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Microscopic analysis of paste and aggregate distresses in pervious concrete in a wet, hard freeze climate

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ABSTRACT

In a recent survey, the durability and condition of 29 in service pervious concrete pavements built in a wet, hard freeze environment were assessed, and 33 core samples were collected. Following up on this survey, this paper identifies some of the common subsurface distresses observed in the core samples with optical microscopy instruments. In the distressed samples, cracks went through the aggregate, paste, and interfacial transition zone (ITZ). The cracks were similar to cracks in conventional concretes that formed due to known freeze/thaw damage. In addition to cracking patterns, it was discovered that none of the 33 pervious concrete samples contained the recommended quantity or spacing of entrained air bubbles. There was a lack of entrained air bubbles despite the addition of air-entraining admixtures to all of the pervious concrete mixtures. It is unknown if the lack of entrained air bubbles contributed to the cracks in the pervious concretes.

1. Introduction

Pervious concrete is a type of Portland cement concrete with interconnected voids that comprise 5–30% of the concrete matrix volume so water can freely flow through the concrete matrix. The pervious concrete void space is created by a gap-graded aggregate with a typical maximum aggregate size between 1/2 in. and 3/8 in. The paste volume, consisting of cement and water, is intentionally under-proportioned so as to not fill the voids created by the aggregate. Sand is typically omitted from pervious concrete as the sand gets incorporated into the paste and causes an increase the paste volume, which ultimately causes a decrease in the volume of the interconnected void network. The voids are further created with a stiff cement paste that has a low water-to-cement (w/c) ratio typically between 0.27–0.33. The paste consistency is such that it coats each aggregate particle and creates a workable mixture that is easily placed without sloughing off the aggregates before the concrete sets.

The primary application of pervious concrete is stormwater runoff management. Stormwater infiltrates pervious concrete, and the pervious concrete voids capture sediment that was suspended in the runoff. As a stormwater management tool, pervious concrete is used to construct low volume pavement infrastructure such as sidewalks, driveways, parking lots, and residential roads [1].

In the United States, pervious concrete was introduced in the mid 1970s when the construction industry briefly considered reducing energy costs and exploring alternatives to building with non-renewable mineral resources [2]. In the preceding 30 years, pervious concrete's use has been more prevalent in the warmer, southern regions of the United States [3] than in the colder, northern regions. In the last decade, however, the stormwater management benefits of pervious concrete have spurred an interest and increased use of pervious concrete in wet, hard freeze climate regions. In order to be a viable stormwater management tool, pervious concrete must also be a structurally sound and durable pavement material. While pervious concrete has proved to be a durable pavement material in wet, freeze thaw regions, it has not been consistently durable [8].

A majority of pervious concrete research has focused on its hydraulic characteristics and creating the optimum balance between strength and permeability. Structural aspects of pervious concrete has also been considered in [4]. One aspect of pervious concrete research that has not received sufficient attention is material durability. Yang and co-workers investigated pervious concrete freeze/thaw durability with laboratory tests [5–7], but the relationship between the performance of pervious concrete samples in standardized laboratory freeze/thaw tests and in service pervious concrete pavements is not entirely understood.

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In an effort to identify aspects of the pervious concrete microstructure that affect its durability, pervious concrete core samples were taken from both distressed and non-distressed pervious concrete pavements that had been in service in a wet, hard freeze environment from between 1 and 5 years. This paper presents the results of a microscopic evaluation of these in service pervious concrete pavements.

2. Methodology

2.1. Sample region

In the state of Minnesota, USA, which is in a wet, hard freeze environment, pervious concrete has been in service since 2005, and it has showed varying degrees of durability. During an initial study on pervious concrete in this environment, 29 unique, in service pervious concrete pavements at 19 different locations throughout Minnesota were assessed for surface distresses. During site surveys, the most commonly observed material distress was raveling, or the separation of paste and aggregate particles. Most frequently, raveling occurred within the first two aggregate layers, but in the most severely distressed pervious concretes, raveling was observed to a depth of 1 in. (25 mm) to the entire thickness of the pavement section [8].

2.2. Coring methodology

For this study, 33 cores were taken from 18 in service pervious concrete pavements. The core diameters ranged from 2 in. to 4 in. (50–100 mm). Before the cores were taken, a clear, non-viscous epoxy was injected into the pervious concrete pavements and allowed to harden. The amount of epoxy injected into each sample area varied according to the permeability of the pervious concrete in the sample area (Fig. 1, left). The epoxy was necessary to strengthen the concrete matrix to prevent further cracking due to the coring process and, in the cases where raveling had occurred in the pervious concrete, to capture the concrete constituents in a moment of time (Fig. 1, right).

It is important to note that the pervious concrete cores were primarily taken from the areas within the pervious concrete pavements that showed surface distresses. The frequency with which distresses were reported in relation to the number of cores taken is not representative of the performance of pervious concrete in Minnesota as a whole, but rather captured the range of potential pervious concrete material distresses. Furthermore, the areas of the pervious concrete pavements ranged from 75 ft^2 (7 m^2) to over 100,000 ft^2 (9200 m^2). In most instances, distresses were localized and the majority of the pervious concrete pavement area did not show surface distresses.

2.3. Sample preparation

Once the pervious concrete samples were collected, they were cut in half longitudinally and one half was arbitrarily chosen for polishing with a lapping wheel. Polished samples were observed with an optical stereomicroscope.

2.4. Concrete constituents

Pervious concretes investigated in this study incorporated three types of aggregate including river gravel, crushed dolomite limestone, and granite. In all cases, the top size aggregate passed either the 3/8 in. (9.5 mm) or 1/2 in. (12.5 mm) sieve. A small amount (3–7% by weight) of sand was included in approximately one quarter of the pervious concrete pavements studied. Cementitious material including cement and fly ash typically exceeded 600 lbs/yd^3 (356 kg/m^3). Typical admixtures included air entrainer, water reducer, set retarder, and viscosity modifier. The w/c ratios were between 0.27–0.30.

3. Results and discussion

3.1. Subsurface cracks

The frequency of cracking patterns and cracking direction were observed in the polished pervious concrete samples. Subsurface cracks appeared both parallel and vertical to the concrete's surface and also propagated around and radiated at different angles from aggregate particles (radial cracking). The cracks propagated through the paste, aggregate, and interfacial transition zone (ITZ). The locations of the cracks in a majority of the samples were within 2 in. (50 mm) from the surface, but in the most severely distressed pervious concretes, the cracks occurred throughout the full depth of the samples. Table 1 summarizes the mediums through which the subsurface cracks propagated. The summary is segregated by aggregate type. Notice that the number of cores exceeds the number of sites because, in some instances, more than one core was taken from a site.

Table 1 indicates that cracks through the paste were most prevalent, followed by cracks through the interfacial transition zone (ITZ), and cracks through aggregate particles were observed with the least frequency. Each type of aggregate is represented according

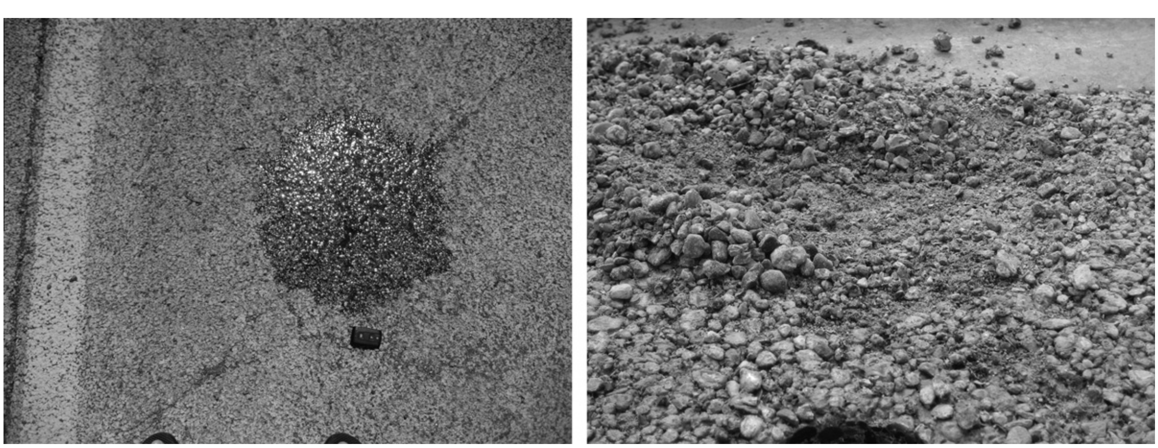

Fig. 1. (Left) epoxy setting in pervious concrete (Right) severely raveled pervious concrete.

Table 1
Summary of subsurface pervious concrete cracks.

Aggregate type	Number of sites	Number of cores	Number of cores with subsurface cracks through specified medium							
			None	Paste	Aggregate	ITZ	Paste & aggregate	Paste & ITZ	Aggregate & ITZ	Paste, aggregate, & ITZ
Limestone	11	21	3	6	2	1	0	1	1	7
Gravel	5	8	1	1	0	0	0	3	0	3
Granite	2	4	3	0	0	1	0	0	0	0
Total	18	33								

to the frequency with which it was used in the field. The type of aggregate used in the pervious concretes was dictated by the type of aggregate available to a particular concrete supplier or contractor in the locations where the pervious concretes were placed. Table 1 suggests that the aggregate type did not dictate the medium through which the cracks propagated. It is interesting to note that three out of four, or 75%, of the pervious concrete samples utilizing granite aggregates showed no subsurface cracking compared to 14% and 12.5% of the limestone and gravel aggregate pervious concretes, respectively. However, due to the small sample size of pervious concrete sites and cores utilizing granite aggregates, it cannot be suggested that granite aggregates improve the durability of the pervious concrete matrix. Detailed observations of subsurface cracking in each core are available in [8] and examples of the more frequent and unique cracking patterns are reviewed in the following paragraphs.

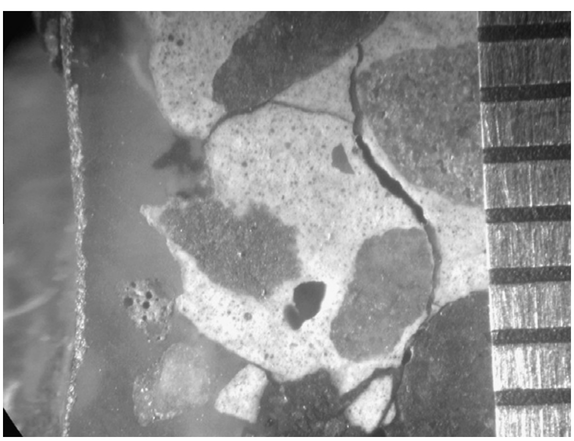

Fig. 2. Parallel and vertical cracks through the paste and around the ITZ. Scale is 1/32 in. (0.8 mm).

One frequently observed cracking pattern in the pervious concrete cores was a pattern in which the cracks propagated in both the parallel and vertical directions in relationship to the surface and frequently followed the paste-aggregate interface. This pattern was observed in 11 of 33 cores. This cracking pattern was observed to depths of the samples' top 2 in. (50 mm) to the full depth of the samples. An example of this cracking pattern is shown in Fig. 2 in which the pervious concrete surface is oriented to the left and is covered in a layer of epoxy. Fig. 2 focuses on the cracks in a small area of the sample that are partially filled with epoxy. When the entire sample is considered, the cracks extended 4 in. (100 mm) below the surface and occurred ubiquitously.

A second cracking pattern frequently observed in the pervious concrete cores was isolated incidences of cracking or cracking that was confined to one region of the sample. These cracks were either parallel to the surface or radial and occurred primarily through the paste and aggregate. This pattern was observed in seven of 33 pervious concrete cores. The cracks occurred from between 1/4 in. (6 mm) to 1 3/4 in. (45 mm) below the concretes' surfaces. Two examples of this cracking pattern are shown in Fig. 3 in which the pervious concrete surfaces are oriented to the left. The cracks in each figure are parallel to the surface and propagate through both the paste and aggregate. The cracks shown are either one of a few cracks or are the only visible crack in the sample.

While the cause of the cracking highlighted in Figs. 2 and 3 is unknown, others have documented similar cracking patterns and attributed them to freeze/thaw distresses [9,10]. Furthermore, similar cracking patterns have been described in conventional concrete pavements in Iowa, Minnesota, and Michigan [11–13], and these cracking patterns were also attributed to freeze/thaw damage.

In a third type of cracking pattern, cracks occurred almost exclusively in the ITZ regions of the pervious concrete. The cracks occurred in a clearly delineated area of the pervious concrete from the surface to between 1/4 in. (6.5 mm) and 1/2 in. (12.5 mm) below the surface. This crack pattern is shown in Fig. 4 in which the

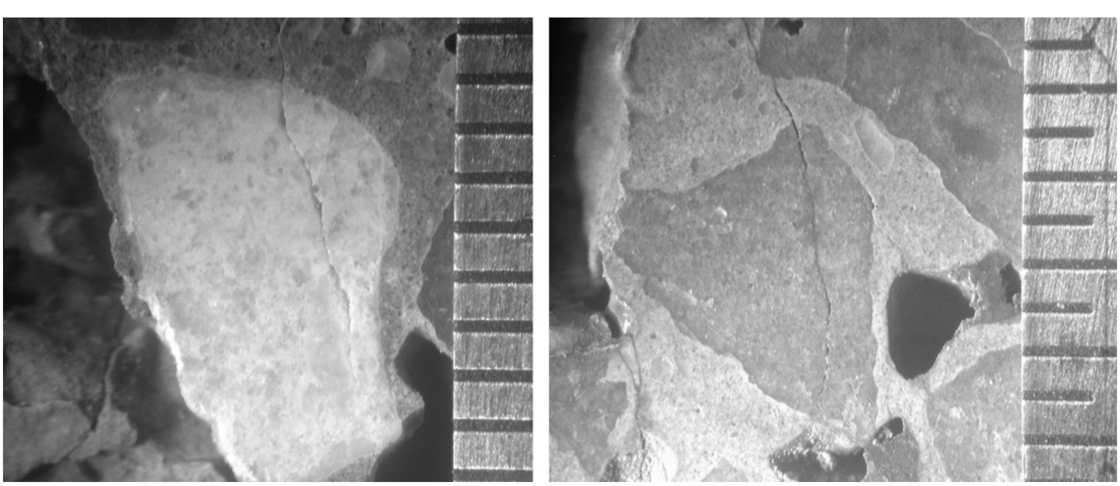

Fig. 3. Cracks parallel to the surface that propagated through aggregate and paste. Scale is 1/32 in. (0.8 mm).

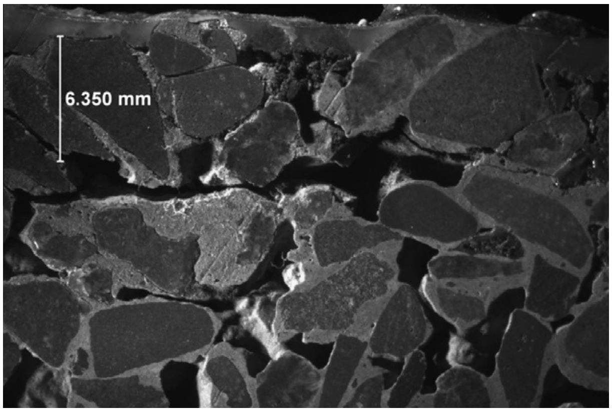

Fig. 4. Pervious concrete in which cracks propagated primarily through the ITZ.

pervious concrete surface is oriented to the top of the photo. This pattern was only observed in 1 of 33 pervious concrete cores, which came from pervious concrete that incorporated gravel aggregate. This cracking pattern cannot necessarily be attributed to gravel aggregate because it was the only one of seven gravel pervious concrete core samples that exhibited this type of subsurface crack. According to Table 1, a granite pervious concrete sample also exhibited subsurface cracking exclusively through the ITZ. This was different than the highlighted gravel pervious concrete sample because the crack in the granite sample was the only crack observed in the entire sample compared to cracks through almost all ITZs within 1/2 in. from the gravel sample's surface.

In a laboratory study of the behavior of pervious concrete tested according to ASTM C 666 [14], pervious concrete samples were reported to fail by the separation of the concrete paste from the aggregates [6]. This description of pervious concrete failure due to known freeze/thaw distresses matches the failure pattern observed in the pervious concrete shown in Fig. 4.

A fourth type of cracking pattern was distinct due to lines of fractured paste. This phenomenon of small, fractured paste particles was observed in two pervious concrete samples that were extracted from severely raveled pervious concrete pavements. The cracks propagated in all directions primarily through the paste and, in both samples, occurred between the concrete's surface and one inch below the surface. One of these samples is shown in Fig. 5 in which the pervious concrete surface is oriented to the top of the photo. The figure shows a layer of fractured paste particles suspended in epoxy that extended approximately 0.47 in. (12 mm) below the surface and another layer of fractured paste approximately 1 in. (25 mm) below the surface. Also observed were parallel and vertical cracks with respect to the surface through the paste, aggregate, and ITZ between the layers of fractured paste. The horizontal line of fractured paste 1 in. (25 mm) below the surface delineates the distressed from the non-distressed pervious concrete. Fractured paste and the strict delineation of distressed and non-distressed concrete were also reported in a petrographic analysis of pervious concrete samples obtained from a severely raveled pervious concrete parking lot in Denver, Colorado. A forensic analysis of the distressed concrete indicated that the cracking was due to freeze/thaw damage [15].

It is interesting to note that the concrete samples highlighted in Figs. 4 and 5 were taken from two different areas of the same pervious concrete parking lot. On one hand, the pervious concrete failed due to debonding of the aggregate and paste in the ITZ. On the other hand, the pervious concrete failed due to paste fracture. A third core sample taken from a non-distressed area of the parking lot was free of subsurface cracks. In general, if the pervious concrete pavements showed no surface distresses, there were either no subsurface cracks or the cracks were singular or occurred in small groups.

Concrete durability problems can be caused by lack of resistance to frost, sulfate, corrosion, and abrasion as well as alkali-silica reactivity [16]. The cracks presented in Figs. 2–5 are attributable to one of the following expansive mechanisms [9]:

1. Alkali-aggregate reaction.
2. Reformation of ettringite in situ.
3. Recrystallization of salts.
4. Corrosion of reinforcement.
5. Surface cracks over an expanding core.
6. Thermal gradient from the environment.
7. Freeze/thaw attack.

Observation of the pervious concrete samples with a stereomicroscope confirmed that the cracking in the pervious concrete samples was not caused by reactions one through three, as there were no signs of alkali-aggregate reaction, reformation of ettringite in air voids, or salt recrystallization. Only two of the 33 pervious concrete samples showed subsurface distresses due to reactive aggregates, and the aggregate in both pervious concrete samples was traced to one aggregate source. Furthermore, no secondary products were observed within the microstructure. None of the pervious concrete pavements observed in this study were reinforced, which eliminates cracking due to reinforcement corrosion. This suggests that cracking in the pervious concrete samples could be attributable to mechanisms five through seven.

An addition to the crack patterns shown in Figs. 2–5, three pervious concrete cores showed a cracking pattern similar to that shown in Fig. 6 in which the pervious concrete surface is oriented

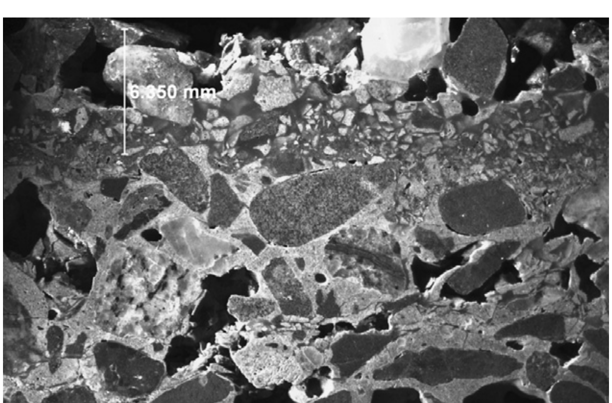

Fig. 5. Cracked pervious concrete between two layers of fractured paste particles.

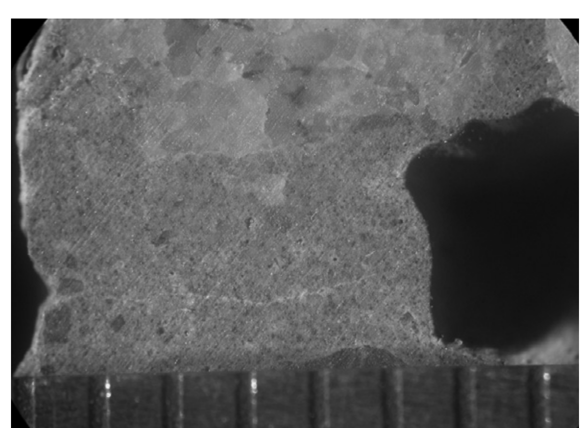

Fig. 6. Two, tightly spaced cracks perpendicular to the pervious concrete surface. Scale is 1/32 in. (0.8 mm).

towards the left. This type of cracking can be attributed to drying shrinkage [9]. In this figure, the tightly spaced vertical cracks extend approximately 3/16 in. (4.8 mm) below the surface and are connected by a horizontal crack at approximately 1/16 in. (1.6 mm) below the surface. Shrinkage cracks were only observed in a few pervious concrete cores, but could have been present in many others. Because shrinkage cracks are tight, they are more difficult to observe in core samples with optical microscopy.

3.2. Entrained air bubbles

In addition to subsurface cracking, it was observed that none of the 33 pervious concrete cores contained adequate entrained air bubbles according to ASTM C 457 [17] even though all of the concrete mixtures were dosed with air-entraining admixture (AEA). Because pervious concrete has gained popularity in wet, hard freeze regions relatively recently, there have not been many opportunities to investigate the amount of entrained air in pervious concretes, and according to the recommendations for freeze/thaw durability of pervious concretes, it had been taken for granted that the addition of AEA resulted in the expected quantity and spacing of air bubbles in pervious concrete pastes.

The American standard for evaluating entrained air bubble quantity, spacing, and specific surface area in hardened cement paste is ASTM C 457: Standard Test Method of Microscopical Determination of Parameters of the Air-Void System in Hardened Concrete [17]. The challenge of using ASTM C 457 to evaluate the entrained air bubble characteristics of pervious concrete paste is that this method does not distinguish between entrained air bubbles and the pervious concrete's voids, so it must be modified if used for pervious concrete [18]. However, due to the lack of entrained air bubbles observed in the pervious concrete samples, a modified ASTM C 457 was not used for evaluation.

The survey of the pervious concrete core samples showed that the entrained air bubble spacing in most of the pervious concrete pastes was on the order of 0.03125 in. (800 μm) to several inches. 0.03125 in. (800 μm) is approximately four times the ASTM 457 recommended entrained air bubble spacing in extreme freeze/thaw environments. Fig. 7 compares a properly air entrained conventional concrete paste (left photo) [17] to a typical example of the pervious concrete paste observed for this project (right photo). The two photos are approximately the same scale, and the scale in the right photograph is 1/32 in. (0.8 mm).

It is suspected that the reason why AEAs do not produce entrained air bubbles in pervious concretes is that the 0.27 w/c ratio, typical of the pervious concretes evaluated in this study, does not provide enough water for both cement hydration and for entrained air bubble stabilization. The mechanism of AEA requires that a certain amount of water be available to form a film around the entrained air bubbles [19]. The water helps the air-entraining molecules to stabilize the entrained air bubbles.

In addition to the low w/c ratio, other characteristics of pervious concrete decrease the potential stability of entrained air bubbles. The stability of entrained air bubbles increases as fly ash and cement content decrease and increases with sand content [20]. This occurs because cementitious materials demand water. The more cementitious materials used, the more water is used to coat the cement particles and the less water is available to stabilize the entrained air bubbles [21]. Many of the pervious concrete mixtures included fly ash and required higher cement contents than a conventional concrete used for the same purpose. Furthermore, pervious concrete typically includes little to no sand.

Others studies have also reported a lack of entrained air bubbles in pervious concrete. Following a modified ASTM 457 procedure to count entrained air bubbles in pervious concrete, Lukkarila reported that the paste fractions of several pervious concrete samples were, "essentially non-air entrained based on the lack of small spherical voids that were less than one mm in diameter" [18]. Additionally, both Kevern and Whiting reported the spacing factor of entrained air voids within pervious concrete paste as greater than 0.008 in. (200 μm) [22,23].

This study has not proven that the subsurface cracks observed in pervious concrete samples were caused by freeze/thaw damage. However, if freeze/thaw damage were assumed to be the cause of the subsurface cracks, it would be logical to conclude that the lack of entrained air bubbles in the pervious concrete paste was responsible for the lack of durability in the pervious concrete pavements because there were not an adequate quantity or spacing of entrained air bubbles in any of the pervious concrete samples. The blame cannot necessarily be assigned to the lack of entrained air bubbles, however, for three reasons. First, it has been shown by others that the ASTM 457-recommended quantity and spacing factor of entrained air can be decreased as the w/c decreases from 0.6 [21,24–27]. This suggests that entrained air bubbles in a 0.27 w/c ratio concrete mixture are not as vital to creating freeze/thaw resistant concrete paste as in concrete mixtures with a higher w/c ratio. Secondly, as hypothesized by Litvan, AEA may amend the capillary pore structure of the pervious concrete paste in a way that increases the freeze/thaw durability of the concrete even though the entrained air bubbles are visibly absent from the paste [28]. Finally, even though 100% of the pervious concrete samples showed that the pervious concrete pavements lacked the recommended amount and spacing of visible entrained air bubbles according to ASTM C 457, approximately 60% of the pervious

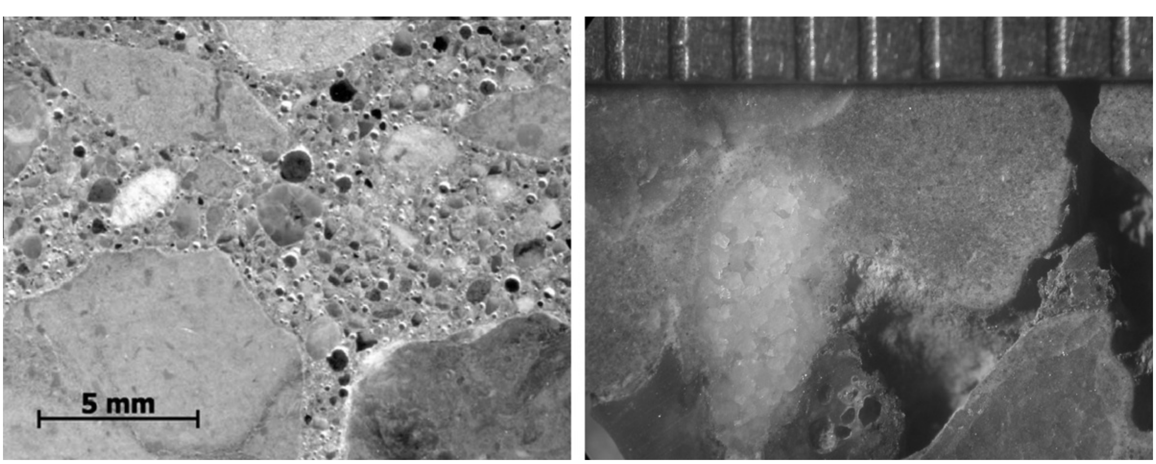

Fig. 7. (Left) sufficiently air-entrained concrete [17]. (Right) pervious concrete with no visible entrained air bubbles.

concrete pavements observed did not exhibit distresses concurrent with freeze/thaw mechanisms.

4. Conclusion

In the last decade, attention has been given to the durability of pervious concrete pavements because their durability has not been consistent or predictable in climates with extreme cold temperatures and multiple freeze/thaw cycles. In this study, microscopic analysis of one to five year-old pervious concrete pavement samples taken from visibly distressed pervious concrete pavement sections revealed extensive subsurface cracking. Freeze/thaw distresses were the suspected cause of a majority of the subsurface cracks due to the similarity of the cracking patterns in the pervious concrete to cracking patterns in conventional concrete that were caused by freeze/thaw damage. While it appeared that freeze/thaw damage was the cause for the subsurface cracks in the pervious concrete samples, the cracking patterns were not consistent throughout the samples. Furthermore, the cracking patterns were not contingent upon the concrete mixture designs or aggregate type.

This study also revealed that pervious concrete samples taken from both distressed and well-performing pervious concrete pavement areas lacked visible entrained air bubbles even though all of the pervious concrete mixtures included air-entraining admixture. Numerous laboratory and field studies have shown that entrained air bubbles promote freeze/thaw durability in conventional concrete pastes. On the other hand, pervious concrete typically has a water-to-cement ratio between 0.27 and 0.30 and it has been shown that concrete pastes with water-to-cement ratios below 0.40 may not require entrained air bubbles because the paste microstructure of low water-to-cement ratio pastes are more resistant to freeze/thaw action.

The observations that pervious concrete mixture design, aggregate type, and lack of entrained air bubbles did not dictate the extent of damage in the pervious concretes suggests that the microstructure of the pervious concrete paste should be further examined before a conclusion is made about the durability of pervious concrete pavements in wet, hard freeze climates.

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