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2D and 3D Porosity and Permeability of Previous Concrete

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Abstract

Previous concrete is a special, highly porous concrete used in applications that allow water to pass through it, such as parking areas and park walkways. In this research, three pervious concrete mixes were designed and produced by fixing all amounts of their raw materials (cement, water and gravel) but changing the gravel particle sizes as (4.75-10 mm), (10-14 mm) and (14-20 mm). by adopting 2-dimensional and 3-dimensional techniques, porosity (pore volume), compressive strength and permeability of the selected mixes were investigated. The results showed that the volumetric pore volume (3D porosity) of pervious concrete can be predicted by adopting the Image analysis technique (2D method). In addition, using smaller-sized aggregate (4.75-10 mm) helped in enhancing the pore structure, compressive strength (30% more) and permeability (80% less) of pervious concrete than using the bigger-sized aggregate (14-20 mm). Finally, it was found that the best-fitting line for both 2D and 3D porosities and permeability was an exponential model.

1. Introduction

Urban infrastructure has grown faster, with 53.43% more impervious surface, which leads to excessive stormwater runoff, groundwater depletion, urban flooding, as well as deterioration of water quality. In response to such environmental hazards, pervious concrete as a sustainable pavement material allows stormwater infiltration while preserving an adequate structural performance for low- and medium-traffic use [1], [2], [3]. Pervious concrete is an innovative material characterised by its open pore structure, which facilitates prompt surface water drainage, minimises rainwater runoff, enhances groundwater recharge, mitigates urban heat island effects and promotes the construction of sponge-city infrastructure systems [4].

In contrast to conventional dense concrete, pervious concrete is purposely composed of a large percentage volume of interconnected voids (15-30% of the total volume) [5]. These voids control hydraulic and mechanical behaviour; thus, characterising the pore structure of pervious concrete is one of the critical issues in this area of research. Several studies have shown that permeability, compressive strength, sound absorption, and durability performance are affected by the collective effects of porosity; pore size distribution; pore connectivity; tortuosity and pore-throat geometry [6], [7]. Thus, the correlation between pore structure and hydraulic conductivity is important in optimising pervious concrete mixtures.

Porosity has generally been considered the most pertinent parameter for describing the internal structure of pervious concrete. However, new studies indicated that total porosity does not explain the permeability behaviour alone since water flows through connected pores only [1], [8]. Thus, the hydraulic behaviour of pervious concrete is governed not only by void volume but also by pore interconnectivity and spatial distribution of the pore network [1], [6]. Therefore, specimens having similar porosity values may have markedly different gravimetric permeabilities because of differences in pore morphology and connectivity characteristics [7], [8].

Historically, analysis of the pore structure has been done with 2D image analysis that includes optical microscopy, digital image analysis, and polished section analysis [9]. These approaches characterize pore properties in terms of the area of pores, which is measured from only one cross-section. As 2D image analysis is relatively simple, inexpensive, and quick, this technique has become extensively used for calculation of porosity and pore size distribution. However, 2D analysis ignores the three-dimensional nature of the pore network and thus cannot provide pore connectivity and tortuosity information that affects fluid transport through the system [1], [9]. Therefore, the results of permeability calculation based only on 2D parameters might be inaccurate.

The latest developments in X-ray CT scanning, digital imaging, and numerical flow simulations have made it possible to conduct complete three-dimensional (3D) characterizations of the pore structure [6], [10]. These methods give detailed information about the geometry of the pores, their effective porosity, distribution of the pore throats, coordination number and tortuosity, making it possible to visualise the connected flow paths inside the concrete network [6], [10]. The 3D characterisation method gives a more realistic picture of fluid transport compared to traditional 2D characterization [1], [10].

Several recent studies have demonstrated that effective porosity and pore connectivity correlate more strongly with permeability compared to the total porosity alone [6], [8]. It has been observed that pores increase water transportation;

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however, excess tortuosity decreases permeability even if the total porosity increases [11].

In spite of remarkable advances in the study of pore structures, a comparative study to evaluate the 2D and 3D characterization methods has not yet been effectively done. The majority of studies conducted previously have been based on either porosity characterization using the conventional method or on 3D analysis alone. There is no information available on how reliable and consistent pore parameter measurements are using different characterization methods [1], [6]. The effect of 2D and 3D pore properties on predicting permeability has not yet been fully studied. Hence, the objective of this paper is to determine the 2D and 3D porosity properties of pervious concrete and their association with permeability. Using image analysis of the pore structure and evaluation of permeability, it is intended to quantify the difference between area-based (2D) and volume-based (3D) approaches and determine the pore properties which significantly impact the permeability. This research is aimed also to propose a prediction model for pervious concrete permeability.

2. Experimental program

2.1. Materials

The main raw materials of pervious concrete production are cement, water and gravel. Ordinary Portland cement Type I with 3.15 specific gravity (S.G.) and conforming to ASTM C150/C150M-15 was used [12]. Also, fresh, clean and drinkable water was used for wet mixing. Finally, gravel with sizes of (4.75-10) mm, (10-14) mm and (14-20) mm was adopted as coarse aggregate.

2.2. Mix design

In this research, cement content was selected as (350 kg/m^3). While, water to cement and gravel-to-cement ratios were chosen as 0.5 and 3, respectively. Three mixes were designed with the same amounts but with different gravel gradings as (4.75-10) mm (Mixf), (10-14) mm (Mixm) and (14-20) mm (Mixc). Where f refers to fine gravel, m refers to medium gravel, and c refers to coarse gravel. Table 1 represents the material proportions for the three investigated mixes.

Table 1. Mix proportions.

Mixes	Cement	Gravel	Water
Mixf	350	1050 (4.75-10) mm	175
Mixm	350	1050 (10-14) mm	175
Mixc	350	1050 (14-20) mm	175

2.3. Production and Curing

After preparing the predetermined weights of raw materials, the mixing process started with adding half of the gravel and cement and then the rest of the gravel and mixing them as dry materials. After that, the mixing water was added gradually during mixing to produce fresh pervious concrete [13], see Fig. 1a. Then, the fresh mixture was cast in oiled steel moulds (150 mm × 150 mm × 150 mm) and plastic cylindrical specimens (100 mm × 200 mm) as shown in Fig. 1b. The cast specimens were then covered with nylon sheets to prevent evaporation of water during the hardening of the concrete mix, see Fig. 1c. Finally, the specimens were removed from the moulds after 24 hours and immersed in water for curing until the test day as shown in Fig. 1d.

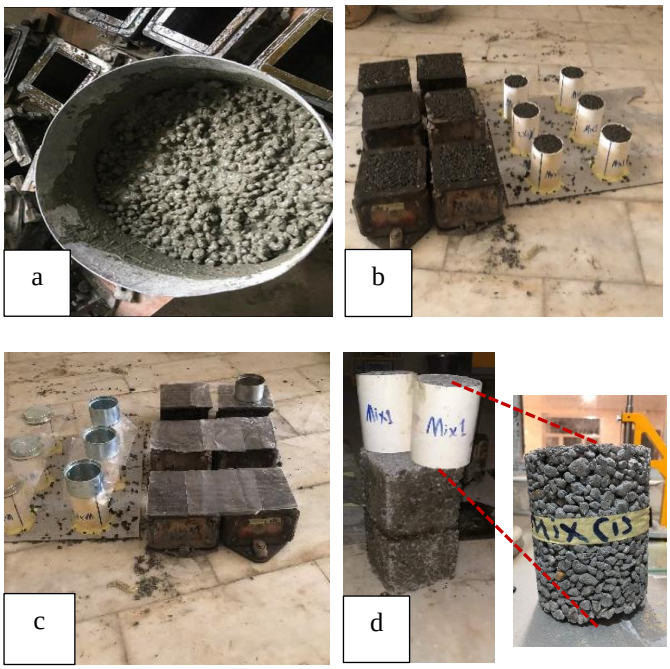


Fig. 1 Production process (a) mixing (b) casting (c) covering (d) removing from moulds and curing.

3. Tests

3.1. Voids distribution

For the investigated concrete mixes, 3 discs (100 mm × 25 mm) were cut from the upper, middle and lower cylindrical specimens, perpendicular to the cast face, for air-void structure investigation.

To easily distinguish between the air pores and the mortar, the cut discs were first polished and cleaned to remove any residues. For enhancing the contrast, the disc surfaces were treated by painting them with permanent marker ink and put in an oven at 50°C for 4 hours. After that, very fine white powder (Sodium bicarbonate, < 5µm) was applied to the disc surfaces and forced into the air pores to make the disc surface black and the air pores white [14]. This makes the treated discs suitable for image capturing and analysis, as shown in Fig. 2. The captured images were then digested, converted into binary form and analysed using ImageJ software. Image acquisition, processing parameters and thresholding procedures were fully explained in [15].

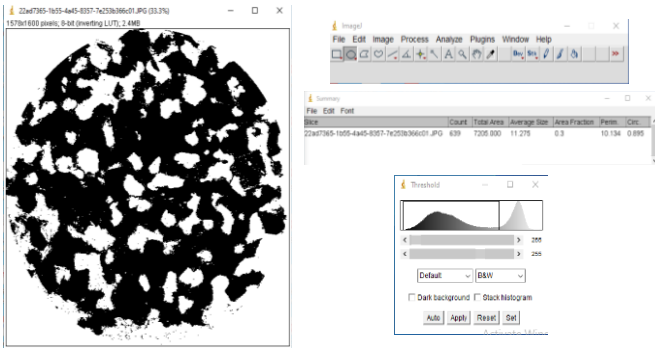


Fig. 2 Analysis of captured image for pervious concrete mix and its binary image by using ImageJ software.

3.2. Compressive strength

Compressive strength of the investigated pervious concrete mixes was measured according to ASTM C39/C39M-15a [16]. At ages of 7 and 28 days, 3 cubes of (100 mm × 150 mm × 150 mm) were tested, and the average reading value was taken.

3.3. Porosity

Concrete porosity can be measured as apparent porosity by the water absorption method or total porosity by the vacuum saturation method. However, due to its large connected pores, the porosity of pervious concrete was measured by adopting the water absorption method [17]. This was done by weighing the oven-dry specimen after wrapping it with cling film from 5 sides to prevent losing the absorbed water. Then, the wet specimen was weighed to measure the weight of absorbed water and then to find the volume of air pores by following Equation (1).

$$V_w = \frac{W_w - W_d}{\gamma_w} \quad (1)$$

Where V_w is the accessed water volume, which represents the air pore volume (porosity), W_w and W_d are the wet and dry specimen weights (kg), respectively, and γ_w is the water unit weight (kg/m^3).

3.4. Permeability

Based on Darcy's law and by following the constant head method, permeability values of pervious concrete mixes were measured on cylindrical specimens (100 mm diameter × 150 mm height). This method is convenient for materials with a permeability coefficient of k greater than 10-4 cm/s, as shown in Fig. 3 [18]. Based on the areas of cross sections of the specimen (A) and the specimen length L, the permeability coefficient K (cm/s) can be calculated as [18]:

$$k = \frac{L}{\Delta h} \cdot \frac{V}{A.\ (t_2 - t_1)} \quad (2)$$

Where k is the permeability coefficient (cm/s), L is height of the sample (cm), Δh is the difference in water levels (cm), t_1 and t_2 are the experiment start time and experiment end times, respectively (s), V is the volume of collected water during the experiment time (cm^3) and finally A is the filtration area (cm^2).

The apparatus for permeability measurement used in this research is shown in Fig. 4.

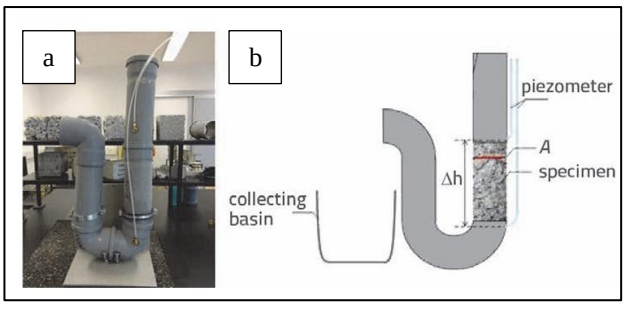


Fig. 3 Permeability apparatus and its schematic view (a) apparatus; (b) apparatus schematic view [18].



Fig. 4 Locally made permeability apparatus used in this research.

4. Results and discussion

4.1. Porosity (air pore volume)

Fig. 5 shows the captured image of cross sections of pervious concrete specimens and their binary images created by ImageJ software. By analysing the captured images, 2D porosity values were found between 30% and 38% as shown in Fig. 6. It can be seen that the finer the aggregate size, the lower the porosity (air pore volume). On the other hand, by adopting the water absorption method, it can be seen from Fig. 6 that the 3D porosity values ranged from 27% % to 37%. Noting that a similar behaviour was noticed in terms of increasing the porosity value with increasing the aggregate particle size [19]. The error bars for the 3D (volumetric) porosities indicate a standard deviation for three pervious concrete cylindrical specimens, while the error bars for the 2D porosities belong to a standard deviation for six captured images. By comparing the results of the 2D and 3D methods, it can be concluded that the 2D technique can be used to predict the pore volume (porosity) of pervious concrete. In other words, the pore volume fraction (3D porosity) should be close to the 2D area fraction of pores obtained from the captured image. It can also be observed from Fig. 5 that the 2D or 3D porosities of pervious concrete mixes made with coarser aggregate sizes are relatively higher than those made with finer aggregate sizes [18].

It should be noted here that the dry density values of investigated mixes were found in consistency with the porosity values, i.e. the lower the porosity, the higher the density and vice versa, see Fig. 7.

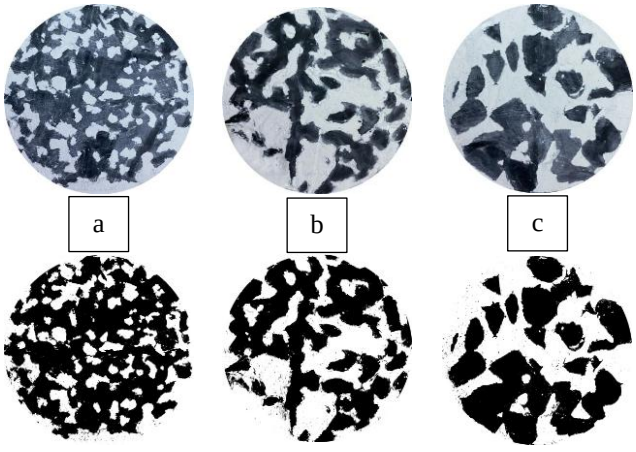


Fig. 5 Surface captured images of investigated pervious mixes and their binary images (a) Mixf (b) Mixm (c) Mixc [scale: 100mm diameter].

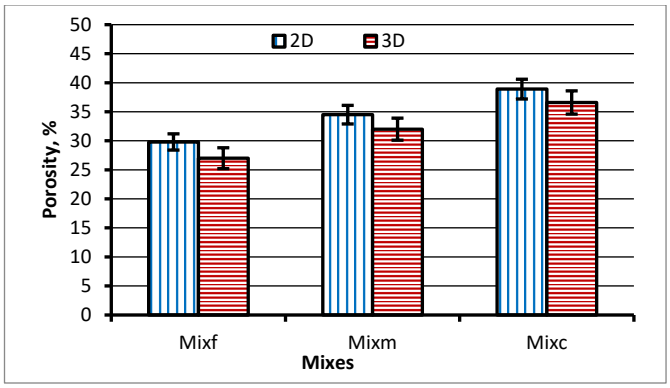


Fig. 6 2D and 3D porosities of investigated pervious concrete mixes.

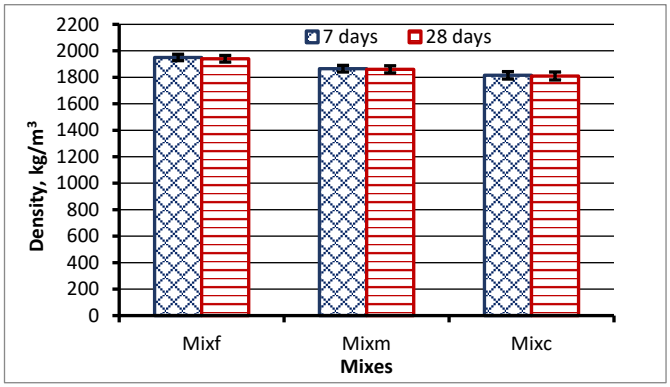


Fig. 7 Density values of investigated pervious concrete mixes.

4.2. Compressive strength

In general, the compressive strength of pervious (permeable) concrete is reasonably reduced due to its porosity. Fig. 8 shows the compressive strengths at ages of 7 and 28 days of investigated pervious concrete mixes. It can be seen that the mix produced with coarse aggregate (Mixc) gained lower strength due to its large air pore volume (porosity).

It was found that pervious concrete produced with multiple-size aggregates was more easily compacted than that containing single-size aggregates [20]. Therefore, pervious concrete strength was enhanced by combining different size distributions aggregate.

From the achieved compressive strength values (less than 16 MPa), the investigated pervious concrete mixes are not suitable for a roadway pavement, but they can simply be used on footpaths, parking and where reduced strength is required.

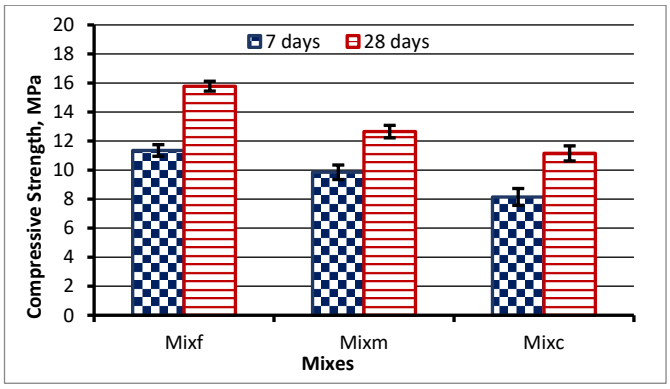


Fig. 8 Compressive strength values of investigated pervious concrete mixes.

4.3. Permeability

Water transport properties are inherently dependent on the air pore structure features of porous concrete. Therefore, permeability is the most important performance characteristic of pervious concrete. Fig. 9 shows the permeability values of investigated pervious concrete mixes. It can be seen that the permeability of Mixf is smaller than that of Mixc by about 80% due to using a finer aggregate particle size. It was stated that not only the air pore volume but also the pore distribution and their connectivity affect the permeability of concrete [21]. From Fig. 5, it is obvious that the pores of Mixf are smaller and less connected than those of Mixm and Mixc. Therefore, the permeability of Mixf was less than that of the two other mixes (Mixm and Mixc). From this test, it can be concluded that the smaller the gravel particle sizes, the smaller the air pore sizes and then the less the permeability value.

The relationships between the permeability of investigated pervious concrete mixes and their 2D and 3D porosities are shown in Fig. 10. It can be seen that the best-fitting line for both relationships was the exponential model as found by [22] and [23].

To summarise the results, Table 2 illustrates the porosity, permeability and compressive strength results obtained from the experimental work.

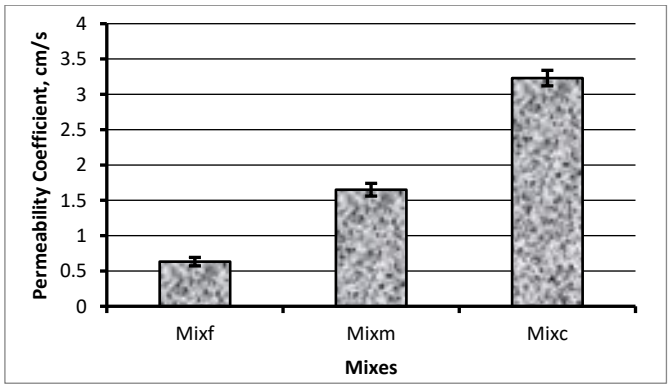


Fig. 9 Permeability values of investigated pervious concrete mixes.

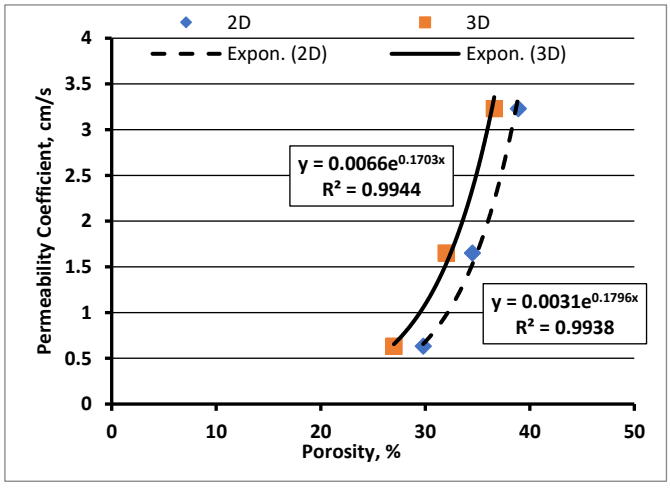


Fig. 10 The relationships between 2D and 3D porosities and permeability values of investigated pervious concrete mixes.

Table 2. Porosity, permeability and compressive strength results.

Mixes		Mixf	Mixm	Mixc
Porosity (%)	2D	29.8	34.5	38.9
	3D	27	32	36.6
Permeability (cm/s)		0.632	1.65	3.23
Compressive Strength (MPa)	7 days	11.35	9.85	8.15
	28 days	15.78	12.65	11.15

5. Conclusions

From the experimental work done on selected mixes of pervious concrete, the following conclusions can be drawn:

- The pore volume (porosity) of pervious concrete may be predicted by adopting the Image analysis technique (2D method).
- Increasing the coarse aggregate (gravel) particle sizes while fixing the other amounts of the pervious concrete constituents negatively affects not only the air pore volume but also their connectivity.
- The size of coarse aggregate has a crucial role in the strength of pervious concrete. Using smaller-sized aggregate (4.75-10 mm) helped in enhancing the compressive strength of pervious concrete by about 30% compared to the strength of a mix made with coarser gravel.
- Using smaller gravel particle sizes led to creating smaller pore sizes and less pore connectivity, and then achieving a lower permeability value by about 80%.
- The best-fitting lines for 2D and 3D porosities and permeability values were found to be an exponential model.

Optimising pervious concrete properties with possible use of additives and recycled aggregate is recommended and will be investigated in future work.

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