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Investigating the effect of mixture design parameters on pervious concrete by statistical modelling

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HIGHLIGHTS

- ▶ W/C, cement content and aggregate content are key parameters controlling the performance of PCPC.
- ▶ The higher aggregate content was optimally covered by cement paste in PCPC.
- ▶ Optimization analysis showed that the desirability function for PCPC change with specified goals.

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ABSTRACT

In this study, the effects of water-to-cement ratio (W/C), cement content and coarse aggregate content on the density, void ratio, infiltration rate, and compressive strength of portland cement pervious concrete (PCPC) were investigated by statistical modelling. Two-level factorial design and response surface methodology (RSM) were used. The PCPC mixtures were made with W/C in the range of 0.28–0.40, cement content in the range of 350–415 kg/m^{3}and coarse aggregate content in the range of 1200–1400 kg/m^3. In addition, examples were given on using multi parametric optimization to produce isoresponses of a desirability function for PCPC satisfying specified criteria including cost. The results show that W/C, cement content, coarse aggregate content and their interactions are key parameters, which significantly affect the characteristic performance of PCPC. The statistical models developed in this study can facilitate optimizing the mixture proportions of PCPC for target performance by reducing the number of trial batches needed.

1. Introduction

With population growth, continual urbanisation has led to an increase of impervious surface areas, which block the percolation of precipitation from rainfall and snow down through the ground. This increases the potential for excess surface runoff, which can lead to downstream flooding, bank erosion and possibly transport of pollutants into potable water supplies. At the same time, there is a public concern about the conservation of water resources and quality. For example, to respond to these challenges, the UK government has recently issued the Flood and Water Management Act 2010 after the flooding events in 2007. It includes requirements for Sustainable Urban Drainage Systems (SUDSs) for all new construction works (e.g. buildings and roads), which prevent direct infiltration of water through natural soil. Schedule 3 of the Act generally describes sustainable drainage as the management of precipitation from rainwater, snow or other sources to reduce the risk of flooding, improve water quality and protect the environment and health and safety [1].

Portland cement pervious concrete (PCPC) is a special type of concrete characterized by an interconnected pore structure and high void content/porosity typically in the range of 15–35% by volume, thus allowing direct infiltration of water through its structure (Fig. 1). While its constituent materials are similar to that of normal concrete, PCPC contains little or no fine aggregate [2,3]. It is also known as no-fines concrete, permeable concrete, porous concrete and enhanced porosity concrete. PCPC has been used in a variety of applications, notable among which are low-traffic pavements such as parking lots and sidewalks.

It is believed that PCPC can effectively assist solving drainage problems and reducing the risk of flash flooding, resulting from continuous urban developments. For example, PCPC pavements are now being used in applications of sustainable developments in US, where its characteristic high permeability is used to reduce surface runoff and the need for separate storm water retention ponds and/or large size storm sewers. Its open cell structure permits storm water to readily filter through the pavement into the

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Fig. 1. PCPC in the fresh state.

underlying soil, thereby contributing to capturing pollutants during the first flush of rainfalls, preserving water quality in streams and rivers and recharging groundwater supplies [2–4]. According to the United States Environmental Protection Agency (EPA), stormwater runoff can send as much as 90% of the pollutants (such as oil and other hydrocarbon liquids found on the surface of traditional parking lots) directly into the rivers and streams. To address this problem, EPA currently requires state and local governments to implement measures to reduce stormwater runoff and improve its quality. PCPC has been recognized by EPA as a best management practice to address this environmental concern. The open cell structure of PCPC provides a media for aerobicbacteria that disintegrate the structure of many pollutants that seep from parking areas. In addition to all of these benefits, PCPC can be produced at a low cost; thus, it can be considered among the most attractive SUDS [5–8].

The optimization of pervious concrete mixture designs often requires several trial batches to achieve adequate balance of porosity/permeability, mechanical properties and cost effectiveness. In this study, a factorial design approach was used to determine the effect of water-to-cement ratio (W/C) and contents of cement and coarse aggregate on key properties (density, void ratio, infiltration rate and compressive strength) of pervious concrete. Based on the experimental results, statistical modelling was used to investigate the balance among mixture design variables, which leads to optimum void ratios and infiltration rates, while maintaining adequate strength and minimum cost.

2. Methodology

2.1. Statistical design and modelling of experiments

A factorial experimental design was used to evaluate the influence of two levels (maximum and minimum) of each mixture design variable on the key properties of PCPC. Three key parameters, which should have significant effect on the characteristics of PCPC, were selected to formulate the mathematical models for evaluating the relevant properties (i.e. $n = 3$ in this study, thus the number of mixtures for the factorial experiment was $2^3 = 8$). Additionally, a mixture at the central point was replicated four times to estimate the experimental error and improve the reliability of the models. The coding and levels of the mixture design variables (W/C and contents of cement [C] and coarse aggregate [CA]) are given Table 1.

The modelled experimental region consisted of mixtures ranging from coded variables of −1 to +1. The factorial models are valid for PCPC mixtures made with W/C of 0.28–0.40, cement content of 350–415 kg/m^{3}and coarse aggregate content of 1200–1400 kg/m^3. The responses modelled were fresh density, hardened density at 7 and 28 days, void ratio, infiltration rates at top and bottom of cylindrical specimens and compressive strength at 7 and 28 days.

Analysis of variance (ANOA) was used to test the significance of regression models, and *t*-tests were performed to identify the non-significant (NS) variables and second order interactions, which were subsequently eliminated from the derived models. Model coefficients were determined using multi-linear regression analysis based on a normal distribution assumption. The error was assumed to be random and normally distributed, so the residual terms, which represent the difference between the actual and predicted values should exhibit similar properties [9]. The probability value (Prob.) obtained from ANOVA determines the statistical significance of each factor and their interactions. For most of the parameters, the probability that the derived coefficients associated with the various variables influencing each response were limited to 10%. This signifies that there is less than 10% chance or 90% confidence limit that the contribution of a given parameter to the tested response exceeds the value of the specified coefficient.

2.2. Materials and mixtures

The PCPC mixtures investigated in this study were prepared with Standard CEM I 42.5 N portland cement (OPC). The chemical and physical properties of cement are given in Table 1. Single-sized crushed basalt coarse aggregate with nominal particle size of 20 mm was used in all mixtures. The specific gravity and water absorption of coarse aggregate were 2.7% and 1.6%, respectively. The ranges of W/C, cement content (C) and coarse aggregate content (CA) were 0.28–0.40, 350–415 kg/m^3 and 1200–1400 kg/m^3, respectively (Table 2). A polycarboxylate based superplasticizer with a specific gravity of 1.1 and solid content of 42% was added to mixtures produced with a W/C of 0.28 to improve workability. The proportions of the PCPC mixtures are shown in Table 3.

2.3. Testing procedures

For each mixture, triplicates of 100 × 200 mm cylinders and 100 mm cubes were prepared in three and two layers, respectively with each layer tamped 15 times using a standard compacting bar, similar to the one described in BS EN 12390–2 [10] and BS EN 12350–6 [11]. Excessive tamping was avoided in order to prevent blockage of the PCPC open pore structure. Excess concrete above the upper edge of the mold was removed, and a steel trowel was used to press on the surface for levelling. It is worth mentioning that there are currently no standard procedures for the preparation of PCPC laboratory specimens. The specimens were demolded after 24 h, and subsequently stored in a water curing tank maintained at a temperature of 20 ± 2 °C until the time of testing.

The fresh properties of the PCPC mixtures were assessed according to BS EN 12350–2:2009: Testing fresh concrete – Part 2: Slump test [12] and Testing fresh concrete – Part 6: Density [11]. Most mixture design combinations of PCPC produced stiff consistency as indicated by almost zero slump values (e.g. Fig. 1), which conforms to common experience with this type of concrete. The compressive strength of cubic specimens (BS EN 12390–3:2009[13], Testing hardened concrete – Part 3: Compressive strength of test specimens) was determined after 7 and 28 days.

The average void ratio of PCPC specimens (cubes and cylinders) was evaluated using an apparatus described in BS EN 12390–7:2009 [14] and calculated by:

$$\text{Void ratio} = \left[1 - \left(\frac{W_2 - W_1}{V\rho}\right)\right] \times 100 \quad (1)$$

Table 1
Chemical and physical properties of cement.

	Material CEM I
SiO_2	20.8
Al_2O_3	5.0
Fe_2O_3	3.2
MgO	2.6
CaO	63.7
Na_2Oeq	0.39
LOI	0.65
Specific gravity	3.14
Specific surface area (m2/kg)	385

Table 2
Coding and absolute values for the parameters investigated.

Parameter	Coding values		
	−1	Central point	+1
W/C	0.28	0.34	0.40
C (kg/m^3)	350	383	415
CA (kg/m^3)	1200	1300	1400

W/C: Water-to-cement ratio.
C: Cement content.
CA: Coarse aggregate content.