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Evaluation of freeze-thaw durability of pervious concrete by use of operational modal analysis

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ABSTRACT

It is well-known that laboratory testing of pervious concrete's freeze-thaw performance is too harsh and does not agree well with field observations. The most commonly used laboratory freeze-thaw test method for pervious concrete is similar to that used for conventional concrete even though the void structure of the two materials is completely different. In the present study, a new freeze-thaw test method for pervious concrete is suggested and tested on one baseline mix, with three different contents of entrained air. The evaluation of freeze-thaw damage on pervious concrete beams was evaluated from the decrease in mass and from operational modal analysis which provides an accurate determination of the change in natural frequencies with freeze-thaw exposure. Operational modal analysis was also used to determine the Young's modulus, shear modulus, and Poisson's ratio of the pervious concrete mix.

1. Introduction

Portland cement pervious concrete (PCPC) is a highly permeable concrete because of its large void content – typically 11–35% [1] – which makes it very applicable for permeable pavements. Several PCPC pavements have been placed with great success, particularly in the US [2]. The large void content is obtained by minimizing the amount of cement paste, avoiding small aggregates, and by using a well-graded coarse aggregate [3]. The void structure of PCPC is more complex than that of conventional concrete because it includes small entrained air voids in the cement paste as well as large interconnected voids between the aggregates. These voids are sometimes referred to as 'effective voids' because they contribute to the main water percolation. Due to the very nature of PCPC, these effective voids are not expected to be water-filled, only at least for a very short period of time, because the permeability of PCPC is much greater than any rainfall to be expected. Typically, the permeability of PCPC ranges from 0.20–0.54 cm/s [3], whereas in Denmark, the maximum intensity of a rain event with a 100-year return period is 6.5×10^{-3} cm/s [4]. Thus, it is typically the permeability of the subbase rather than that of PCPC that is limiting.

There are several examples of how PCPC has been implemented for pavements in regions exposed to many annual freeze-thaw cycles during the winter months. This places requirements on the freeze-thaw durability of the PCPC mix designs used. In lack of a standardized freeze-thaw test method for PCPC, the freeze-thaw performance of PCPC is most commonly tested according to ASTM C666 Procedure A [5] developed for conventional concrete; however, it is well-known that ASTM C666 Procedure A does not represent the on-site freeze-thaw behavior of PCPC very well because PCPC pavements are, in general, found to perform much better in a real outdoor environment than under laboratory conditions [2]. Nevertheless, in lack of a more representative test method, ASTM C666 Procedure A is continuously used. According to ASTM C666 Procedure A, the PCPC specimens are exposed to rapid freezing and thawing – up to 6 frost cycles a day – in a saturated environment of water. The main reason that ASTM C666 Procedure A is not representative of the on-site freeze-thaw performance of PCPC is that the test method is too harsh, because it is based on saturation of the effective voids. In reality, these voids are never expected to be water-filled and will, moreover, also be effective when releasing the pressure caused by water that freezes in the cement paste. Moreover, ASTM C666 does not consider the influence of salt solutions – such as sodium chloride – which pavements in mild climate countries must be expected to be exposed to and which are usually known to decrease the freeze-thaw durability of cementitious materials.

According to ASTM C666, the freeze-thaw behavior of PCPC is estimated from the reduction in transverse frequency, measured by use of an impact resonance test as described in ASTM C215 [6]. For conventional concrete, the use of the impact resonance test is relatively easy to carry out because the surface of the test specimen is uniform, which makes the area where the impact is applied well-defined. For PCPC, however, the surface of the specimen is not uniform due to the large voids, which causes uncertainties on the measured frequencies of PCPC

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specimens and makes it complicated to obtain consistent results for all different impact resonance tests. In contrast to forced vibration testing, such as impacts tests, Operational Modal Analysis (OMA) testing determines the natural modes of vibration by subjecting the specimen to a random excitation and recording only the responses. Afterwards, depending on the modal identification technique used, the natural frequencies of the specimen can be estimated from either the responses in time-domain or from the corresponding Power Spectral Densities (PSDs) computed in frequency-domain.

A very simple and efficient procedure normally used to determine the natural frequencies consists of picking the peaks of the PSDs plots. Since these peaks are associated with the responses of each natural mode, the frequencies at which they occur correspond to the natural frequencies of the tested specimens [7]. Thus, for the evaluation of the reduction in the natural frequencies of PCPC due to freeze-thaw, OMA is believed to provide a much more reliable test procedure compared to the impact resonance test where a high uncertainty on the estimated natural modes is normally observed.

The main objectives of the present study are to develop and test a more realistic laboratory freeze-thaw procedure for PCPC than ASTM C666 Procedure A, and to detect the reduction in frequency caused by freezing and thawing by making use of OMA. Three different mix designs which contain different amounts of entrained air are considered. The baseline mix design of all three mixes is the same. PCPC beam specimens are immersed in a 3% NaCl solution for three days before the salt water is allowed to drain off, and the specimens are sealed in plastic bags and exposed to 56 freeze-thaw cycles. In addition to determining the freeze-thaw performance of the three mix designs, OMA is also used to determine the Young's modulus, shear modulus, and Poisson's ratio of the mix design. Finally, the void content and 28-day compressive strength are also determined.

2. Experimental method

2.1. Material properties

All mixes were prepared with Portland limestone cement CEM II/A-LL 52.5 R with a density of 3100 kg/m^3 [8]. The fine aggregate used was 0–2 mm concrete sand and the coarse aggregate used was 8–11 mm granite from Bornholm, Denmark. Both aggregates belonged to environmental class E [9]. The gradation curves of the aggregates are shown in Fig. 1 and their properties are shown in Table 1. Finally, a combined natural and synthetic air entraining agent (AEA) diluted 1:2 was used and also a stabilizer (viscosity modifying agent, VMA).

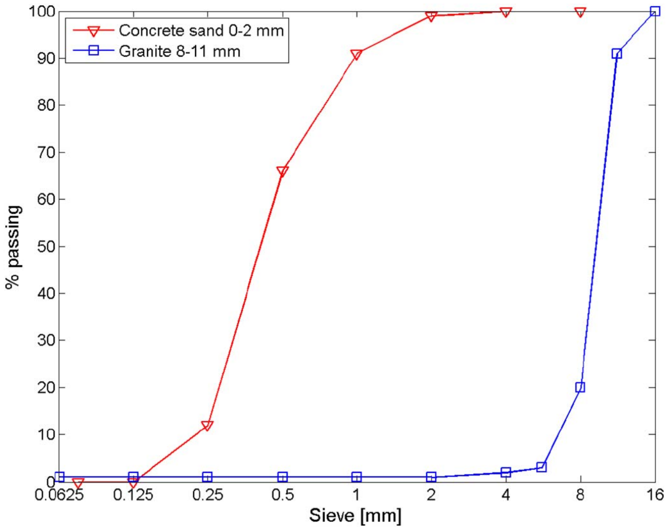

Fig. 1. Gradation curves for 0–2 mm sand and 8–11 mm granite.

Table 1
Aggregate properties.

Material	Density [kg/m^3]	Water absorption [%]
Sand, 0–2 mm	2628	0.1
Granite, 8–11 mm	2720	2.2

Table 2
Mixture proportions of PCPC mix designs A1, A2, and A3.

Material	Mix A1	Mix A2	Mix A3
Cement [kg/m^3]	250.0	250.0	250.0
Water [kg/m^3]	85.2	81.1	79.5
AEA[a] [kg/m^3]	–	4.2	5.8
VMA [kg/m^3]	2.5	2.5	2.5
Sand [kg/m^3]	160.8	160.7	160.7
Granite [kg/m^3]	1497.5	1497.2	1497.1

[a] AEA was diluted 1:2 when delivered from the supplier; however, the table shows the concentrated amount.

2.2. Mixture proportions

Three different PCPC mixes were placed for this study: mix A1, A2, and A3. The baseline mix design of all mixes was the same; however, a different dosage of AEA was used for each mix design. Mix A1 contained no AEA, mix A2 contained 5% AEA of the mass of cement, and mix A3 contained 7%. All mixes had a w/c-ratio of 0.35, a mix design void content of 20%, and a VMA dosage of 1% of the mass of cement. Table 2 shows the mixture proportions of mixes A1, A2, and A3.

2.3. Mixing and sample preparation

The mixes were first prepared by mixing the aggregates and 5% of the cement in a rotating drum mixer for 2 min, to coat all aggregates with cement and thereby improve the PCPC strength [1]. Subsequently, the remaining cement, and half of the water in which half of the AEA was diluted were added to the mix, and mixed for 30 s. Next, the remaining water and AEA were added slowly over a period of 30 s and when foam was observed, the VMA was added and mixed for 2 min. The mixture was allowed to rest for 3 min and mixed for additionally 2 min.

Before preparing the samples, the air content of the fresh PCPC was measured with a press-ur-meter. The press-ur-meter container was filled halfway up with PCPC which was rodded with a steel rod 20 times, and subsequently demineralized water was slowly poured over the PCPC. Next, the sides of the container were tapped 20 times with a rubber mallet to release potential entrapped air. The procedure for filling the top half of the container was similar and finally, the press-ur-meter readings were carried out as for conventional concrete. Previous studies indicate that press-ur-meter readings performed on PCPC can be incorrect because air caught in the large voids is also included; however, because there is no other test method to determine the air content of fresh PCPC, and because entrapped air was effectively released with the rubber mallet, it is believed that the readings were reasonable.

Cylinder specimens were prepared in d100/h200 mm molds for compressive strength determination and beam specimens were prepared in 3 × 4 × 16″ (76.2 × 101.6 × 406.4 mm) molds for freeze-thaw testing. The PCPC mass used to prepare each specimen was determined from the mix design density, and the known volume of the mold. In this way, the void content of the specimens was the same as assumed in the mix design. The cylinder specimens were prepared by filling the mold in three layers, which were each rodded 10 times with a steel rod (3 cm in diameter). Vibration was added for 2 s after placing the second and third layer to mesh the layers together. The beam specimens were prepared by filling the mold in two layers and otherwise follow the procedure already described for preparation of cylinder