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Evaluation and Comparison of Freeze-Thaw Tests and Air Void Analysis of Pervious Concrete

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Abstract

Pearl-Chain Bridge technology is an innovative precast arch bridge solution which uses pervious concrete as fill material. To ensure longevity of the bridge superstructure it is necessary that the pervious concrete fill is designed to be freeze-thaw durable; however, no standards exist on how to evaluate the freeze-thaw resistance of fresh or hardened pervious concrete and correspondingly what constitutes acceptable freeze-thaw durability. A greater understanding of the correlation between the freeze-thaw performance and the air void structure of pervious concrete is needed. In the present study six pervious concrete mixes were exposed to freeze-thaw testing, and their air void structure was analyzed using an automated linear-traverse method. It was found that there is a miscorrelation between these two test methods in their assumption of whether or not the large interconnected voids effectively relieve the pressure when water freezes.

1 Introduction

Pearl-Chain Bridge technology is an innovative arch bridge solution allowing faster, more environmentally friendly, and cheaper road and railway bridge constructions. The Pearl-Chain arch is constructed from plane super-light decks (SL-Decks) that are collected and post-tensioned next to the road and subsequently lifted into place by a crane (Halding, Hertz and Schmidt, 2015). With the Pearl-Chain arch in place, spandrel walls are installed and finally a fill material is placed. To ensure longevity of Pearl-Chain Bridges, Portland Cement Pervious Concrete (PCPC) is considered as fill material. PCPC is characterized by a large interconnected void structure providing excellent drainage properties; thus, penetrating rainwater is efficiently removed from the Pearl-Chain Bridge superstructure by the use of PCPC fill. Thereby the moisture exposure of the Pearl-Chain arch is reduced and the freeze-thaw damages of the fill material itself are minimized if not completely eliminated.

Hard infrastructure, such as Pearl-Chain Bridges, is expected to be in use for a period of 120 years. This places severe demands on the fill material in order to test and document its durability under various conditions. In mild climate countries like Denmark where the temperature during winter times varies around the freezing point, the fill material is particular exposed to harsh freeze-thaw impact, because the bridge superstructure is cooled from several sides; hence, the application of PCPC as fill in Pearl-Chain Bridges requires PCPC to possess some amount of freeze-thaw durability. However, no standards exist on how to evaluate the freeze-thaw resistance of fresh or hardened PCPC or suggestions on what results produce adequate performance in the field. Currently the evaluation of the freeze-thaw durability of hardened PCPC is based on the same ASTM standard, ASTM C666A (ASTM C666, 2008), as conventional concrete even though it is well-known that this test method is too harsh because it does not include the draining nature of PCPC. Several examples have shown that air-entrained PCPC performs much better in the field than in the laboratory (NRMCA, 2004). The void structure of PCPC is more complex than that of conventional concrete because it is a combination of small entrained air voids and large interconnected voids that are also sometimes referred

to as ‘effective voids’ because they contribute to the main water percolation. Previous studies such as those performed by Kevern, Wang, and Schaefer (2008; 2009) have successfully tried to link the freeze-thaw performance of PCPC to the air void system by analyzing the amount of entrained air in hardened PCPC in a RapidAir analysis using the linear-traverse method described in the ASTM C457 standard (ASTM C457, 2006). However, the RapidAir analysis does not include voids larger than 4 mm in diameter and more experiments are needed to fully understand the freeze-thaw mechanisms of PCPC. In this study, the freeze-thaw durability of six different PCPC mix designs is evaluated from their change in mass and relative dynamic modulus during freeze-thaw tests. The results are linked to the air void structure determined from the linear-traverse method using the RapidAir analysis including air voids less than 1 mm, less than 4 mm, and all air voids.

2 Methods

2.1 Material Properties

All mixes were prepared with ASTM C150 cement meeting both Type I and Type II classification and ASTM C618 Class F fly ash with a specific gravity of 3.15 and 2.28, respectively (ASTM C150, 2012; ASTM C618, 2012). Two different types of coarse aggregate were used: granite A and B with a maximum aggregate size of 1/2 in. (12.7 mm) and 3/8 in. (9.5 mm), respectively. Both had a specific gravity of 2.70. Granite A had 0.6% absorption, a dry rodded unit weight of 1524 kg/m³ and a void ratio of 0.43, whereas granite B had 0.7% absorption, a dry rodded unit weight of 1405 kg/m³ and a void ratio of 0.48. As fine aggregate, concrete sand with 100% passing the No. 4 sieve (4.75 mm), a fineness modulus of 3.1, a specific gravity of 2.64 and 1.8% absorption was used. Moreover, vinsol resin-based air entraining agent (AEA) and polycarboxylate based high-range water reducer (HRWR) with a specific gravity of 1.02 and 1.10, respectively, were used.

2.2 Mix Designs

A total of six different mixes were placed for this study. Three used granite A (Mix A) and three used granite B (Mix B). Mix A and B had a water-to-cement ratio of 0.29 and 0.31, respectively, and 20% cement replaced with fly ash, by weight. The fine aggregate to coarse aggregate ratio was 0.09, also by weight. The mixtures were designed for 18% voids and the mixes containing AEA were designed to have additionally 3% entrained air. ‘Mix 1’ did not contain any AEA or HRWR, ‘Mix 2’ contained only AEA, and ‘Mix 3’ contained AEA and HRWR. The AEA dosage was slightly higher than the standard dosage used for conventional concrete, that is, 0.125% of the cementitious material mass. The HRWR dosage was 0.375%. The different mixture proportions are shown in Table 1.

Table 1 Pervious concrete mix designs A and B.

Mix	Cement [kg/m ³]	Fly ash [kg/m ³]	Water [kg/m ³]	Granite [kg/m ³]	Sand [kg/m ³]	AEA [kg/m ³]	HRWR [kg/m ³]
1-A	315	64	100	1435	133	-	-
2-A	315	64	100	1385	128	0.47	-
3-A	315	64	100	1382	128	0.47	1.42
1-B	315	64	114	1401	130	-	-
2-B	315	64	114	1350	125	0.47	-
3-B	315	64	114	1347	125	0.47	1.42

2.3 Sample Mixing and Preparation

The concrete was prepared by first mixing aggregates and 5% of the cement for one minute to ensure that all aggregates were coated with cement (Kevern, Wang, and Schaefer, 2008). The AEA was diluted in the water and added to the mix. When foam was observed, the rest of the cement and fly ash was added and mixed for three minutes. The mixture was allowed to rest for two minutes before it was mixed for additionally two minutes. In mixes with HRWR, one third of the water was held back, mixed with HRWR and added when the mix appeared uniform after addition of cement and fly ash.

The samples for the freeze-thaw tests were prepared in beam molds measuring 75 × 100 × 400 mm (3 × 4 × 16 in.), and the samples for the air void analysis were prepared in d100/h200 mm (4/8 in.) cylinder molds. The mass of PCPC corresponding to the volume of the mold was determined

from the mix design and placed in the mold in three equal lifts. Each lift was rodded a maximum of 25 times for the cylinder specimens and 75 times for the beam specimens depending on the workability of the particular mix design. The layers were meshed together by vibrating each new layer for three seconds. After 24 hours the specimens were demolded and placed in a fog room with a relative humidity of 98% until 28 days.

For the RapidAir analysis, samples measuring $100 \times 100 \times 15$ mm were cut vertically from the cylinder specimens. One side of the sample was wet-sanded with successively finer grit paper finishing with the $6 \mu\text{m}$ grit. Afterwards, the entire surface was colored black with a broad tip black marker and the sample was heated to 80°C in an oven for two hours. Subsequently, a white zinc paste mixed from petroleum jelly and zinc oxide was applied and massaged into the heated surface, thereby melting and flowing into the air voids. The sample was cooled in a refrigerator before all excess zinc paste was removed from the surface with an angled razor blade.

2.4 Testing Procedures

Determination of the void content and the unit weight of the hardened pervious concrete beam specimens were carried out by weighing the specimens below and above water in accordance with the ASTM C1754 standard (ASTM C1754, 2012). Three beam specimens were tested for each mix design except from Mix I-A which was not exposed to freezing and thawing.

The freeze-thaw tests were carried out in accordance with the ASTM C666 standard Procedure A (ASTM C666, 2008), where the specimens are frozen and thawed in water and their core temperature varies between $-18^\circ\text{C} \pm 2^\circ\text{C}$ and $4^\circ\text{C} \pm 2^\circ\text{C}$. Prior to the beginning of the freeze-thaw exposure, the specimens were water saturated for 24 hours at 4°C . The mass loss and the durability factor (DF) calculated from relative dynamic modulus were used to evaluate the freeze-thaw durability of the specimens, and the tests were terminated when the specimens reached 15% mass loss, 300 frost cycles or a reduction in the relative dynamic modulus to 60%. The mass loss and the transverse frequency were measured for every 30 frost cycles. DF [%] was calculated using the formula:

$$DF = \frac{PN}{M} \quad (1)$$

where P [%] is the relative dynamic modulus (RDM) at N cycles, N is the number of cycles at which P reaches the specified minimum value for discontinuing the test—chosen as 60% of RDM—or the specified number of cycles at which the exposure is to be terminated, whichever is less, and $M = 300$ cycles is the number of cycles at which the exposure is to be terminated.

A RapidAir analysis based on the linear-traverse method described in the EN 480-11 standard (EN 480-11, 1998) was carried out using a RapidAir device. For all samples, five traverse lines per frame were chosen. The threshold value was set to 120 and 100 for Mix A and Mix B, respectively. The paste content was 22.8% and 24.2% for Mix A and Mix B, respectively. For each sample, the RapidAir test was performed four times by rotating the sample 90 degree between each test. The values presented herein are average values of these four measurements.

3 Results and Discussion

For conventional concrete, the freeze-thaw durability is typically evaluated from one of two methods: either by exposing concrete samples to freeze-thaw tests in a freezing chamber and consider the decrease in mass and transverse frequency by following, for example, the ASTM C666 standard (ASTM C666, 2008), or by determining characteristic air void properties such as the spacing factor and the specific surface area in a microscopical analysis. Such microscopical analysis is often performed using a RapidAir system (or a similar system) that automatically scans the prepared sample and measures the linear-traverses according to the procedure described in the EN 480-11 standard (EN 480-11, 1998) or in the ASTM C457 standard (ASTM C457, 2006). The results achieved directly from the RapidAir analysis include only voids up to 4 mm. Voids larger than 4 mm are simply omitted from the analysis because the EN 480-11 standard (EN 480-11, 1998) does not consider air bubbles with a diameter greater than 4 mm. This is because the formulas used to determine the air void characteristic in the linear-traverse method build on Powers' formulas that distinguish between whether or not the paste-to-air content (p/A) is less than or greater than 4.342 (Powers, 1949) which relates to whether a paste has a low or a rich air content. For p/A -ratios greater than 4.342, the results become erroneous if air voids larger than 4 mm are included in the analysis, and for conventional concrete it is reasonable to leave such coarse air bubbles out of the analysis because they are rarely

present. In the ASTM C457 standard (ASTM C457, 2006) no upper size limit is specified; however, one should be aware of this possible error when using the method. Because PCPC and conventional concrete are similar in many perspectives it is natural to apply the same methods as used for conventional concrete to determine the freeze-thaw durability of PCPC. However, the void structure of PCPC is considerably more complex than that of conventional concrete because it contains small entrained air in the cement paste (as conventional concrete) but also larger voids that often exceed 4 mm between the aggregate particles. Hence, when considering the freeze-thaw durability of PCPC three questions naturally arise:

- 1) What is the error by omitting the largest voids (> 4 mm) when applying the linear-traverse method described in the EN 480-11 standard (EN 480-11, 1998) on PCPC?
- 2) Is it reasonable to determine the spacing factor for PCPC from the same expressions as used for conventional concrete when the void structure of PCPC is so distinctively different than the void structure assumed in the EN 480-11 standard (EN 480-11, 1998) relating to conventional concrete?
- 3) How do freeze-thaw tests of PCPC compare to the air void characteristics determined from the linear-traverse method described in the EN 480-11 standard (EN 480-11, 1998)?

The following sections will address these questions by considering the tendencies and correlations discovered in the present study.

3.1 Freeze-Thaw Tests

Fig. 1(left) shows the remaining mass of the specimens as function of the number of freeze-thaw cycles. Because there was a certain variation in the freeze-thaw behavior within each mix design, the results are shown for all specimens.

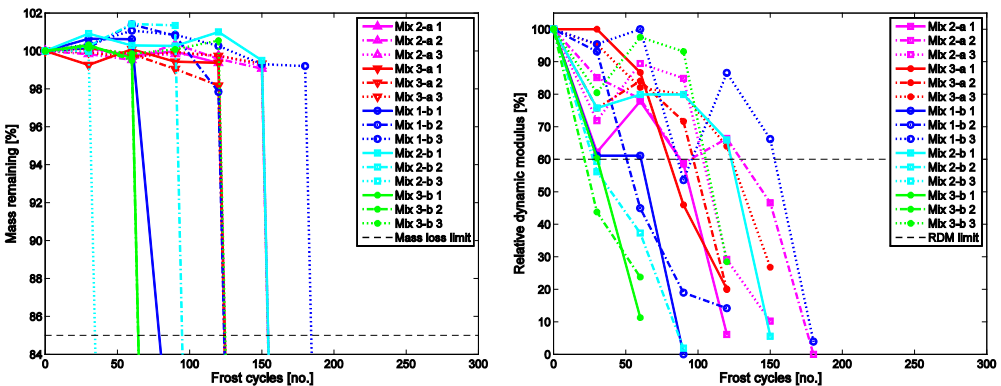


Fig. 1 Remaining mass (left) and RDM (right) for PCPC specimens as function of the number of freeze-thaw cycles.

Fig. 1(left) shows that the mass loss of most PCPC specimens was insignificant until the point of failure at which an abrupt decrease in the mass took place as the paste deteriorated to the point of loose aggregate. Although specimens were first soaked in water before initial testing, the figure also shows that some specimens gained weight during the freeze-thaw tests. This is because the cement paste absorbed water when the specimens were immersed. At the point of failure the specimens were completely deteriorated and it was not possible to measure the mass; hence, the mass loss is set to 100% in Fig. 1(left). A mass loss of 15% is typically defined as the acceptable maximum mass loss for PCPC. Table 2 summarizes the number of frost cycles at which the specimens had 15% mass loss. The table also shows the air void content of the beam specimens used in the freeze-thaw tests determined. No freeze-thaw tests were performed on Mix 1-A.

Fig. 1(right) shows the decrease in RDM as function of the number of freeze-thaw cycles, and the 60% cut-off limit. Compared to the decrease in mass loss, the decrease in RDM occurred faster and more gradually as it was also observed in Shu *et al.* (2011). Hence, most specimens failed per the selected criteria due to a reduction in RDM rather than due to the mass loss. Table 2 also shows the average DFs calculated from Eq. (1). The size of DF is very dependent on the choice of M and P which means that DFs can only be compared if they were calculated using the same assumptions. The

results in Kevern, Wang, and Schaefer (2010) and Shu *et al.* (2011) suggest that acceptable freeze-thaw behavior occurs for DF s larger than 40%; hence, the DF s determined for the specimens in this study are low which indicate a poor freeze-thaw resistance. Based on DF , Mix 3-B had the worst freeze-thaw durability even though the beams used for the test had the lowest void content which is known to improve the freeze-thaw durability of PCPC. Mix A showed slightly improved freeze-thaw durability compared to Mix B. Moreover, the freeze-thaw results were much more variable than what is typically observed and allowable for conventional concrete.

Table 2 Air void content and hardened unit weight (UW) of PCPC beam specimens used for freeze-thaw tests measured according to the ASTM C1754 standard (ASTM C1754, 2012). Moreover, the initial transverse frequency, f_0 , and the durability factors, DF , for the different mix designs, are shown (average value (av.) and coefficient of variation (COV)), and the number of frost cycles, n , corresponding to a mass loss of 15%.

Mix	Voids [%]		UW [kg/m ³]	f_0 [Hz]	DF [%]		n [-]		
	Av.	COV	Av.	Av.	Av.	COV	1	2	3
2-A	19.4	0.6	2008	1627	18.6	9.6	154	184	124
3-A	18.5	1.0	1979	1673	20.0	22.0	124	124	184
1-B	18.8	2.5	1977	1680	16.3	55.1	86	124	184
2-B	19.0	1.3	1964	1685	12.0	91.0	183	95	34
3-B	13.8	5.0	1976	1696	10.5	88.3	64	64	125

3.2 Air Void Analysis using the Linear-Traverse Method

3.2.1 Air Void Content

The results achieved directly from the RapidAir analysis include only voids up to 4 mm; however, the raw data was processed to also include all void sizes. Fig. 2 visualizes the air void distribution of the mix designs by distinguishing the void content for air voids less than 1 mm, air voids less than 4 mm and all air voids. Both numerical and relative values are shown.

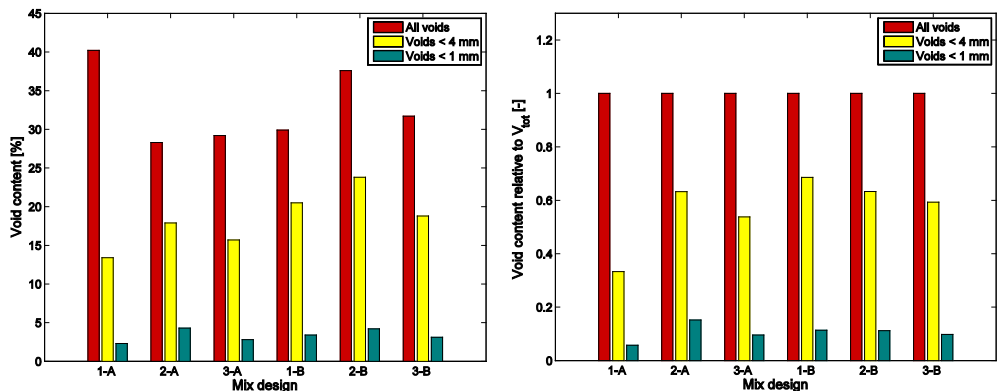


Fig. 2 Void content of specimens divided between voids less than 1 mm, 4 mm and all voids determined from the RapidAir analysis on cylinder specimens (left), and void contents relative to the void content that includes all voids for the particular mix designs (right).

Because Mix 1-A and 1-B did not contain AEA it was expected that those mixes would have less fine air than the remaining mixes. Fig. 2(right) shows that Mix 1-A had a slightly lower air content of voids less than 1 mm than Mix 2-A and 3-A; however, for Mix B the same tendency was not observed, and even for Mix A the difference was small. It is well-known that addition of AEA increases PCPC workability by which PCPC compacts better and the void size decreases. For Mix A, the voids less than 4 mm constituted a larger part of the total void content for Mix 2-A and 3-A with AEA than for Mix 1-A without AEA; however, for Mix B this was not the case. For neither Mix A nor Mix B, did the addition of AEA have the desired effect. Fig. 3 shows scanned 10×10 cm² images of specimens 2-A, 1-B and 2-B together with 1×1 cm² close-ups of the same sections.

For air entrained PCPC, a clear gray phase, that is a combination of the black solid phase and the white void phase, is typically present (Kevern, Wang, and Schaefer, 2008). Fig. 3 shows that such phase was neither present for Mix A nor Mix B. This indicates that the amount of AEA added to the mixtures was not sufficiently high enough to create a fine entrained air void system in the cement paste. The AEA dosage used has previously shown to be sufficient for PCPC (Kevern, Wang, and Schaefer, 2008; 2010). A possible explanation of the lacking entrained air content observed in this study is the high fly ash content compared to the studies in Kevern, Wang, and Schaefer (2008, 2010) that did not contain any fly ash. Fly ash is known to consume AEA and therefore a higher AEA dosage is typically used for concretes containing fly ash.

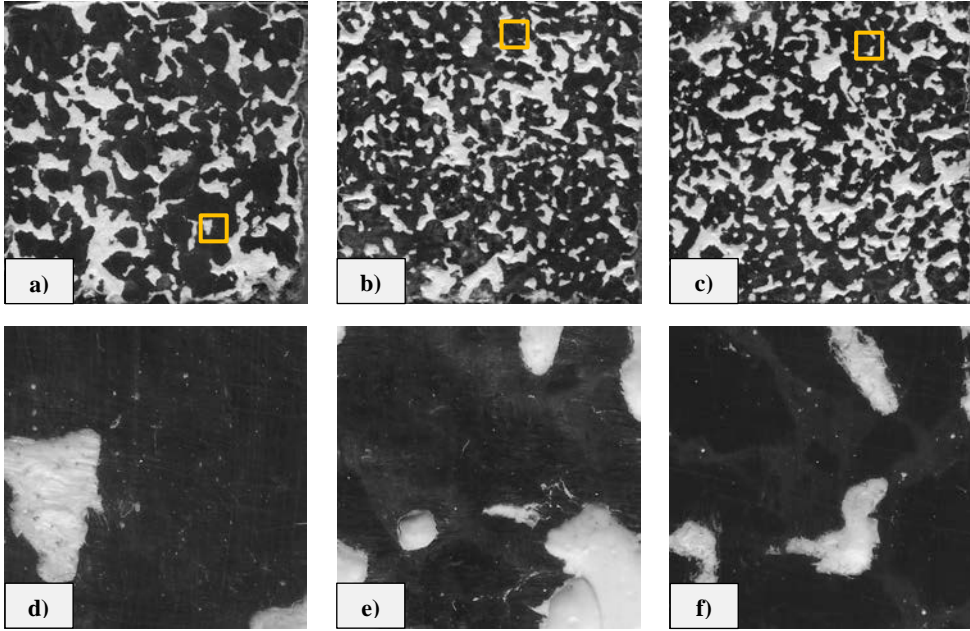


Fig. 3 Scanned PCPC images: a,b,c) $10 \times 10 \text{ cm}^2$ section of mix 2-A, 1-B and 2-B, respectively, and d,e,f) $1 \times 1 \text{ cm}^2$ close-up of mix 2-A, 1-B and 2-B, respectively. No entrained air phase was observed for any of the mixes.

3.2.2 Spacing factor of PCPC

The paste content and the total air void content of the PCPC mixes in this study represent typical values for PCPC, and as seen from the mix design, the p/A -ratio is 1.2 which is significantly less than 4.342 because of the large PCPC void content. Therefore, for PCPC the following expression is always used to determine the spacing factor, \bar{L} [mm], when applying the linear-traverse method:

$$\bar{L} = \frac{T_p}{4N} = \frac{p}{SA} \quad (2)$$

where T_p is the traverse length through paste, N is the total number of air voids intersected, p is the paste content, S [mm^{-1}] is the specific surface area of the voids (the surface area of air voids divided by their volume), and A [%] is the total void content (EN 480-11, 1998; Powers, 1949). For conventional concrete, p/A is typically larger than 4.342 and a different and more complex expression is used to determine the spacing factor: $\bar{L} = \frac{3}{S} [1.4 \left(1 + \frac{p}{A}\right)^{1/3} - 1]$. However, for PCPC the expression used to determine the spacing factor based on Powers' formula is fairly simple. Eq. (2) builds on the assumption that for cement paste with high air content, the maximum distance to an air void can be determined by spreading the cement paste in a uniformly thick layer over each air void. The thickness of this paste layer equals the spacing factor, and Eq. (2) therefore expresses the ratio between the paste content and the total surface area (the second expression in Eq. (2)). For cement paste to be

freeze-thaw durable, it is a typical requirement that the spacing factor should be less than 0.2 mm (ASTM C457, 2006).

Table 3 shows the spacing factor determined from the linear-traverse method. The spacing factors were determined by considering air voids less than 1 mm, less than 4 mm and all air voids. Table 3 shows that the mix designs containing AEA did not have smaller spacing factors than the mix designs without AEA, which confirms the tendencies observed from Fig. 2 and Fig. 3.

Table 3 Spacing factor (\bar{L}) determined from the RapidAir analysis for voids less than 1 mm, less than 4 mm and for all air voids, and difference between spacing factor including voids less than 4 mm and all air voids.

Mix	$\bar{L}_{1mm} (< 1 \text{ mm})$		$\bar{L}_{4mm} (< 4 \text{ mm})$		$\bar{L}_{tot} (\text{all voids})$		$\bar{L}_{4mm} - \bar{L}_{tot}$
	Av. [mm]	COV [%]	Av. [mm]	COV [%]	Av. [mm]	COV [%]	
1-A	0.28	10.4	0.33	13.4	0.27	11.8	0.06
2-A	0.26	5.26	0.22	7.75	0.21	7.64	0.01
3-A	0.35	12.6	0.33	12.1	0.29	9.56	0.04
1-B	0.27	8.82	0.24	8.77	0.23	11.6	0.01
2-B	0.22	6.32	0.18	6.30	0.17	5.94	0.01
3-B	0.25	4.72	0.24	5.80	0.22	5.53	0.02

The spacing factors based on voids less than 4 mm and all voids were calculated from Eq. (2) which states an inverse proportionality between the spacing factor and the number of air voids. Hence, when increasing the number of air voids included in the analysis, the spacing factor decreases. Table 3 shows that the decrease was up to 0.06 mm. The large air voids have a larger total surface area (SA) than the small voids and Eq. (2) shows that the spacing factor decreases with increasing SA . Thus, the difference between spacing factors including all air voids and voids less than 4 mm depends on the content of voids larger than 4 mm. Fig. 2(right) shows that Mix 1-A had the largest content of voids larger than 4 mm; hence, this mix experienced the largest difference in the spacing factor as it is also clear from Table 3. However, for Mix 2-A, 1-B and 2-B, the content of voids larger than 4 mm was less and the difference in the spacing factor was small. Thus, if the content of air voids greater than 4 mm is low, the error by using the RapidAir analysis that includes only air voids up to 4 mm is small. Table 3 also shows that the spacing factors decrease if all voids are included rather than air voids less than 1 mm. However, in this situation a similar rationale as the abovementioned cannot be applied because the expression used to determine the spacing factor for air voids less than 1 mm is different than Eq. (2) and builds on different assumptions. However, the spacing factor determined for voids less than 1 mm can be considered to only relate to the cement paste.

3.3 Reflection and Evaluation of Freeze-Thaw Durability Test Methods for PCPC

The results in Table 3 show that even without the expected entrained air content in the cement paste, the spacing factors calculated when including all air voids were fairly close to 0.2 mm for most mixes, and for Mix 2-B less than 0.2 mm, even though Fig. 3e and Table 2 clearly show that the cement paste was not air entrained and the freeze-thaw durability was not good. Fig. 3 shows that the large air voids of PCPC are not spherical but irregular and twisted. Because the linear-traverse method directly transforms a given chord length to the volume of a spherical void, the method possibly exaggerates the total air content. This is clear by comparing the total void content of Fig. 2(left) with that in Table 1 determined from the ASTM C1754 standard (ASTM C1754, 2012).

When performing the freeze-thaw tests according to the ASTM C666 standard (ASTM C666, 2008), the large air voids are water-filled; however, in the microscopic analysis they are considered to be as effective as the small entrained air voids to relieve the pressure caused by water that freezes. This is contradictory. On one hand it is known that the large voids positively influence the freeze-thaw durability of PCPC, but on the other hand, the tools available to characterize the freeze-thaw properties of PCPC are developed for conventional concrete that has a different void structure. A possible solution to overcome this misinterpretation between the microscopic test method and the freeze-thaw test method could be to include only entrained air voids less than, for example, 1 mm in the determination of the spacing factor because these voids are not water-filled during freeze-thaw

testing. By doing so, the misinterpretation between the two methods would be minimized; however, it would not link the test methods to the PCPC freeze-thaw performance experienced in real life, and future studies should clarify how to include the large voids in a more reasonable way in laboratory testing.

4 Conclusions

The main conclusions from this study were:

- 1) The air entrainment (AEA) dosage of 0.125 weight-% of cement and fly ash was not sufficient to create an entrained air content in the cement paste containing fly ash even though the dosage has previously been found to provide good results for cement paste without fly ash. This is possible due to the high content of fly ash used in this study. The entrained air contents of specimens with and without AEA were similar.
- 2) The decrease in the relative dynamic modulus (RDM) was faster and more gradual than the decrease in the mass during the freeze-thaw tests. Most specimens failed due to reduction in RDM rather than due to reduction in mass.
- 3) The freeze-thaw durability results were much more variable than what is typically observed and allowable for conventional concrete. The freeze-thaw durability of all specimens tested was poor even though the spacing factor was less than 0.2 mm for one mix design and fairly close to 0.2 mm for others. When the spacing factor is determined from the linear-traverse method, the large voids are considered to effectively relieve the pressure caused by water that freezes; however, in freeze-thaw laboratory tests of PCPC they are water-filled and thereby not effective which causes a misinterpretation between the two test methods.
- 4) If the content of air voids greater than 4 mm is low, the error by using the linear-traverse method that includes only air voids up to 4 mm is small.

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