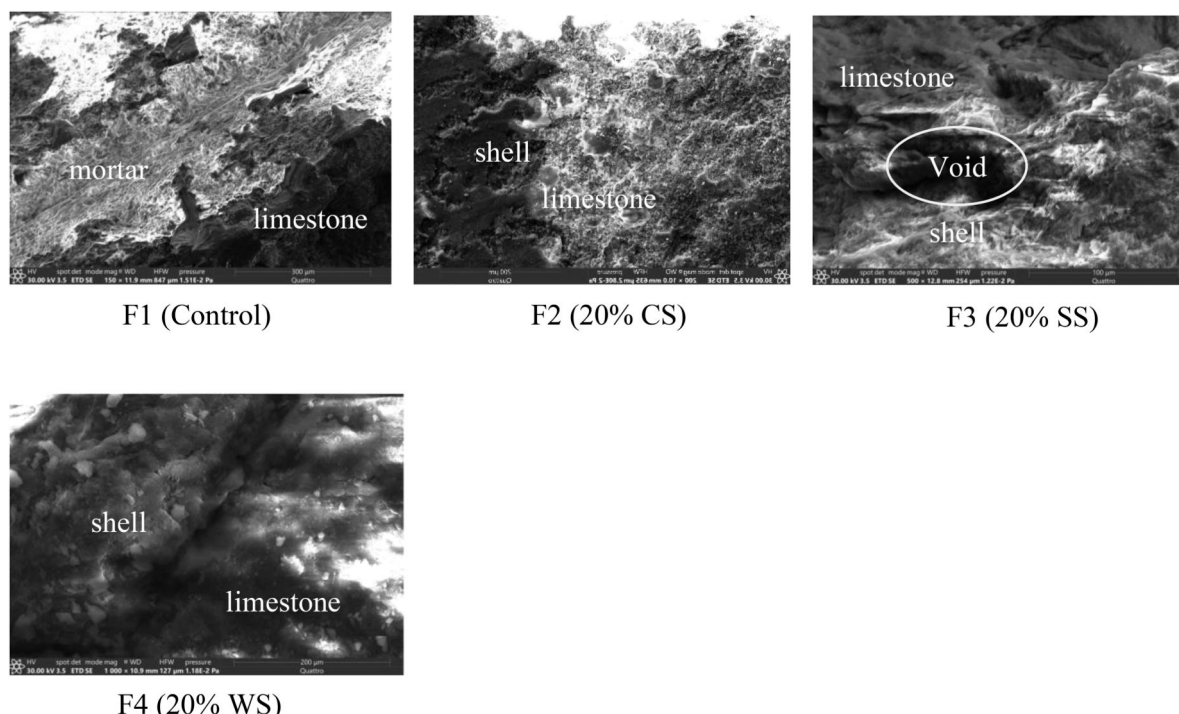


Figure 11. SEM images of the control formulation and the PC formulations with single shell type.

was determined at 7 and 28 days, as presented in Figure 10. The 7-day strength was found to be 78%–90% of the 28-day strength. This range of values agrees with the findings of previous authors (Chandrappa & Biligiri, 2016), who reported that the 7-day compressive strength of PC is 70%–90% that of the 28 days.

According to Seifeddine et al. (2021), the compressive strength of PC required for pavement application ranges from 3.5 MPa to 28 MPa. It can be observed from Figure 10 that the compressive strength of PC for all the mixes investigated exceeded this minimum requirement of 3.5 MPa. The results showed that the addition of crushed seashells as a substitute for coarse aggregate in PC mixes had a reduction effect on the compressive strength, and the shell type and shape are influential to this trend. This is expected because the presence of crushed seashells increases the void content of PC, and the shell with flat shape acts as a wall in the concrete mix, thereby reducing compactness (Nguyen et al., 2013). Different seashells differ in morphology, which will have an impact on packing density of the concrete mixtures and, ultimately, the compressive strength.

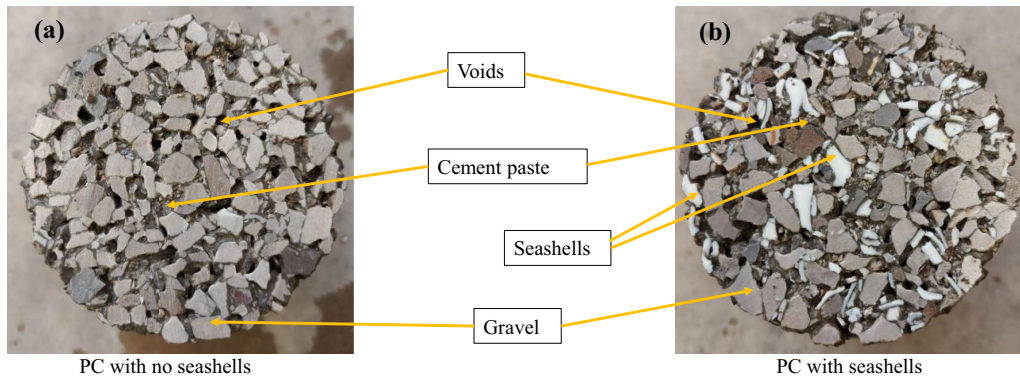


Figure 12. Cross-sections of PC: (a) without seashells (b) with seashells.

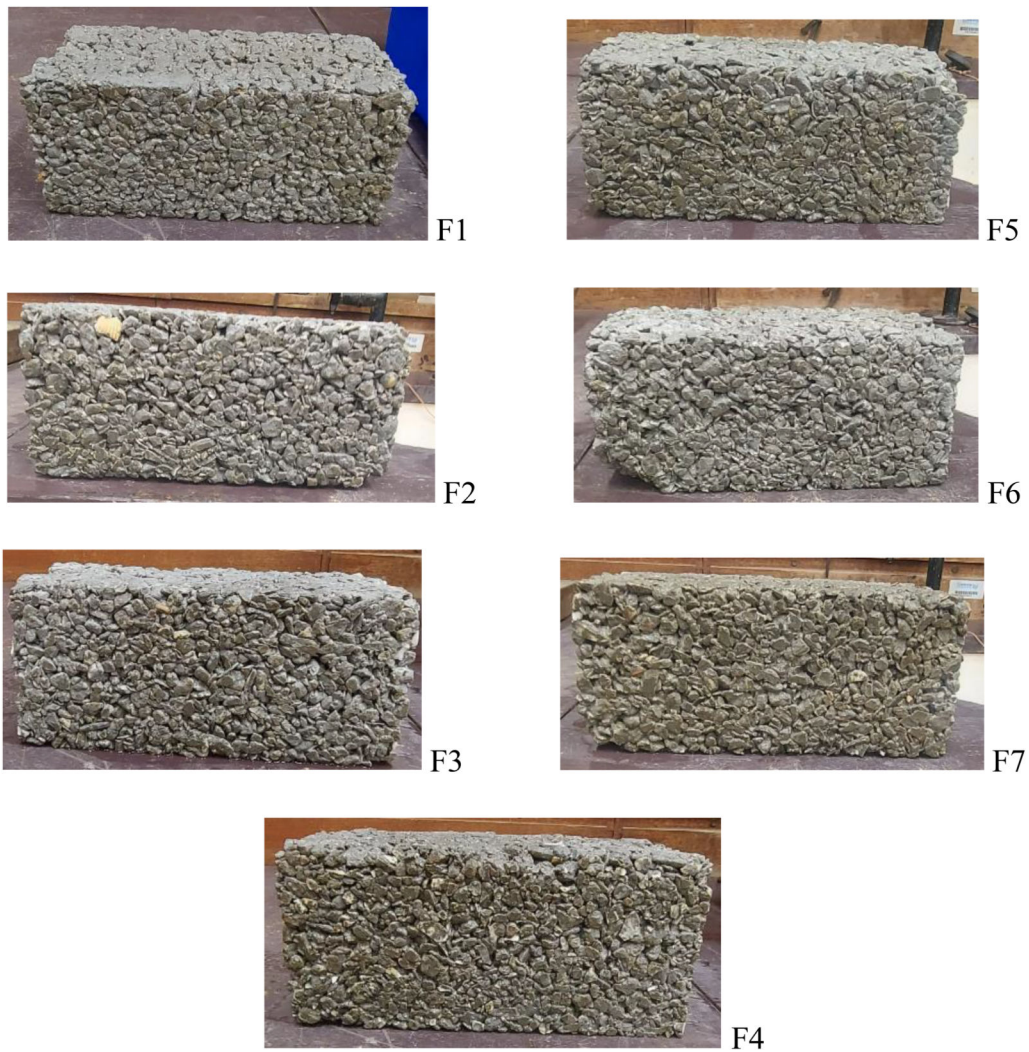


Figure 13. Specimens after 300 cycles of freeze and thaw test.

According to Figure 10, the 7-day compressive strength was decreased by 19.5%, 28.9%, 3.8%, 11.2% and 11.7% when F1 was compared with F2, F3, F4, F5 and F6 formulations, respectively. Interestingly, formulation F7 made of a binary combination of seashells exhibited higher compressive strength at 7 days than the other formulations, including the control. At 28 days, the compressive strength of F2, F3, F4, F5, F6 and F7 was reduced by 5.7%, 29.8%, 13.9%, 22.3%, 13.2% and 5.1%, respectively when compared to F1. The data presented in Figure 10 show that formulation F2 composed of CS gave a higher compressive strength compared to F3

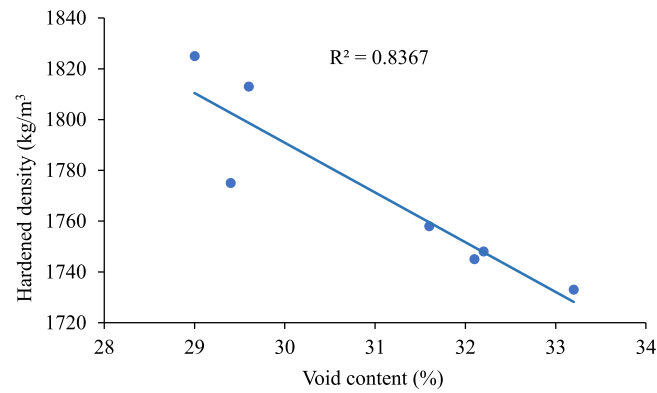


Figure 14. Relationship between hardened density and void content.

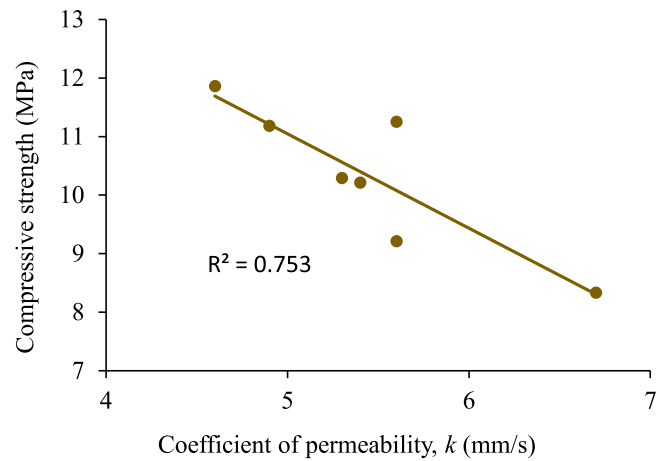


Figure 15. Relationship between the compressive strength and permeability of PC.

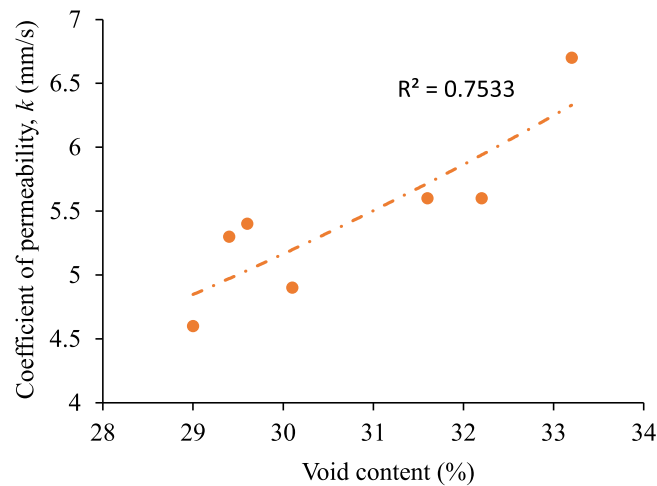


Figure 16. Relationship between permeability, k and void content of PC.

and F4 incorporating SS and WS, respectively. While the formulation F4 with WS, in turn, exhibited higher strength performance than the comparable formulation F3 with SS. Because both CS and WS are curved in shape and SS is flat-shaped, this demonstrates that the shape of seashells affects the compressive strength of the concrete. This is in accordance with previous research, which upheld that seashells of rounded shape reduce voids within the aggregate and improve bonding with cement paste (Mo et al., 2018; Yoon et al., 2004),

while the flat-shaped seashells do not have a good granular arrangement, thereby limiting the concrete strength (Nguyen et al., 2013). Thus, the rounded CS and WS particles gave a higher strength performance than their corresponding SS of flat-shaped particles. The flat shape of the SS particles reduces the packing density and cause stress concentrations, leading to a lower strength. It can also be deduced that the binary combination of seashells improved the strength performance of the individual shell type (for example, F5, F6 and F7 compared to F3).

The causes of strength reduction in shell-substituted PC include, but are not limited to, the following factors:

- (i) Increased overall void content,
- (ii) Inherent weaker strength of the crushed seashells,
- (iii) Morphology of crushed seashells—the bonding between NA and flat-shaped seashells is weak and,
- (iv) Greater surface area of crushed seashells when compared to NA, which results in thin coating of the cement paste between the grains of the NA and seashells.

The SEM images obtained with 1000 times magnification for the control formulation and the formulations with single shell types are shown in Figure 11. The focus of the SEM analysis was on the interface between the shells and NA. The existence of void in the SS–limestone interface suggests the reason why F3 formulation had the lowest compressive strength. Conversely, the shell–limestone interface visually observed in F2 sample shown in Figure 11 is similar to the limestone–mortar interface in the control PC. This demonstrates why F2 exhibited the highest compressive strength among all the formulations incorporating seashells.

5.1.2. Density

The hardened densities of the different PC mixes studied were determined and are presented in Table 6. It can be deduced that the presence of crushed seashells caused a decline in this property of the pervious concrete. Nevertheless, the use of WS gave a comparable result to that of the control mix, and the formulations constituting binary combinations of shells (that is, F5, F6 and F7) exhibited higher density when compared with F2 and F3 prepared with a single shell type. Also, looking at density of F4 in Table 6, it is expected that any formulation containing WS in the binary combination of seashells would produce PC of higher density than those made of CS or SS combination. But this is not the case when the density of F5 is compared with that of F7. F5 which comprises of CS and SS had a higher density than F4 made of SS and WS. This can be attributed to the fact that CS and SS have a similar gradation (see Figure 5), offering a better packing density of the aggregates and thus a higher density of the PC mix.

5.1.3. Flexural and tensile splitting strengths

Even though the flexural and tensile strengths of concrete are not among the factors upon which PC should be specified, they are required for functionality purposes and to examine the effect of seashells on these properties. In a review carried out by Singh et al. (2020), the flexural strength of PC ranged from 1 to 3 MPa. From the data provided in Table 6, the flexural strengths obtained lie within this range, but the inclusion of seashells reduced this property by up to 50% when compared with the reference mix without seashells. However, it can be deduced that the reduction observed in the flexural strength of PC containing seashells does not depend on the shell type used. The PC formulations (F5–F7) incorporating binary combinations of seashells exhibited a lower flexural strength than their equivalent formulations with one type of seashell. For instance, the highest flexural strength attained by PC mixes made of binary combination of shells was 1.85 MPa, while those prepared with single shell type attained up to 2.35 MPa. This significant reduction may be due to stress concentration and microcracks under bending created by different shell types. Another factor could be as a result of weak zones created by local changes in paste properties or a reduction in paste available for hydration due to the different water absorption capacities of the combined shells. Moreover, different textures and surface chemistries between the two shells may produce inconsistent bonding with the cement paste and more weak zones where cracks initiate.

On the other hand, the tensile splitting strength of PC was not negatively affected by the addition of seashells. In fact, formulations F4, F5 and F6, containing either single or two types of seashells had higher tensile strength than the standard formulation (F1), with no seashell. Owing to the flaky nature of seashells, some particles may have split during the mixing operation and acted as fillers in the mix, thereby bridging crack propagation and leading to improved tensile strength. This result shows that seashell PC has a similar crack resistance as the comparable conventional pervious concrete, leading to similar durability and structural integrity. Additionally, this result indicates that the tensile splitting strength of PC is not affected by the shell type, provided the same range of particles size is used.

5.2. Hydraulic properties of permeable concrete

5.2.1. Void content

The objective of PC from mix design to production is to achieve adequate void content and connected pores to allow the passage of water. The void content of all the concrete formulations investigated fall within the acceptable range of values (22.6% to 37.0%) specified in the test standard ACI 522R-10 (2010) adopted in this study. Although the PC formulations containing SS had void content values above the target range, the values are within the permissible range. According to ACI 522R-10 (2010), there is a tolerance of $\pm 5\%$ of the specified void content. The results in Table 6 show that there is no significant difference between the void content of the concrete mixes consisting of curved-shaped seashells (F2, F4 and F6) and that of the reference mix without seashells. Conversely, all the PC formulations containing flat-shaped seashells (that is, F3, F5 and F7) showed up to 13% higher void content than the reference formulation. It can be deduced that the shape of the seashells affected the void content of the developed pervious concrete. This is obvious when F4 prepared with only WS is compared with F7 consisting of 70% WS and 30% SS. The void content increased from 29.6% to 32.2%, demonstrating the effect of replacing curved shape seashell particles with flat ones. Similar trend can be seen when the void contents of F2 prepared with CS is compared with F5 constituting of 70% CS and 30% SS. Furthermore, with binary combination of seashells, the void contents of the resulting PC were normalised closer to that of the standard PC.

5.2.2. Permeability

This property of PC was measured by determining the coefficient of permeability, k using the falling-head test method. According to Table 5, the introduction of seashells as aggregate replacement increased the permeability of PC. This observation agrees with the findings reported by Khankhaje et al. (2017) and Nguyen et al. (2013). In this study, the use of SS in PC formulation resulted in a higher permeability coefficient when compared with the use of CS or WS. This demonstrates that different shell types have varying degree of influence on the permeability of PC. As already explained, the morphology of the SS increases the overall void content which has a direct effect on the permeability coefficient. However, PC with binary combination of seashells produced permeability values lying between those made of one shell type and the standard PC.

Figure 12 shows the cross-section of both PC samples with seashells and without seashells. It can be observed that crushed seashells have angular shapes which tends to create larger interparticle voids, thereby increasing permeability. This may be the reason why F3 formulation prepared with SS (which is angular in shape) showed a higher permeability than the comparable F2 and F4 formulations prepared with CS and WS, respectively. On the other hand, curved seashells may partially overlap or interlock in the concrete mix, obstructing continuous pore connectivity and thereby reducing permeability. However, it is obvious from Figure 12 that the orientation of the seashells in the mix is either linear or at an angle of 90° to the direction of the cut. Linear orientation is likely to bridge the interconnectivity of pores in the mix, thus reducing permeability, while perpendicular orientation may favour the connectivity of pores, which enhances permeability.

5.3. Freeze and thaw durability of permeable concrete

The freeze and thaw resistance of the PC mixes investigated in this study is presented in Figure 13 and Table 7. The test was carried out using $100 \times 100 \times 220$ mm specimen prepared from each mix and cured by water immersion for 28 days.

After subjecting the specimens to 300 cycles, the freeze and thaw durability as a function of mass loss was evaluated, and presented in Table 6. The result indicates that:

- (i) the control specimen had the highest resistance compared to the other specimens incorporating seashells,
- (ii) PC made of binary combination of curved-shaped (CS&WS) seashells offers higher resistance to freeze and thaw than those composed of curved and flat shapes (CS&SS or SS&WS) seashells.

It can be concluded that the substitution of 20% by weight of aggregate with one or two types of seashells in PC does not adversely affect the performance of the concrete against freeze and thaw cycle.

5.4. Relationships between material properties

As expected, the results show that both the hardened density and compressive strength of PC have an inverse relationship with the void content and coefficient of permeability, as shown in Figures 14 and 15, respectively. However, the coefficient of permeability increased exponentially as a function of void content, as indicated in Figure 16.

6. Life cycle assessment

This study investigated the environmental impacts of conventional PC and PC containing waste seashells for pavement applications using ISO14040 (ISO: 14040 2006) life cycle assessment (LCA) methodology. The environmental impact, based on the life cycle inventory of the different concrete mixtures, was estimated. SimaPro 9.1 software was used to conduct the estimation of life cycle impact assessment. Inventory analysis was used to quantify the inputs (energy and materials) and outputs (emissions and waste) of the pavement system. The inventory included data on the production of raw materials, transportation of raw materials to the concrete mixing and manufacturing sites and concrete production. Life cycle inventory data was converted into potential environmental impacts using the CML-IA baseline method. The impact categories considered were: (a) abiotic depletion, (b) acidification, (c) eutrophication, (d) global warming potential (GWP), (e) ozone layer depletion (ODP), (f) human toxicity, (g) freshwater aquatic ecotoxicity, (h) marine aquatic ecotoxicity, (i) terrestrial ecotoxicity and (j) photochemical oxidation.

6.1. Environmental impacts

Figure 17 presents the values obtained from the quantification of the environmental impact categories for the different PC mixtures: F1 control pervious concrete, F2 is the PC made of 20% seashells with a reject loss of 50% of shells during preparation and F3 represents the PC comprising of 20% seashells with no loss of shells during preparation. The environmental impacts are presented as a percentage of the greatest impact in each category. The results indicate that, except for Abiotic depletion (fossil fuels) and ODP, F1 had higher environmental impact in all other environmental impact categories, including GWP, human toxicity, acidification and eutrophication as compared to F2 and F3. F3 had the lowest impact on all the environmental impact categories when compared to F1 and F2. The results show that the comparatively poor environmental performance of F2 in abiotic depletion and ODP is attributed to the loss of seashells during the processing stage and their subsequent disposal within landfill sites. In this case, the environmental benefits of substituting limestone with waste seashells are reduced by sending 50% of the seashells to landfills.

Table 7. Freeze and thaw results.

Formulations	Mass before testing (g)	Mass after testing (g)	% Reduction
F1	4607.2	4599.5	0.17
F2	4203.5	4187.6	0.38
F3	4318.8	4296.2	0.52
F4	4419.2	4390.7	0.64
F5	4282.4	4242.1	0.94
F6	4237.8	4218.5	0.46
F7	4323.0	4258.8	1.49

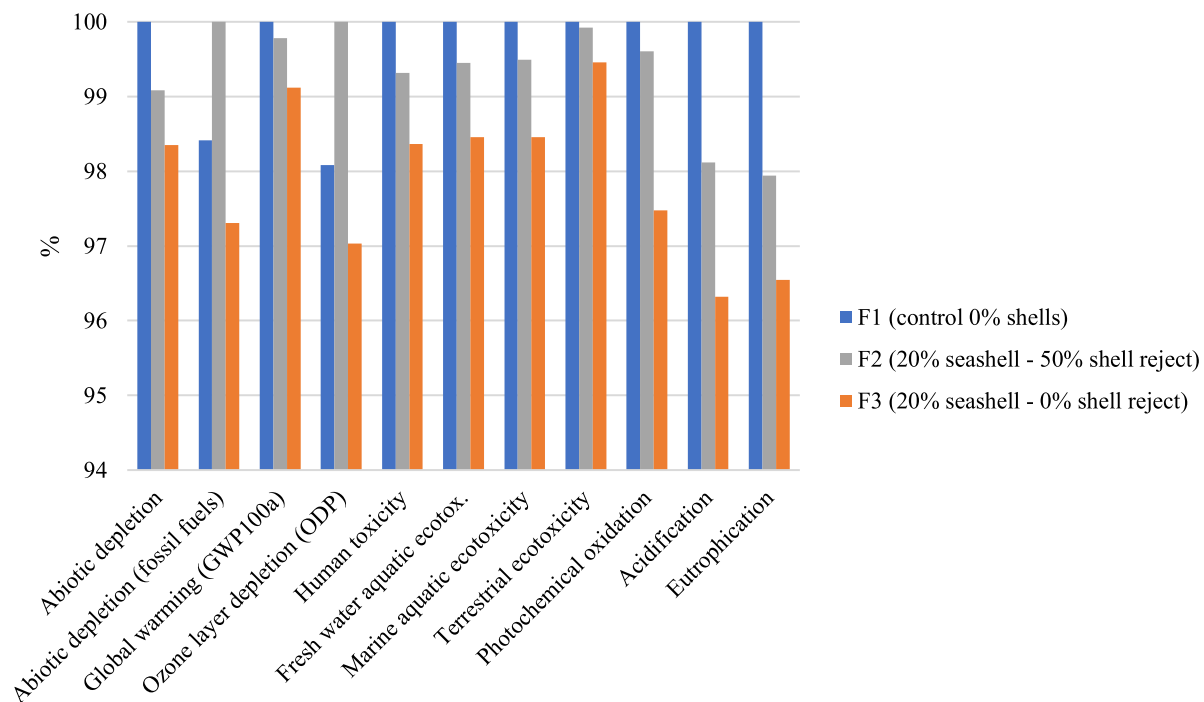


Figure 17. The comparative environmental impacts of pervious concrete mixtures.

The GWPs of F2 and F3 were 0.2% and 0.9% lower than that of F1, indicating the ability of the waste seashells to improve the environmental performance of the pervious concrete mixtures. It is important to highlight that, though the GWP differences are not as high as other studies have demonstrated, especially when replacing cement with seashell waste, if the carbon burden associated with sending waste seashells to landfill is considered, GWP savings for F2 and F3 would be higher.

Also, Figure 18 shows that 20% replacement of limestone with seashells (with a 50% rejection rate, F2) results in an average reduction of 24% GWP, while replacing 20% of limestone with seashells (with a hypothetical 0% rejection F3) results in a 91% reduction in GWP. It can be deduced that a reduction in shell rejection during processing to below 30% would significantly reduce the GWP of PC with seashell. The water and energy used in processing the rejected shells which are sent to landfill will be saved. However, it is important to highlight that cement production is the main GWP contributor for all three PC formulations and therefore applying sustainable cement substitutes would improve the overall impact of the material. The results clearly demonstrate that replacing limestone with waste seashells is an important step toward producing low-carbon sustainable pervious concrete.

7. Conclusions and recommendation for future studies

7.1. Conclusions

This paper presents an investigation carried out on the mechanical, hydraulic and durability properties of permeable concrete (PC) prepared with natural and waste seashell aggregates for low-strength applications in cycle paths, car parks and pavements. Three types of seashell aggregates, namely, cockle, scallop and whelk shells, were investigated, in which the crushed seashells were first of all used individually and thereafter combined to replace 20% by weight of natural aggregate (NA) in the formulation of PC mixtures. The characteristics of the crushed seashells showed that they are lightweight aggregates with loose bulk densities less than 1200 kg/m³. Based on the experimental results and analysis, the following conclusions are drawn:

- The use of crushed seashells as NA replacement in PC increased the void content of the concrete by up to 13%, with the morphology of the seashell-aggregates determining the degree of influence.

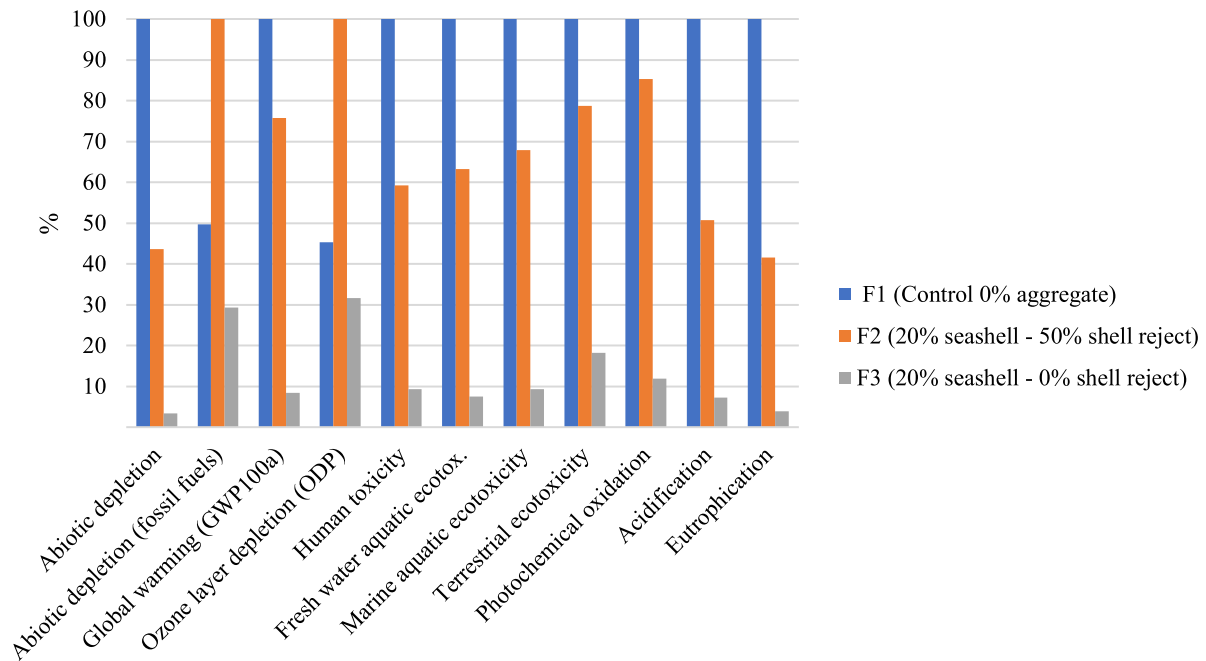


Figure 18. The environmental impact of substituting limestone with seashells.

- The permeability of PC was significantly enhanced by up to 31% for mixes with scallop shells compared with the reference mix. Similarly, 18% increase in the permeability coefficient was recorded when a binary combination of seashells was adopted.
- Adapting to binary combination of seashells in PC formulations did not cause any devastating effect on the properties of the concrete investigated, and the results obtained did not vary significantly with the control formulation when cockle and whelk shells were combined.
- Hardened density was not adversely affected by the replacement of NA with seashells. The results of the hardened density obtained were above the minimum required for the use of PC, with a negligible difference between the density of PC incorporating whelk shells and that of the control formulation.
- Other mechanical properties of PC were reduced by the addition of seashells. The compressive strength was reduced by up to 30%; however, all the values obtained remained above the 5 MPa strength requirement for pavement application. Conversely, the splitting tensile strength of the majority of the mixes incorporating crushed seashells was found higher than that of the control mix. Freeze and thaw durability of PC was marginally reduced by the presence of seashell-aggregates.
- The LCA results demonstrated, based on the functional unit of the study, that it is possible to replace 20% limestone with shells. This is equivalent to 52 kg of waste seashells per 1 m² of concrete.

7.2. Recommendation for future studies

The use of seashell by-product (which is currently destined for the landfill) as a partial replacement for NA in PC can reduce the pressure on depleted NA reserve, contribute towards a circular economy and help in climate change adaptation. However, further research is recommended to understand the long-term performance of PC made of seashells under various environmental conditions. Specifically, future studies should investigate both the chemical resistance and the clogging behaviour and maintenance of PC containing two different shell types as aggregates. These two aspects would deepen understanding of the durability and functionality of the material, as well as facilitate its adoption as a sustainable construction material in diverse environmental contexts.

Acknowledgements

The authors would like to express appreciation for the support of the CIRCLE project Interreg V-A France (Channel) England Programme, co-funded by the European Regional Development Fund (ERDF) under Project ID 26757 (CCI 2014TC16RFCB038).

Disclosure statement

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

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