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Flexural strength and fracture size effects of pervious concrete

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HIGHLIGHTS

- Pervious concrete notch bend tests were conducted to ascertain strength size effects.
- Inverse analysis was used to determine the tensile strength of bending specimens.
- Flexural strength size effects are observable if unit weight is normalized.
- A modified unit weight dependent SEL can be used to predict strength size effect.
- Pervious concrete is more ductile than conventional concrete.

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ABSTRACT

A low strength/low unit weight and high-strength/high unit weight pervious concrete mix is studied using notched three point bend specimens to ascertain strength and fracture size effects using beam depths ranging from 100 to 200 mm. The results indicate the flexural strength is size dependent and can be predicted using Bazant's size effect law utilizing a unit weight-dependent tensile strength parameter and a characteristic crack length with reasonable accuracy: $R^2 = 0.84$ and MSE = 0.07 MPa. The tensile strength, and initial and total fracture energy, however, were not found to be size dependent.

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1. Introduction

Concrete is one of the most diverse and popular materials used in construction. Mixes vary from high performance, high strength, self-consolidating, photocatalytic, ultra-ductile, and pervious concrete, among others. Pervious concrete in particular, is a specialty mix that utilizes cement, high performance additives, and coarse aggregate. The void content of pervious concrete is generally in the range of 10–30% [1], has permeability between 0.2 and 3 cm/s [2], and compressive strength between 10 MPa and 50 MPa [3]. The enhanced surface drainage properties warrant its use in low volume roadways, highway shoulders, and parking lots that suffer excessive flooding and necessitate perhaps some modest hazardous waste filtration [4].

The critical engineering properties governing the usability of pervious concrete are compressive strength, porosity, permeability, freeze thaw durability, and surface abrasion resistance. Lian et al. [3] showed the porosity and compressive strength of pervious concrete follows a decaying exponential relationship. Compressive strength will increase when blended aggregates are used, and also increases with paste volume fraction [5]. Rehder et al. [6] developed an empirical equation relating pore size, mean free pore spacing, tortuosity, porosity and fiber volume fraction to critical fracture toughness using three-point single edge notch beam specimens.

The strength and durability properties strongly depend on the coarse aggregate texture, angularity, and size [7]. Kevern et al. [8] concluded that increases in coarse aggregate absorption will decrease freeze thaw durability. The addition of long macrofibers can increase freeze thaw durability, but will decrease permeability [9]. Aggregates significantly impact surface abrasion resistance. Gaedicke et al. [10] studied the abrasion resistance, porosity, and compressive strength of virgin and recycled coarse aggregates and concluded recycled aggregate has approximately 20% lower permeability for specimens of similar porosity. Pea gravel mixes were also shown to have approximately 20% less abrasion

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resistance than crushed limestone and a recycled concrete aggregate blend. Curing regime has also been shown to influence abrasion resistance. Kevern et al. [11] showed that curing pervious concrete under plastic and using soy bean oil as a curing membrane leads to increased abrasion resistance. Wu et al. [12] studied the effects of latex modifiers using the Cantabro and APA tests and showed enhancement of surface abrasion. Aggregate angularity has also been shown to affect compaction and dynamic compressive strength under drop hammer tests [13].

Chen et al. [14] studied the fatigue properties of pervious concrete using three-point bend specimens and showed that it is significantly influenced by porosity. The fatigue life of pervious concrete can be quantified using a Wohler curve [15] and has been shown to follow a two-parameter Weibull probability distribution function [16]. Under cyclic loading, pervious concrete pavement layers should be increased by a factor of two when basing the initial thickness values on static structural analysis [17]. The fatigue resistance in both compression [15] and flexure [16] can be increased by polymer modification of the cement paste. Other High performance and specialty pervious concretes have also been developed for a variety of purposes that include the addition of superplasticizer and viscosity modifying agents [2], crumb rubber and tire chips [18], and latex modifiers [19]. Pervious concrete has also been mixed with a geopolymer cement and shown to yield modest improvements to performance when mixed with a 15 M sodium hydroxide solution [20].

1.1. Research needs

Although the mechanical and physical properties of pervious concrete have been studied extensively, there is a need to quantify the strength and fracture size effects so one can confidently extrapolate from laboratory scale to full field scale and improve design recommendations therein.

1.2. Research scope and objective

The focus of this research is to characterize the flexural strength and fracture properties of pervious concrete beams of different sizes and develop a model that can be used to predict size effect.

2. Experimental program

2.1. Materials

Two mix designs are evaluated in this study: 1) mix N: low strength/low unit weight and 2) mix H: high strength/high unit weight. The aggregate used in both mixes is a uniform 10 mm maximum (d_{max}) size pea-gravel (ASTM C136). The gradation is shown in Fig. 1. The bulk dry specific gravity and absorption of the aggregates is 2.66 and 1%, respectively (ASTM C127). A summary of the proportions for both mixes is provided in Table 1. For Mix H, an ASTM C1017 Type I polycarboxylate superplasticizer (SP) and ASTM C494 Type S viscosity modifying agent (VMA) was used. The concrete was mixed and rodded according to ASTM C192. The pervious concrete was finished by gently screeding the excess material with the tamping rod. The top of specimens were then covered with plastic for 24 h, demolded, and placed into a lime curing bath for an additional 27 days before testing.

2.2. Physical and mechanical properties

Each mix was tested for compressive strength, split tensile strength, surface abrasion, void content, permeability, and unit weight. The four specimen average and standard deviation for each test is shown in Table 2. The concrete compression cylinders were capped with 50 durometer neoprene pads and steel retainers. The permeability coefficient, k, was obtained from a constant head test as shown in Tho-in et al. [20] and Ghafoori and Dutta [21]. The concrete was wrapped with a flexible rubber seal around the sides from top to bottom to prevent leakage along the walls of the PVC pipe. The head was held constant by introducing a side drain in the inlet pipe above the concrete specimen and a drain in the reservoir used to collect the water being transmitted through the concrete. The head was held constant and equal to the difference in elevation between the inlet side drain and reservoir drain. The water exiting the reservoir drain was then collected and weighed over a 30 s time interval to calculate the flow. As expected, Mix N has substantially lower strength, higher void content, and permeability than mix H. The void content, surface abrasion resistance, permeability and compressive strength for both mixes are in the range of acceptability for pervious concrete and consistent with the results from Gaedicke et al. [10].

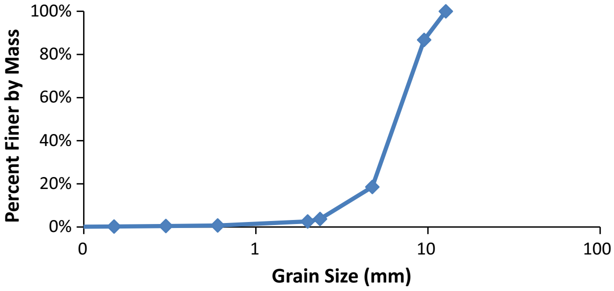

Fig. 1. Coarse aggregate particle distribution.

Table 1
Pervious concrete mix proportions.

Mix	N	H
Cement (kg/m^3)	260	370
Coarse Agg. (kg/m^3)	1800	1398
Water (kg/m^3)	70	111
Water/Cement	0.27	0.3
SP (kg/m^3)	–	3.7
VMA (kg/m^3)	–	0.96

Table 2
Summary of mechanical and physical properties of pervious concrete cylinders.

Mix	N	H
Compressive Strength, f'_c (MPa), ASTM C39	9.00 ± 26%	34.9 ± 9%
Split Tensile Strength, f'_t (MPa), ASTM C496	0.98 ± 20%	3.04 ± 32%
Surface Abrasion (Mass Loss, g), ASTM C944	2.4 ± 83%	1.3 ± 54%
Void Content, ASTM C1754	0.27 ± 3.4%	0.09 ± 16.9%
Constant Head Permeability (cm/s)	0.86 ± 15%	0.24 ± 37%
Unit Weight (kg/m^3), ASTM C1754	1855 ± 1.0%	2228 ± 1.3%

2.3. Three-point bend test setup

A total of 23 three-point bend specimens were tested under monotonic crack mouth opening displacement (δ_{CMOD}) controlled loading. This was accomplished using a crack opening displacement (COD) gage closed loop feedback testing system with an INSTRON servo-hydraulic actuator. The specimens were loaded a rate of 0.0005 mm/s and reached peak load at approximately two minutes. The specimens were then un-loaded and reloaded cyclically so beam compliance could be measured. Fig. 2 shows a photograph of the three point bending specimen, mounted COD gage, and the three loading points.

Table 3 shows a summary of the beam dimensions and self-weight of each of the three-point bend specimens. Each specimen has a nominal effective span (S) to depth (D) ratio of 2.5 and initial non-dimensional notch length (a_0/D) of 0.15 (nominal). The beams were pre-notched (not sawed) using a 1.5 mm thick aluminum plates. The nominal beam depths were 100 mm, 150 mm, and 200 mm and the nominal width, b, was exactly half the depth, D/2. The nominal dimensions differ slightly form the actual dimensions. The discrepancy between the two dimensions is due to the molding geometry. The variation in notch length was due to the scattered coarse aggregate packing around the tip of the notching shim. The concrete could not smoothly take the shape of the notching shim at its tip leading to the shown discrepancy between the nominal and actual lengths.

The COD gage was mounted to the bottom face of the beam, centered from both ends of the notch mouth using a pair of 3 mm thick knife edges and used to measure the crack mouth opening displacement (CMOD). The knife edges were glued onto a thin layer of mortar that was finished onto the hardened pervious concrete (to smoothen the surface on either side of the notch mouth) using a rapid drying epoxy resin (applied one week prior to testing). The effective thickness of the thin mortar layer was determined using digital calipers and was found to be on average 1 mm.

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