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Compression response of normal and high strength pervious concrete

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HIGHLIGHTS

- Investigation of compression response of pervious concrete.
- Matrix mixture design up to 174 MPa.
- Distinction between effective porosity and total porosity.
- Evaluation of existing compressive strength predicting models.
- Proposal of semi-empirical equation to predict compressive strength.

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ABSTRACT

The last century in the construction industry has shown an increasing interest in pervious concrete, an environmentally friendly material. Although emphasis has been placed on the relationship between compressive behavior of conventional pervious concrete and total porosity, not much research has been carried out to characterize the relationship between compressive behavior of pervious concrete with varied matrix strengths, aggregate to binder ratios, and aggregate sizes. In this research 27 series of pervious concrete were mixed and experimentally tested in compressive strength using matrix strengths ranging from 29 MPa to 174 MPa, aggregate to binder ratios from 2.5 to 3.5 and aggregate sizes from 1.2 mm to 4.8 mm. A systematic analysis has been carried out to quantify the influence of matrix strength, amount of binder, and size of aggregates on the compressive strength of pervious concrete. Four existing compressive strength prediction equations are examined and their validity for the different series investigated. Based on the existing equations, an extended equation is proposed and its validity is verified by the enhanced agreement between predicted and experimentally measured compressive strength. In this context, the necessity to distinguish total porosity from effective porosity is highlighted and taken into account.

1. Introduction

Pervious concrete, also referred to as porous or permeable concrete, is a class of concrete characterized by a relative high volume of connected pores, typically in the range of 15–30% with pore sizes ranging from 2 to 8 mm [1], and a water permeability of about 2–6 mm/s [2–3]. This is achieved by intentionally incorporating continuous voids through gap grading the coarse aggregate and eliminating or minimizing the fine aggregate. The American Concrete Institute (ACI) defines pervious concrete as "concrete containing little, if any, fine aggregate that results in sufficient voids to allow air and water to pass easily from the surface to underlying layers" [4]. The ability to allow water penetrating through its open pore structure makes it a very effective tool to control storm water runoff. Although pervious concrete has been used for over 30 years, the material is attracting renewed interests due to the Federal Water Pollution Control Act [5] and the Environmental Protection Agency (EPA) storm water regulations [6]. Despite the various environmental benefits, the limited bond between the aggregates covered with cementitious matrix limits the raveling resistance of the material and thus its structural integrity. Therefore, conventional pervious concrete has typically been applied to sidewalks, parking lots and other light traffic areas. The bonding force between the aggregates is mainly influenced by the contact area (aggregate size) and the matrix tensile strength (directly correlated to the matrix compressive strength). The compressive strength of pervious concrete is a quick indicator reflecting the bond strengths between the gap-graded aggregates and the effect of its porosity (aggregate to binder ratio).

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Typical compressive strengths of conventional pervious concrete with porosities between 15% and 30% range from 7 to 25 MPa [3]. The variation of compressive strength with changes in porosity is shown in Fig. 1. Results with porosity lower than 15% or higher than 30% [1] or specimens with special treatment [7] were not included here. Among researchers, consensus exists that an increase of porosity will decrease the compressive strength. Furthermore, Fig. 1 demonstrates the influence of matrix strength, and thus bond strength between the aggregates, on the compressive strength of pervious concrete. Emphasis is placed on comparing the compressive strength of high strength pervious concrete (HSPC) using a cementitious matrix with strength of 174 MPa to the compressive strength of conventional pervious concretes from the literature [1,8–13]. In most cases the matrix strength of conventional pervious concrete is not provided. However, based on the provided range of water to cement ratio (0.27–0.38), the expected matrices strengths potentially range between 40 and 60 MPa based on Abram's law [14].

HSPC has been developed by Wille and Zhong [15–16] through the application of mixture design principles of ultra-high performance concrete (UHPC) to the pervious concrete matrix.

Beside porosity and matrix strength, it is hypothesized that the contact area between the aggregates affects the compressive strength of pervious concrete. The contact area can be increased by using smaller aggregates. It is worth noting that changing aggregate size and aggregate to binder ratio could have a significant effect on porosity. Therefore, it is necessary to isolate the parameters to draw suitable conclusions.

In this investigation, 27 series of various pervious concretes have been designed, characterized in their compressive strength and porosity, and analyzed to address the following current deficiencies:

- Most publications do not provide the matrix strength of the pervious concrete mixes. This limits correlation between matrix strength and pervious concrete strength.
- No test results for pervious concretes with matrix strength in excess of 150 MPa have been reported.
- Current equations to predict the compressive strength of pervious concrete have not been verified for pervious concretes using high and ultra-high strength matrices.
- The effect of aggregate size and aggregate to binder ratio has not been taken into account to predict the compressive strength.
- The distinction between total and effective porosity and how each affects the prediction of the compressive strength is often overlooked.

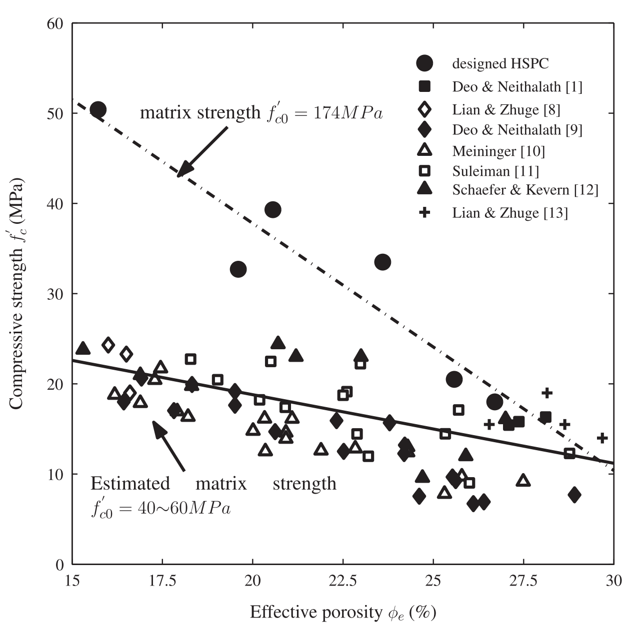

Fig. 1. Influence of porosity and matrix strength on the compressive strength of pervious concrete.

2. Experimental study

2.1. Materials and mixture proportions of the matrix

In total 27 series of pervious concrete were investigated in their compressive strength and porosity. The mixture designs include three different matrices, three different sizes of quartz aggregates and three different aggregate to binder ratios. The three matrices are designated in accordance to their strength as normal strength matrix (NSM), high strength matrix (HSM) and ultra-high strength matrix (UHSM). Their mixture proportions are presented in Table 1 together with their spread values (see Fig. 2) and compressive strengths (see test set up in Fig. 3).

White cement was selected as a constituent for the design of ultra-high strength matrix due to its high amount of tricalcium silicate (C_3S) and dicalcium silicate (C_2S), as well as its low quantity of tricalcium aluminate (C_3A). For simplicity, white cement (Type I) was used for all matrices in this research meeting the ASTM C150 specification for Portland cement. For the normal strength matrix a water to cement ratio of 0.55 was employed leading to a spread value in accordance to ASTM C230/C230M of 220 mm (8.7 in) and a compressive strength of 29 MPa (4.2 ksi) after 28 days obtained by using a 2-inch cube in accordance to ASTM C109/C109M-13. Reducing the water to cement ratio to 0.45 and adding a high range water reducer (HRWR) in the amount of 0.2% to the weight of the cement yielded comparable workability (spread = 240 mm [9.4 in]) and an enhanced compressive strength of 61 MPa (8.8 ksi). The mixture design of the ultra-high strength matrix (UHSM) was based on prior research on the material design of ultra-high performance concrete [17–18]. The mix proportions of the UHSM, shown in Table 1, led to a compressive strength of 174 MPa (25.2 ksi). It is observed that for UHSM there is a loss of viscosity and workability during mixing and casting of pervious concrete. This result is because the low water to cement ratio of 0.22 accelerates the process of surface drying. Therefore, considering the large surface area of pervious concrete the workability of the UHSM was increased to a spread value of 340 mm (13.4 in) to counteract the effect of viscosity loss.

2.2. Mixture proportion of pervious concretes

In addition to the variation in matrix strength (29 MPa, 61 MPa, 174 MPa), three sizes of aggregates (1.19 mm, 2.38 mm, 4.75 mm) and three aggregate to binder (A/B) weight ratios (2.5, 3.0, 3.5) were combined to design the 27 pervious concrete series listed in Table 2.

2.3. Specimen preparation and curing

Prior to mixing, all aggregates were washed to remove adhered clay and impurities, dried and sieved to obtain single sized aggregates. First the matrix was mixed and then the aggregates were added. After mixing, the pervious concretes were cast in three layers in cylindrical molds (76 mm [3 in] by 152 mm [6 in]) to full capacity using slight vibration. Each layer was slightly compacted by a 2.4 kg (5.3 lb) hammer with three blows. During casting and compaction emphasis was placed on mitigating discontinuity in material porosity over the specimen height. After casting, each specimen was covered with plastic sheets and stored at room temperature for 24 h. The next day the specimens were demolded and stored in a water tank at 20 °C for an additional 27 days. For each series, a total of five cylinders were cast, three for compressive strength testing and two for porosity testing.

2.4. Test methods

2.4.1. Compressive strength

The compressive strength of pervious concrete was determined based on ASTM C39. The load was applied under displacement control at a rate of 0.5 mm/min. Prior to testing, specimens were removed from the curing tank for test preparation. About 6 mm (1/4 in) was cut from each load surface of the cylinder. After being left to dry in laboratory environment, the specimens were sulfur capped at both ends ensuring smooth and parallel loading surfaces. The reported results reflect the average compressive strengths of three specimens at an age of 28 days.