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PREMATURE DETERIORATION OF JOINTS IN SELECTED INDIANA PORTLAND CEMENT CONCRETE PAVEMENTS

PRZEDWCZESNE ZNISZCZENIE SZCZELIN DYLATACYJNYCH BETONOWYCH NAWIERZCHNI W STANIE INDIANA

Abstract In the last decade, the progressive deterioration of relatively new portland cement concrete pavements was observed in several locations in Indiana. This deterioration took a form of cracking and spalling localized in the upper part of the pavement, typically around the bottom of the saw cut groove. In order to investigate the cause of this deterioration, 36 of 150-mm diameter cores were extracted from four different pavements. Although the obtained specimens were subjected to various tests, this paper only contains the results of air void system analysis, as the ultimate mode of failure appeared to be freeze-thaw related. The results indicate that even though some of these concretes might have had satisfactory air-void system at the time of placement, its effectiveness became compromised over time by combined effects of water and salt ingress (formation of ettringite and Friedel's salt).

Streszczenie W ciągu ostanich kilkunastu lat w stanie Indiana (USA) zaobserwowano postępujące zniszczenie stosunkowo nowych nawierzchni betonowych. Przedwczesne zniszczenia w postaci pęknięć i wykruszeń wystepowaly wokół podlużnych i poprzecznych szczelin dylatacyjnych (w górnej części nawierzchni, na dnie nacięcia dylatacyjnego). W celu zbadania przyczyn występujących zniszczeń wykonano 36 odwiertow, z których pobrano walce o średnicy 150 mm do badań laboratoryjnych. Próbki zostały wycięte z czterech różnych odcinkow drogowych. Chociaż pobrane walce poddano kilkunastu testom, w artykule przedstawiono wyniki jednego z oznaczen. Analiza systemu pustek powietrznych w stwardniałym betonie wskazuje, że przyczyną przedwczesnego zniszczenia nawierzchni było częściowe wypełnienie pustek powietrznych etryngitem lub solą Friedela. Obecność tych związków wskazuje na duży stopień akumulacji soli odladzających i zawilgocenia betonu w obrębie nacięć spowodowany brakiem zdolności dylatacji do odprowadzania wody.

1. Introduction

Some of the 5-10 years-old concrete pavements located in various part of Indiana, USA, that otherwise perform well, show signs of premature deterioration (in the form of excessive cracking and spalling) primarily in areas near the longitudinal joints; in several cases, the transverse joints areas have been affected as well. The deterioration has been observed (among others) at SR 933 near South Bend, on some sections of I-65, as well as on several roads in the Indianapolis area (i.e. 86th and Payne Rd). Some of the typical examples of the distress observed are presented in Figure 1.

Fig. 1. Section of pavement on W 86th Street, Indianapolis, IN (left) and SR 933 near South Bend, IN (right)

This paper contains the results of air-void system analysis (using ASTM C 457) performed on number of cores extracted from the following locations:

- “on” ramp from US 67 to east-bound I-465 located in the south-west section of Indianapolis, IN;
- W 86th Street (near Michigan Road) located in the north section of Indianapolis, IN;
- SB I-65 (near MLK Street exit) in Indianapolis, IN
- SR 933 near South Bend, IN (section between Darden Road and Willow Street).

The cores obtained from the W 86th Street were actually removed from two locations along the eastbound lane. The first location was immediately to the west of the intersection of W 86th Street with N. Payne Road and it is referred to in this paper as “before lights” (BL) location. This section of the pavement was in good condition, with no visible signs of distress. The second location was immediately to the east of the intersection and it is referred to in this paper as “after lights” (AL) location. The condition of the pavement at this location was considerably worse than that to the west of the intersection, with severe to moderate deterioration observed in both longitudinal and transverse joints (see left side of Figure 1). Due to the significant differences in the pavement conditions for the BL and AL locations, the test results obtained from these two sections were analyzed separately.

2. Collection of cores

When selecting the coring locations on the ramp from US 67 to eastbound I-465E and on W 86th Street an attempt was made to obtain specimens for various cases presented in Figure 2 and listed below:

A – damaged area of the transverse joint
B – damaged area of the longitudinal joint near the junction of the longitudinal and transverse joints
C – damaged area of the longitudinal joint away from the transverse joint

D – mid-span of the slab, undamaged section
E – undamaged transverse joint adjacent to the damaged transverse joint

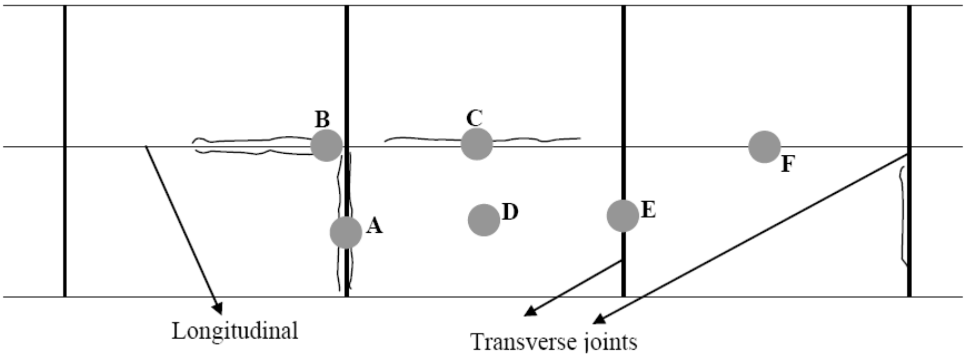

Fig. 2. Proposed coring locations

3. Preparation of test specimens

3.1 Sampling and testing procedure

A number of specimens needed for various types of tests were prepared by dissecting each of the collected cores as shown in Figure 3. The specimen for air-void system analysis (shown hatched), had planar dimensions of 110×110 mm and was generally collected from the top section of the core. In four instances, the damage to the cores removed from the joints was so extensive that it was not possible to obtain the specimens directly from the top section of the core. As a result, these specimens were obtained from the lower portion of the core.

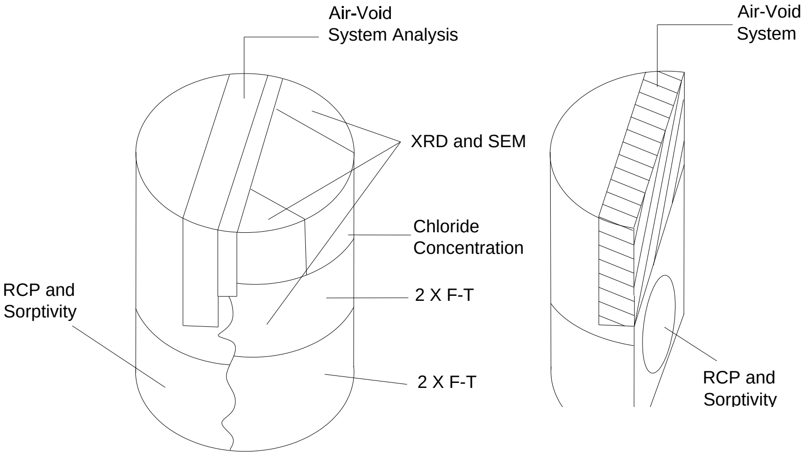

Fig. 3. Schematic of test specimen locations within each core

3.2 Polishing of specimens for air-void system analysis

All the specimens for air-void system analysis were polished using automatic lapping wheel, following the procedures of ASTM C 457 [1].

3.3 Testing procedure

The air-void system analysis was conducted using modified point-count method following ASTM C 457 [1]. The test was performed in such way that the results were recorded for each line (traverse) separately, which allowed for determination of the distribution of air voids with depth of the core (the results for every four lines were averaged to increase the accuracy). In addition, distinction was made between the entrained and entrapped voids. The selection of entrapped voids, although arbitrarily, was based on the size (larger than about 1 mm), shape (irregular rather than round) and location (mostly adjacent to at least one particle of aggregate). Finally, it should be pointed out that voids in-filled with secondary products were not counted (regardless of whether they appeared to be entrapped or entrained) as such voids do not contribute to the freeze-thaw resistance of concrete.

4. Test results

The summary of all test results obtained during the ASTM C 457 analysis is presented in Table 2. Additionally, the average values and standard deviations for all the relevant air-void system parameters (total air content, entrained air content, void frequency and spacing factor) were calculated separately for the group of undamaged and damaged cores at each location. These results are presented in Figures 4-7.

For reference, provided below are the approximate recommended values of parameters of air-void system for freeze-thaw resistant air-entrained concrete [2, 3]:

- air content: 6.5% (by volume of concrete);
- void frequency: > 1.5 times the air content;
- specific surface area: 23.6 mm^2/mm^3;
- spacing factor: 0.20 mm.

5. Analysis and discussion

As seen in Table 2, for the group of cores obtained from the US 67 ramp, the air content (both total and entrained) was highest for cores 5F and 9D (5.5 – 6.0%). The air content in all other cores was about 4% or less, which is significantly lower than 6.5% typically specified for PCC pavements exposed to freezing and thawing [2,3]. The lowest entrained air content was obtained for cores 6D and 8A (2.0 - 2.4%). Accordingly, these two cores exhibited the highest values of spacing factor (0.52 mm and 0.62 mm, respectively), which is considerably above 0.20 mm considered to be indicative of frost-resistant concrete [2,3]. Both damaged cores (1A and 8A) had relatively high spacing factor (0.39 mm and 0.62 mm, respectively).

All cores from W 86th Street BL location had relatively uniform amount of entrained air (in the range of about 3.0 - 5.0%). However, the values of spacing factor for these specimens were found to be very low (0.11 mm to 0.16 mm), which is below recommended value of 0.20 mm. It should be also noted that the values of both void frequency and specific surface (although these are not independent variables) are very high for all cores from W 86th Street BL (Table 2). Thus, the good parameters of air-void system of cores collected from that location appear to explain the lack of damage observable at the joints.

Table. 2. Summary of test results from air-void system analysis

Location	Label	Paste content (%)	Avg. chord length (mm)	Total air content (%)	Entrained air content (%)	Void frequency (voids/mm)	Specific surface ($\text{mm.}^2/\text{mm.}^3$)	Spacing factor (mm)	Descending trend in void frequency with depth	Filled air voids observed
US 67	US67_1A	26.8	0.35	5.8	3.8	0.17	11.5	0.39	Yes	Yes
	US67_2F	32.8	0.28	5.2	3.5	0.19	14.4	0.36	Yes	Yes
	US67_3E	29.0	0.27	5.2	3.0	0.19	15.0	0.32	Yes	Yes
	US67_4D	24.0	0.19	5.3	3.1	0.28	21.0	0.21		Yes
	US67_5F	42.4	0.13	6.3	5.5	0.50	31.6	0.17	Yes	Yes
	US67_6D	29.5	0.38	4.0	2.1	0.11	10.7	0.52		
	US67_7F	27.9	0.17	5.5	4.2	0.32	23.3	0.20		
	US67_8A	31.4	0.45	4.3	2.4	0.09	8.8	0.62	Yes	Yes
	US67_8E	na								
	US67_9D	24.0	0.13	6.4	6.2	0.49	31.0	0.13		
	US67_10D	31.6	0.07	3.8	3.5	0.54	56.5	0.10		
W 86th St. BL	86BL_1D	25.5	0.08	3.4	3.1	0.43	50.8	0.11		
	86BL_2D	25.6	0.15	6.3	4.9	0.43	27.0	0.16		
	86BL_3D	26.9	0.10	4.2	4.1	0.43	40.2	0.13	Yes	
	86BL_4D	28.4	0.11	4.5	4.3	0.40	36.1	0.14		
	86BL_5D	22.9	0.14	4.9	4.5	0.34	27.9	0.16		
	86BL_6D	25.5	0.13	5.4	5.3	0.43	32.0	0.14		
W 86th St. AL	86AL_1D	29.4	0.20	3.7	3.7	0.18	19.9	0.29		
	86AL_2D	29.1	0.41	4.1	2.5	0.10	9.9	0.55		
	86AL_3D	31.9	0.16	5.2	3.7	0.33	25.2	0.20	Yes	
	86AL_4D	30.0	0.25	4.3	2.5	0.17	16.2	0.33		
	86AL_5D	30.5	0.23	5.3	4.1	0.23	17.5	0.28		
	86AL_6D	27.1	0.23	5.2	4.4	0.23	17.7	0.27		
	86AL_7A	29.1	0.44	3.5	2.9	0.08	9.2	0.63	n/a	Yes
	86AL_8B	28.9	0.32	4.7	3.8	0.15	12.4	0.41	Yes	Yes
	86AL_9F	28.5	0.38	3.8	3.2	0.10	10.5	0.53	Yes	Yes
	86AL_10E	27.4	0.28	6.0	4.7	0.21	14.3	0.31	Yes	
	86AL_11C	30.0	0.29	4.1	4.1	0.14	14.0	0.39	Yes	Yes
SR 933	SR933_0D*	28.9	0.31	4.5	3.7	0.14	14.0	0.40	n/a	Yes
	SR933_1D	29.6	0.17	4.6	4.4	0.28	23.9	0.22		
	SR933_2E	26.9	0.25	5.7	4.2	0.23	16.1	0.28	Yes	Yes
I-65	I65_2C	13.7	0.52	5.9	5.3	0.11	7.7	0.42	n/a	
	I65_3B	23.2	0.59	4.9	3.9	0.08	6.8	0.67		
	I65_4C	19.2	0.37	4.0	2.7	0.11	10.9	0.41		
	I65_5C	22.6	0.40	5.1	3.7	0.13	10.0	0.44		
	I65_6F	22.2	0.46	7.9	6.1	0.17	8.8	0.41	n/a	

Note: only empty air voids were included in the count
n/a denotes the specimens which were not obtained from the very top part of the core
* average of five specimens obtained from the same core

All cores obtained from W 86th Street AL location had relatively low entrained air content varying from 2.5% (cores 2D and 4D) to 4.7% (core 10E). The cores from this location also exhibited high scatter in the spacing factor, with values ranging from 0.20 mm (core 3D) to 0.63 mm (core 7A). It can also be noticed that for all damaged cores (7A, 8B, 9F[*] and 11C) the measured spacing factor was 0.39 mm or higher.

The entrained air content of all three cores obtained from SR 933 was about 4.0%. The spacing factor for the cores from mid-span of the slab was 0.41 mm (core 0D) and 0.23 mm (core 1D). The core obtained from the undamaged transverse joint (2E) had a value of spacing factor of 0.28.

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[*] Core 9F appeared to be undamaged (no surface damage) but was deteriorated beneath the surface

The total air content of 7.9% (entrained air content of 6.1%) obtained for the only undamaged core from I-65 (6F) was the highest among all cores retrieved from that location (Table 2).

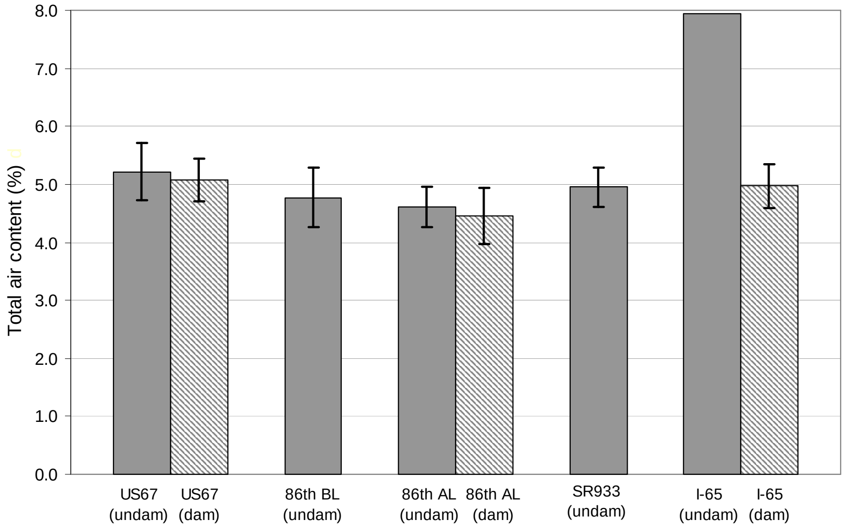

Fig. 4. Average total air content for undamaged (undam) and damaged (dam) cores from each location

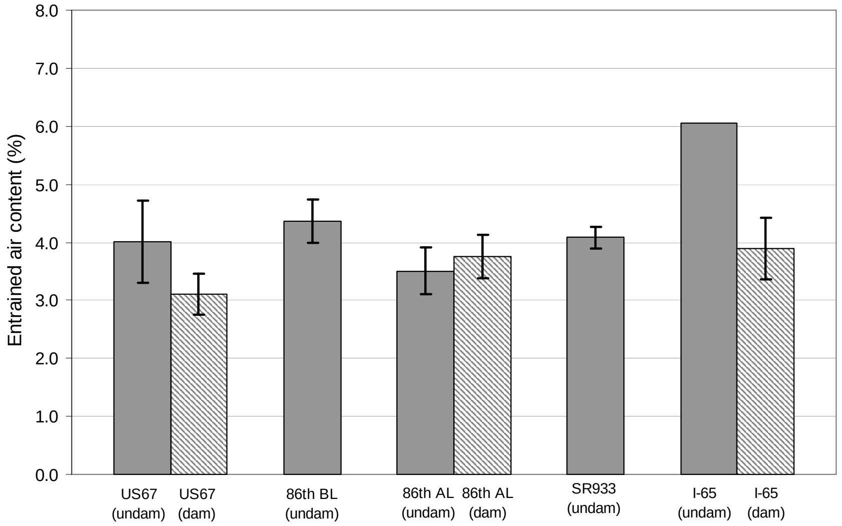

Fig. 5. Average entrained air content for undamaged (undam) and damaged (dam) cores from each location

The lowest total air content of 4.0% (2.7% of entrained air content) was found for core 4C. However, high spacing factor of about 0.41 mm was obtained for all cores, including the undamaged core 6F. The only exception was core 3B, for which a value of 0.67 mm was obtained.

Figure 4 reveals that, with the exception of core 6F from I-65, the average total air content of both damaged and undamaged cores was almost the same (~5.0%). Similarly, with the same exception, no significant differences in the average amount of entrained air content were present between the undamaged and damaged cores (Fig. 5). However, as seen in Figure 6, the average values of the void frequency for all undamaged cores were higher than those in the damaged cores, indicating that the specific surface area of the air-bubbles system in these cores is high (see Table 2) and thus offers good frost-resistance potential. Particularly high average void frequencies were found for undamaged cores from US 67 (0.35 voids/mm) and W 86th Street BL (0.41 voids/mm). Similarly, as shown in Figure 7, the average values of spacing factor in the undamaged cores was always lower than that in the damaged cores, again indicating potential for better freeze-thaw resistance of the former.

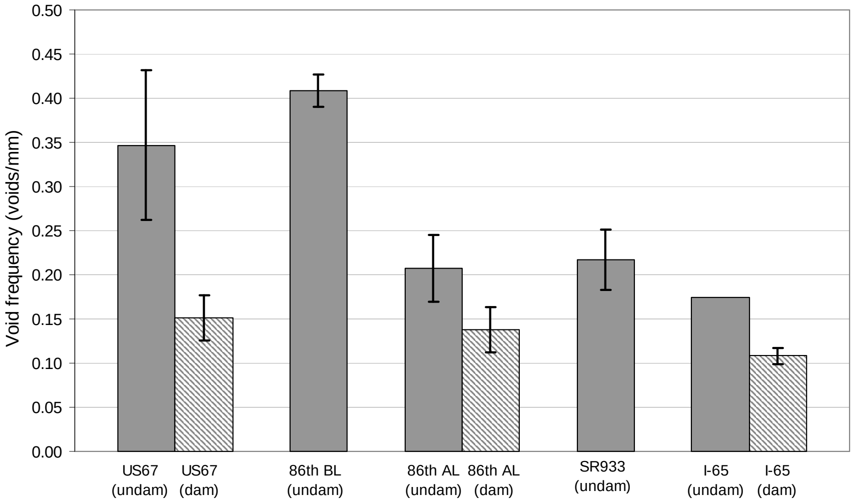

Fig. 6. Average void frequency for undamaged (undam) and damaged (dam) cores from each location

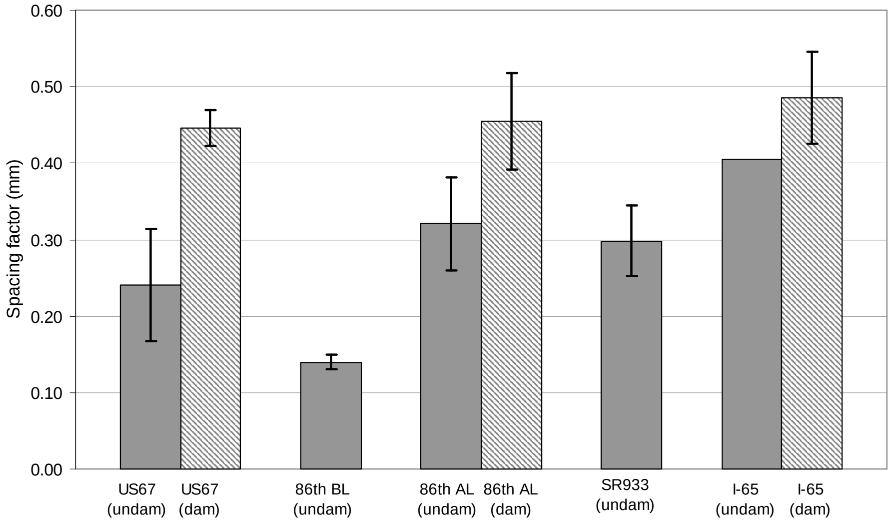

Fig. 7. Average spacing factor for undamaged (undam) and damaged (dam) cores from each location

Two other important features were observed during the air-void system analysis. First, the descending trend in void frequency with depth was found for the total of 12 specimens from all locations (see Table 2). The example of this thrend is presented in Figure 8. It is clear that within about 25 mm from the surface of the core the void frequency was two to three times higher than that observed in the lower section of the specimen.

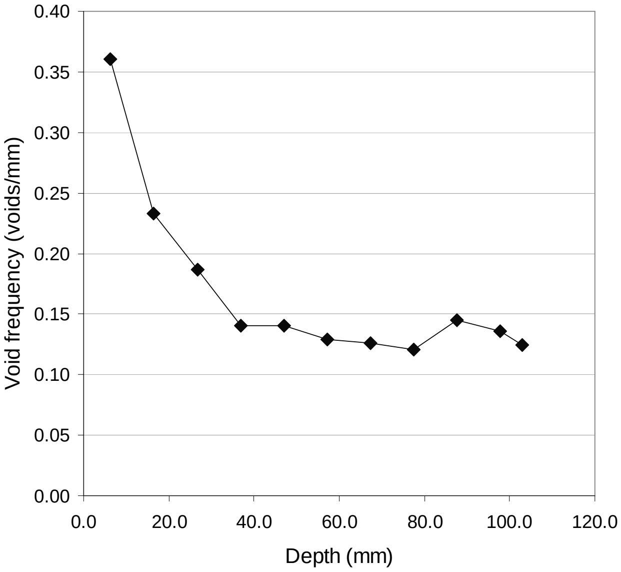

Fig. 8.Void frequency vs. depth for US 67 core #1A

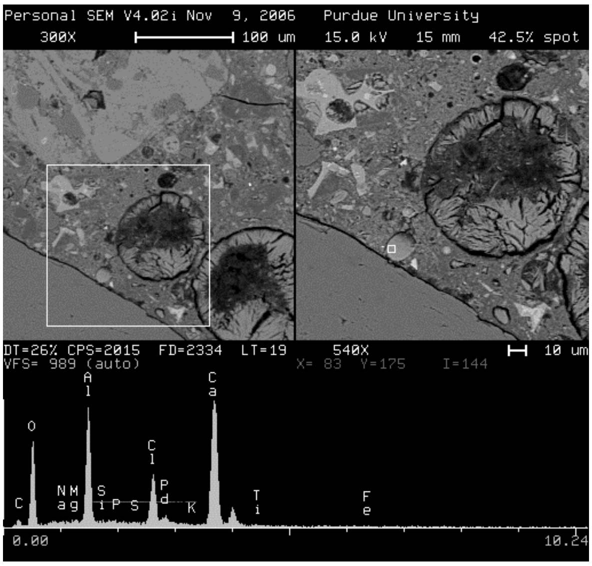

Fig. 9. Air-voids filled with ettringite and Friedel's salt present in core I-65_3B

Second, in all but three of the specimens displaying this trend numerous in-filled voids were found (Table 2). The voids were filled with either ettringite ($3CaO{\cdot}Al_2O_3{\cdot}3CaSO_4{\cdot}32H_2O$) or (occasionally) with Friedel's salt ($Ca_3Al_2O_6{\cdot}CaCl_2{\cdot}10H_2O$) as seen in Figure 9. In their paper on delayed ettringite formation (DEF) Stark and Bollmann [4] suggested a change in thermodynamic stability of monosulfate at low temperatures that leads to formation of ettringite (through partial decomposition of monosulfate). They also found that freeze-thaw cycling in 3 % NaCl solution resulted in transformation of monosulfate to Friedel's salt and ettringite.

As an example, Figure 10(a) shows the typical appearance of empty air voids in the upper section of the ASTM C 457 specimen obtained from core #1A from US 67, whereas Figure 10(b) illustrates completely in-filled air voids observed in the lower section of the same specimen (about 25 mm below the top).

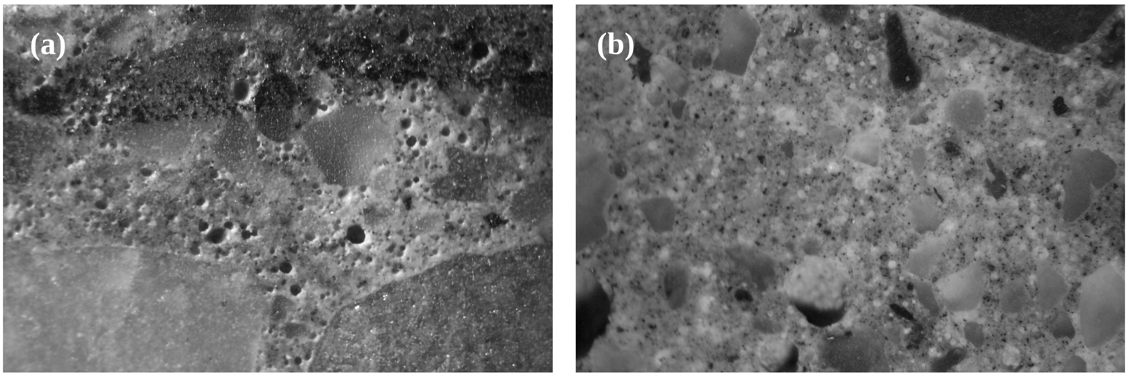

Fig. 3. Empty air voids in the top portion (a) and in-filled air voids in the bottom portion (b) of ASTM C 457 specimen obtained from core #1A from US 67 ramp

The reason for the discrepancy in the amount of air (as represented by void frequency) between the upper and lower parts of the ASTM C 457 specimens (shown in Fig 8) may be explained by the presence of the sealing material in the upper part of the joint. This material, by adhering to the walls of the joint, might have blocked the ingress of water to the interior of concrete near the top part of the joint, thus preventing precipitation of deleterious products and in-filling of the air voids. At the same time, relatively poor air void-system parameters found in most of the cores in which the joints sealer has been lost (US 67 and W 86th Street AL cores) can be attributed to the fact that their air voids were progressively filled with precipitates, and thus become ineffective. This observation implies that the "original" parameters of the air-void system could have been well within the expected limits, but become compromised over time, perhaps because of poor drainage, locking-up of joints, water ponding, etc.

Different from the discussed above is the case of I-65 cores for which the microstructural analysis using optical microscope did nor reveal the presence of the in-filled air voids. This observation has initially led the authors to believe that this concrete must have had poor quality air-void system at the time of placement. However, subsequent analysis of the same specimens performed using the scanning electron microscope (SEM) indicated that substantial amount of air voids were in fact in-filled (Fig. 9). The reason that these voids might have not been visible under optical microscope was related to excessive content of sulfate in the entire matrix. The uniformly distributed sulfate phase reduced the contrast between the in-filled voids and surrounding paste, thus making the in-filled voids more difficult to detect.

6. Summary

The results of the petrographic air-void system analysis supplemented by the SEM observations suggest that the deterioration of the joints in the investigated sections of concrete pavements can be attributed to in-filling of the entrained air voids with various precipitated products such as ettringite or Friedel's salt. Although the exact cause of in-filling is not exactly known, the previously discussed mechanism of both of these precipitates forming in the presence of chloride-based deicing salts could have taken place. It is also possible that the sulfates originated from some external source, e.g. contaminated deicing salt, which resulted in delayed ettringite formation (DEF). Finally, both these phenomena might have occurred simultaneously. Regardless of the cause, however, it has been widely recognized that once in-filled, the air voids become ineffective in protecting concrete from freeze-thaw damage [5].

Certainly, in those of the examined cases where water was literally standing in the joints, the concrete must have been critically saturated. That condition will not only increase the rate of freeze-thaw damage, but it will also facilitate formation of ettringite in the air-voids (thus gradually reducing their effectiveness).

7. References

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