PETROGRAPHIC EXAMINATION OF CONCRETE CORES TAKEN FROM PAVEMENT SLABS ON THE ODOT DEL-23 TEST ROAD PROJECT AND THE ODOT HAN-75 14.41 PROJECT: Phase A: The Effect of Air Void Content and Parameters of the Air Void System on the Freeze/Thaw Durability of Ohio Department of Transportation Pavements

Dr. David Lankard

for the Ohio Department of Transportation
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This study investigated the effect of air void content and parameters of the air void system on the freeze/thaw durability of Ohio Department of Transportation pavements. Previous studies had shown that despite the fact that the entrained air void system of the concrete does not meet historical and current ODOT requirements for this parameter, the pavements show no evidence of any freeze/thaw related distress. The investigation showed that the satisfactory freeze/thaw durability could be attributed to (1) the likelihood that the pavement concretes did not reach a level of critical moisture saturation, (2) a low water to cementitious material ratio of the concretes, (3) the concretes all contain some level of air entrainment, and (4) less severe freeze/thaw conditions in the field relative to those experienced by laboratory specimens. It is recommended that consideration be given to the development of new procedural guidelines which describe the steps to take in the instances where air content measurements on ODOT pavement projects fall short of the current minimum value of 4 percent.
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State Job No. 134239

By

Dr. David Lankard
Lankard Materials Laboratory
Columbus, Ohio

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The contents of this report reflect the views of the author who is responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views or the policies of the Ohio Department of Transportation or the Federal Highway Administration.
BACKGROUND

Over the course of the past two and one half years, Lankard Material Laboratory has been involved in research projects investigating the nature and origin of cracking distress in two Ohio Department of Transportation (ODOT) pavement projects. The projects include (1) the Ohio Strategic Highway Research Program (SHRP) Specific Pavement Studies Test Road in Delaware County Ohio (DEL-23 Test Road), and (2) pavement on Interstate 75 in Hancock County Ohio (ODOT HAN-75-14.41:State Job No. 134239).

DEL-23 Test Road

Construction of the 3-mile mainline pavement on this project was completed in 1996. Within several years cracking of some of the Portland cement concrete (PCC) slabs was observed. Cores were taken from these pavements in 1999. In May 2003 the cores were provided to Lankard Materials Laboratory
for study. This work at LML was completed on November 1, 2003 at which time a Final Report was provided to The Ohio Research Institute for Transportation and the Environment in Athens, Ohio.

Concrete used in the construction of all ODOT pavements are specified as air-entrained concretes. Air entrainment is provided to protect the cementitious matrix phase of the concretes from the effects of freeze/thaw cycling. To achieve this function, the amount of air-entrainment is specified by ODOT at 6% plus or minus 2%. It is well known that with decreasing air content below the target value, the ability of the air void system to provide freeze/thaw durability is diminished.

In the DEL-23 study it was learned that, although the concrete used on this project is air-entrained, the air void content in some of the pavement sections is well below the minimum air void content specified by ODOT. The study further showed that none of the cracking distress in the mainline pavements, base slabs, and ramp slabs on this project was due to the effects of freeze/thaw cycling; this, despite the fact that the concrete represented by the cores was exposed to the severe weather conditions of the central Ohio area for over three years.

Following the 2003 LML study of the DEL-23 Test Road, it was concluded by ODOT and LML personnel that a more detailed characterization of the entrained air void system in the Test Road concretes might provide valuable insights into the requirements for air-entrainment in pavement concretes that in all other respects have met the material and performance requirements for ODOT pavement applications. On future pavement projects where in-place concrete air contents fall below the current minimum value of 4 percent, it may not be necessary to consider a removal of the pavement if the other parameters of the air void system reflect values obtained on the DEL-23 cores.

An air void system characterization study of the DEL-23 cores forms one part of the research study that was awarded to LML by ODOT in May 2005 (HAN-75). At the start of the HAN-75 project it
was assumed that the characterization of the air-void system on the DEL-23 pavement concrete would stand alone as a separate study. However, once work on the HAN-75 pavement concrete was underway, it became apparent that a similar situation had occurred here. That is, although some of the pavement sections showed air-void contents well below the minimum target value, none of the cracking distress is related to the effects of freeze/thaw cycling. For this reason it was decided to include the HAN-75 results within the broader context of the study to define the requirements of the entrained air system for freeze/thaw durability in ODOT pavements.

**HAN-75 Pavements**

This 5-mile section of pavement was constructed in 1989-1990. Cracking distress was first observed in the late 1990s. Repairs were first made to the pavement in 2002. Cores were taken from the mainline pavement and the shoulders on this project in the fall of 2004. A total of thirteen cores were provided to LML for study in June 2005. Seven cores were taken for use in the petrographic examination and companion cores for strength measurements were provided for six of the petrographic cores. As part of this study to identify the nature and origin of the cracking distress in the HAN-75 pavements, the air-void system of the concretes was fully characterized.

**SCOPE AND OBJECTIVES OF THE PRESENT STUDY**

What is available here are detailed petrographic studies of concretes from two major ODOT pavement projects in which the air contents were well below recommended and specified levels; yet the pavements in both projects show no freeze/thaw-related cracking or scaling distress. The principal objective of the present study is to use the data from these two projects to learn what factors contributed to this outcome. The intent is to establish improved or more meaningful guidelines regarding acceptance/rejection criteria for air entrainment in ODOT pavement concretes.
The Purpose of Air-Entrainment in Concrete

The purpose of air entrainment in concrete is to protect the cementitious phase from the effects of freeze/thaw cycling when the concrete is in a state of critical water saturation.

Entrained air voids in concrete are tiny spherical voids that are intentionally created through the use of air-entraining admixtures added to the fresh concrete during mixing. In the hardened concrete the millions of air voids are empty cavities of space contained within the cementitious matrix phase. When a concrete that is critically saturated with water experiences a freezing event, the water in the concrete turns to ice. The ice has a lower density; hence it occupies a greater volume than the liquid water. If this increase in volume of the water is not accommodated stresses are generated within the cementitious matrix and cracking can result. The air void spaces provide a relief valve for the pressures that would otherwise develop. Inadequate air-entrainment in concrete pavements exposed to severe weather conditions can result in (1) scaling of the wearing surface and (2) cracking and spalling of the concrete below the wearing surface.

Over the years research and field experience has shown that the target values of an “adequate” entrained air system are (1) a total air void content of 6 percent, (2) a minimum specific surface area of 600 in\(^2\) per in\(^3\), and (3) a maximum spacing factor of 0.008 in. (200 µm).

**Total Air-Void Content:** The recommended total air void content depends upon the maximum size of the coarse aggregate in the concrete. As the aggregate size decreases, the recommended total air content increases. An air content of six percent is recommended for concretes containing 1-inch maximum size aggregate. The American Concrete Institute guidelines for allowable variations in air void content in the field are plus or minus 1.5%. ODOT permits a variation of plus or minus 2 percent.
**Specific Surface Area (SSA):** This is a term derived from measurements made using the procedure of ASTM C 457, “Procedure for the Microscopical Determination of the Air-Void Content and Parameters of the Air-Void System in Hardened Concrete”. It is expressed in units of square inches of surface area of the air voids per cubic inch of air void volume (in$^2$/in$^3$). The higher the SSA, the smaller the size and the greater the number of air voids within a given volume of the concrete. Within limits “more is better” in this regard. Ideal entrained air void systems have a large number of very small diameter air voids, which will be reflected in a high specific surface area value.

For non air-entrained concretes the SSA will typically be in the range of 150 to 300 in$^2$/in$^3$. Non air-entrained concretes typically have 1 to 3 percent of entrapped air voids, most of which have a diameter greater than 1 mm.

The SSA of air-entrained concretes can range from the target minimum value of 600 in$^2$/in$^3$ to as high as 1500 in$^2$/in$^3$.

**Spacing Factor:** This is a term that is also derived from measurements made on hardened concrete using the procedure of ASTM C 457. Spacing factor is a parameter relating to the maximum distance in the cementitious phase to the periphery of an air-void. In practical terms it is the maximum distance that water must travel in the cementitious phase of the concrete to reach a pressure relief point (an air void) during a freezing event. The recommended maximum spacing factor of 0.008 in. (200 µm) was arrived at empirically by researchers at the Portland Cement Association many years ago. Concretes having spacing factors of 0.008 in. or less typically showed “satisfactory” durability in laboratory freeze/thaw tests. Subsequent experience in the laboratory and field has shown this to be a meaningful benchmark of the ability of a concrete to survive freeze/thaw cycling without unacceptable damage.
Other Factors Affecting the Freeze/Thaw Durability of Concrete

In addition to air-entrainment there are a number of material, environmental, and construction variables that influence freeze/thaw-related damage in concrete pavements. They include,

- The water to cementitious material ratio (w/cm) of the concrete (which controls the total porosity of the cementitious phase as well as the rate at which water migrates through the cementitious phase).
- The degree of saturation of the concrete at the time freezing occurs (controlled by the w/cm of the concrete, slab thickness, surface drainage, base drainage, level of precipitation, and the proximity of joints and cracks).
- The number of freeze/thaw cycles.
- The minimum temperature experienced during the freezing event.
- The quality of the coarse aggregates regarding freeze/thaw durability
- The use of deicing chemicals

One problem that has plagued ODOT pavements over the years is D-Cracking. D-Cracking is a freeze/thaw-related distress phenomenon that has been traced to coarse aggregates that expand an abnormally high amount when frozen in the saturated condition. The presence of air-entrainment does not “cure” the D-Cracking problem. Most of the ODOT pavements that have experienced D-Cracking distress have been air-entrained concretes. There are a number of diagnostic features revealed in a petrographic examination that make it relatively easy to identify D-Cracking distress in pavement concretes.

Scope of the Present Study

In the present study all of the variables identified above were considered as they relate to the objectives of the study. The entrained air void system was characterized on six cores from the DEL-23 project and seven cores from the HAN-75 project. The characterization was done using the modified point count method of the ASTM C 457 procedure. Information was obtained on (1) the total air void
content, (2) the specific surface area, and (3) the spacing factor of the air voids. These data were interpreted in light of previous open-literature research studies that have examined the effect of these variables on freeze/thaw durability in concretes exposed to cyclic freezing and thawing.

The ASTM C 457 procedure is conducted on surfaces of the hardened concrete that have been saw-cut and lapped on a steel wheel using successively finer grits. This procedure followed the guidelines of ASTM C 856 “Standard Practice for Petrographic Examination of Hardened Concrete”. The lapped surface of the concrete is traversed using a stereoscopic microscope at a magnification of 90X. For every 0.05-inch of the traverse, the operator notes and records the microstructural feature that is present at that site, which can be (1) cement paste, (2) an entrained air void, (3) an entrapped air void, (4) a fine aggregate particles, or (5) a coarse aggregate particle.

**DESCRIPTION OF THE CORES AND THE PROJECT CONCRETES**

Full air-void system characterization data were obtained on six cores from DEL-23 and seven cores from HAN-75. It is reemphasized that none of the cores examined here showed any evidence of any freeze/thaw related distress including (1) scaling of the wearing surface, (2) classic freeze/thaw cracking, or (3) D-Cracking.

**DEL-23 Cores**

The mainline pavements from which the cores were taken are 8-inches of Portland cement concrete (PCC) on 6-inches of lean concrete base (LCB). Cores were also taken from ramp lanes with the PCC placed at a thickness of 8-in. and 11-in. The air void system was characterized on six, 6-in. diameter cores from this project including,

- Four mainline pavement cores
- One core from the lean concrete base
• One core from a ramp

**Mainline Concrete:** For three of the cores the concrete is identified as “Mix 900”, which is an air-entrained concrete containing 750 lb of Portland cement and 113 lb of fly ash per cubic yard. The target water to cementitious material ratio (w/cm) is 0.31. These cores are from Mainline Test Section 390206. These cores are identified in Table 1 as ML-1, ML-2, and ML-3.

The other mainline core is ODOT’s Class C, Option 1 concrete, which is an air-entrained concrete containing 510 lb of Portland cement and 90 lb of fly ash per cubic yard. The target w/cm is 0.40. This core is from Test Section 390205. This mainline core is identified in Table 1 as ML-4.

**Lean Concrete Base:** The lean concrete base (LCB) was placed without joints at a thickness of 6-inches. The mix design for this concrete is an air-entrained concrete containing 160 lb of Portland cement and 48 lb of Class C fly ash per cubic yard. At a water content of 235 lb, the target w/cm is 1.13. One LCB core was examined, which came from Test Section 390205. This core is identified in Table 1 as LCB-4. It underlies the mainline concrete core ML-4.

**Ramp Concrete:** The core representing this concrete was taken from a southbound ramp in Test Section 390810. This mix design for this concrete is an air-entrained concrete containing 350 lb of Portland cement and 120 lb of Class F fly ash per cubic yard. At a water content of 235 lb the target w/cm of the concrete is 0.50. This core is identified in Table 1 as DEL-R-810.

**Concrete Aggregates:** All of the Delaware Test Road concretes contain the same coarse aggregate; a dolomitic limestone identified as “Carey Stone, produced by National Lime. This is a 1-inch maximum size aggregate with a good service record. The fine aggregate is a natural sand identified as “Prospect Sand”. This is a natural sand composed of both carbonate and siliceous rock and mineral types. The aggregates in the DEL-23 concretes were judged to be of good quality based upon (1) their...
condition following 3 years of service in a severe weather environment, (2) their soundness, and (3) their mineral content.

**HAN-75 Cores**

Of the seven cores examined here, four were taken from mainline pavement slabs and three from shoulder slabs. All of the cores have a diameter of 6-inches except one mainline core which has a diameter of 4-inches. All of the concretes used on this pavement project represent the same mix design, which is the ODOT Class C concrete. This is an air-entrained concrete with a Portland cement content of 600 lb per cubic yard and a target maximum w/cm of 0.50. The w/cm of the in-place concrete is lower, estimated at 0.40.

The coarse aggregate used in the concretes is a 1-inch maximum size crushed limestone. The fine aggregate is a natural sand. The aggregates are judged to be of good quality based upon (1) their condition following 15 years of exposure in a severe weather environment, (2) soundness, and (3) their mineral content.

**Mainline Concrete:** The mainline concrete cores are identified (see Table 2) as HAN-6, HAN-17, HAN-19, and HAN-20. Core HAN-6 is a 4-inch diameter core. All of the other cores have a 6-in. diameter.

Core HAN-17 was taken from a mainline pavement slab that showed no distress at the time of coring (October 2004). At the start of the research project this core was intended to serve as the reference for “good” concrete on the project.

The mainline concrete pavement slabs on HAN-75 were placed at a thickness of 11-inches using a paving machine. The pavement slabs were placed on 6-inches of compacted recycled Portland cement
concrete graded to the 304 stone base standard. Underlying the compacted recycled PCC base is 11-inches of lime-stabilized base.

**Shoulder Concrete:** The shoulder concrete cores are identified (Table 2) as HAN-15, HAN-16, and HAN-18. The thickness of the shoulders tapers from 9 to 10-inches adjacent to the mainline slabs to around 6-inches at the berm edge.

**RESULTS AND DISCUSSION**

The results of the ASTM C 457 air-void characterization of the six DEL-23 cores are presented in Table 3 and the results for the seven HAN-75 cores are given in Table 4. The target air-void content for all of the concretes is 6 %. The allowable range in air content for ODOT pavement concretes is plus or minus 2 %.

The industry recommended minimum specific surface area for the air void system is 600 in$^2$/in$^3$ and the industry recommended maximum spacing factor is 0.008-in. (200 µm).

The concretes represented by the thirteen cores are air-entrained. There is a high degree of core-to-core variability in the parameters of the air-void systems, both within and between the two projects. For the thirteen cores,

- The total air content varies from 2.2 % to 8.9 %.
- The specific surface area varies from 268 in$^2$/in$^3$ to 754 in$^2$/in$^3$.
- The spacing factor varies from 0.0055 in. to 0.0218 in.
- Five of the 13 cores have a total air void content under the ODOT allowable minimum of 4 %.
- Ten of the 13 cores have a specific surface area under 600 in$^2$/in$^3$.
- Seven of the 13 cores have a spacing factor above the recommended maximum of 0.008 in.
The range in values of the parameters of the air-void systems is similar for the DEL-23 project and the HAN-75 project. For both the HAN-75 cores and the DEL-23 cores only one of the cores meets or exceeds all three of the industry recommended values for total air content, specific surface area, and spacing factor.

The principal finding that prompted the conduct of the present study is, despite the fact that 3 of the 4 mainline pavement cores on the DEL-23 project have a total air content under 3%, none of these cores show any evidence of freeze/thaw related cracking or scaling. The satisfactory freeze/thaw durability of these concretes can not be attributed to an air void system that meets current industry standards.

Numerous laboratory freeze/thaw studies have shown that even if the total air void content is below the minimum recommended value, the concrete can still have an acceptable specific surface area and spacing factor if the air-voids have a small enough diameter. A specific surface area in excess of 600 in$^2$/in$^3$ and a spacing factor less than 0.008-in. can provide adequate freeze/thaw durability even when the total air content is well below the industry standard. Conversely, it is expected that any concrete having a specific surface area below 600 in$^2$/in$^3$ and/or a spacing factor greater than 0.008 in. (200 µm) may not show satisfactory durability. Reference to Table 3 shows that the three DEL-23 mainline pavements that have air contents in the range of 2.3% to 2.9% have a specific surface area ranging from 546 to 644 in$^2$/in$^3$, and a spacing factor ranging from 0.0103 in. to 0.0127 in.

A similar situation exists for the HAN-75 pavement concretes (Table 4). The two cores showing air contents of 2.2% and 3.2% do not show anywhere near the minimum requirement for the surface area and spacing factor parameters. It is of particular interest that one of these two cores is Core 17, which was taken in a non-distressed pavement slab to provide a standard reference on the HAN-75 project for “good” concrete.
The obvious conclusion to be drawn here is that the current industry standards for the parameters of entrained air systems as related to freeze/thaw durability do not strictly apply to ODOT pavement concretes. Clearly, other factors have played a role in this matter. These factors, which are listed below, are considered in the remainder of this report.

1. The relevance of the current industry standards for air entrainment in pavement concretes.
2. Field conditions vs. Laboratory conditions
3. The water to cementitious material ratio of the concrete (w/cm).
4. “Some” air entrainment vs. no air entrainment

**The Relevance of Current Industry Standards for Air Entrainment in Pavement Concretes**

The historical and current industry recommended values for the parameters of the entrained-air system in concrete are based on the results of laboratory tests such as ASTM C666, “Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing”. In this test, the temperature is alternately raised and lowered from 0º F to 40 F in not less than 2 hours and not more than 5 hours. This is an allowable cycling rate of 20 F/hr to 8 F/hr (11.1 C/hr to 4.5 C/hr). This laboratory procedure, as well as others like it, differ from field conditions for concrete pavements in severe weather applications in at least two important respects.

1. The rate of freezing and thawing is higher in the laboratory tests.
2. The concrete specimens in the laboratory tests are in a condition of critical moisture saturation, while often this condition is not present in the field.

**The Rate of Freezing and Thawing:** In a 1981 paper in the American Concrete Institute Journal, Pigeon and Lachance reported the results of tests on concretes subjected to “slow” freeze/thaw
cycles\textsuperscript{(1)}. They had previously determined that the most rapid rate of freezing in their area (Quebec City, Canada) was 2 C (3.6 F) per hour. This is the test rate that they used in their studies.

The concretes used in their studies contained fine and coarse aggregate sources with a good durability record in service, with a moderately high water to cementitious material ratio (w/cm) of 0.50 and 0.60.

The slow cycle test procedure used by Pigeon and Lachance used length change of prism specimens as the indicator of concrete deterioration. Figure 1 shows change in length as a function of spacing factor at 300 cycles for concretes with a w/cm of 0.50. For these concretes the critical spacing factor for satisfactory freeze/thaw durability is 680 µm (0.0268 in.). For 0.60 w/cm concretes, the critical spacing factor in their tests is 570 µm (0.0224 in.). These spacing factors are well above the industry recommended maximum of 200 µm (0.008 in.). The authors acknowledge the limitations of their findings by pointing out that “the experimental limits of 680 um and 570 um can be defined as those necessary for satisfactory resistance against 300 freeze/thaw cycles in air at 100 percent relative humidity at a freezing rate of 2 C/ hr for concretes with a w/cm of 0.50 and 0.60”. In their comparison, the critical spacing factor of 200 µm applied to concretes tested at a cooling rate of 12 C/ hr.

One other interesting and significant finding of the Pigeon-Lachance study is that when the spacing factor was “too high”, all of the damage was internal; there was no evidence of scaling distress.

Shortly following publication of the Pigeon-Lachance paper, Bryant Mather\textsuperscript{(2)} challenged their conclusions by pointing out that for the conditions of their study the concretes may not have been critically saturated. He suggested that these authors may simply have showed that “concrete which is less than critically saturated with water as it goes through freezing and thawing requires a less-than adequate air void system”. Pigeon and Lachance acknowledged this possibility but pointed out that
weight measurements made in their study did not indicate any significant and continuous loss of water from the specimens. They further pointed out that the most interesting feature of their work is that “there is a critical value of the air-void spacing above which concretes will be rapidly deteriorated by these mild (low freezing rate) cycles. That is, the use of the spacing factor as a measure of freeze/thaw resistance of concrete is still a valid and meaningful concept. The critical spacing factor for a given concrete will vary depending on the freeze/thaw rate and the degree of saturation of the concrete. It is this possibility that is of considerable importance as regards the requirements for the parameters of the air-void systems in ODOT’s pavement concretes.

**Critical Moisture Saturation:** Historically, critical moisture saturation has been defined as the saturation level in a concrete at which over 91 percent of the available porosity is filled with water. This definition is predicated on the fact that water expands about 9 percent in volume in the liquid to ice conversion. With no open pore spaces to move into, a critically saturated concrete defined in this way will experience damage on freezing.

Within the context of their study, Pigeon and Lachance define the critical degree of saturation as the highest degree of saturation that a specimen can attain during freezing without damage; adding that it varies with material properties and freezing conditions. These latter two variables are thought to be of prime importance when considering why the “inadequately air-entrained” ODOT pavement concretes have nevertheless shown acceptable freeze/thaw durability.

**Freeze/Thaw Durability of ODOT Pavement Concrete**

The results of the present study, as well as published findings from previous work, suggest that the satisfactory freeze/thaw durability of the “inadequately air entrained” ODOT pavement concretes can be explained on the basis of,
1. The otherwise good quality of the concretes (w/cm, quality of the aggregates).

2. The fact that the concretes do have some level of air entrainment.

3. The possibility that for (1) the level of air entrainment in-place, (2) the rate of freezing experienced in service, and (3) the level of saturation attained in service, that “the critical spacing factor” as redefined by Pigeon and Lachance is higher than the historical maximum of 0.008 in. (200 µm).

**Water to Cementitious Material Ratio of the DEL-23 and HAN-75 Concretes:** In the petrographic examination of the DEL-23 concretes the water to cementitious material ratio (w/cm) was estimated at 0.30 to 0.40. For the 390205 test section the average 1-year cylinder compressive strength of the concrete was 7910 psi. For the 390206 test section the average 1-year cylinder strength was 8120 psi.

For the HAN-75 mainline pavement and shoulder concretes, the cores tested in the present study at an age of 15 years had an average compressive strength of 8270 psi, with a range of 6880 psi to 10,500 psi. The w/cm of the concretes was estimated at 0.40.

By both of these criteria (w/cm and strength) the cement paste in the DEL-23 and the HAN-75 pavement concretes are of excellent quality.

The w/cm of these ODOT pavement concretes has importance for freeze/thaw durability not only regarding strength, but also as regards the permeability of the concrete. Figure 2 shows the effect of w/cm on the permeability of cement paste. The permeability is very low at a w/cm under 0.45, while above 0.45 the permeability increases very rapidly with increasing w/cm. For a pavement in service, the permeability of the cement paste phase exerts a significant influence on the rate at which water can move into and through the concrete. The expected low permeability of the DEL-23 and HAN-75 pavement concretes suggests the possibility that critical saturation in the historical sense may never
have been reached. Equally important is the idea, that for the degree of air entrainment that is in-place for these concretes, the critical saturation factor as defined by Pigeon and Lachance\textsuperscript{(1)} was also not reached.

**“Some Air-Entrainment vs. No Air-Entrainment:** The results of Pigeon and Lachance\textsuperscript{(1)} provide direct evidence and the results of the present petrographic examinations of the DEL-23 and HAN-75 pavement cores provide indirect evidence that some air entrainment is better than no air-entrainment as regards freeze/thaw durability of these pavement concretes in service. An extension of this conclusion is that, for the DEL-23 and HAN-75 pavement concretes, air entrainment in the 2 % to 3 % range with spacing factors as high as 0.02-inches (550 µm) has provided acceptable resistance to freeze/thaw damage in service.

**Results of Other ODOT Studies:** A 1996 study of pavement joint problems by the University of Toledo for ODOT showed a similar air entrainment situation at three locations identified as State Route 33, Interstate-75, and State Route 50\textsuperscript{(4)}. Air void contents were measured at 3.2 %, 2.2 %, and 1.9 %, with spacing factors of 0.006-in., 0.010-in., and 0.018-in. Again, although the air void systems do not meet the aforementioned historical guideline standards, no evidence of freeze/thaw damage was reported.

**Results of Other Industry Studies:** In 1960 and 1978 the Portland Cement Association conducted freeze/thaw studies on low w/cm concretes (0.30 and 0.40) at various levels of air entrainment\textsuperscript{(5,6)}. They concluded that even non air entrained concretes were “very frost resistant” when air-dried before freezing and thawing in water.

For the non air entrained concretes, spacing factors were measured (ASTM C457) at 0.02 in. (500 µm). The authors concluded that “the results indicate that, at a w/cm at or below 0.40 and for
freezing and thawing in water, the usual requirements of the air-void system do not apply, probably due to the greatly reduced freezable water content, and to a lesser degree, to the increased tensile strengths of such high quality concretes.

A 1963 PCA study of durability of precast concrete panels prepared with 0.40 w/cm concrete also concluded that the historical standards for the parameters of the air-void system did not strictly apply to these concretes in field exposure conditions. Some of these concretes were intentionally non air entrained. In other concretes air-entraining admixtures were used which in normal concretes would produce the recommended amount of air. In the “stiff” mixes used in the panels, the admixtures produced no increase, or only a very small increase in air content. This situation may explain in part the failure to consistently achieve the target levels of air entrainment in ODOT pavement concretes which are typically placed at a low slump.

In 1987, Pigeon reported on the results of a further study of the critical air-void spacing factors for 0.30 water-cement ratio concretes; with and without a silica fume addition. In this study the rapid cycling rate of ASTM C 666 (Procedure A) was used. The values of the critical spacing factor for both types of concrete ranged from 300 µm (0.0118 in) to 500 µm (0.0197 in); again, greater than the historical maximum of 200 µm (0.008in). The conclusion drawn from this study is in accord with the results previously discussed; namely that, although air entrainment is required to provide freeze/thaw resistance in these low w/cm concretes, the spacing factor requirements are not as strict as those of the historical standard. Giving a global context to their conclusion, Pigeon and his co-authors state that “for a given concrete, the critical air void spacing factor can be defined as that value below which it will not be damaged by internal cracking when submitted to a given freeze-thaw cycle test”.
SUMMARY AND CONCLUSIONS

Air entrainment has long been specified for concrete flatwork and pavements exposed to freeze/thaw environments. For 1-inch maximum size coarse aggregate concrete the recommended guidelines for satisfactory freeze/thaw resistance include (1) an air void content of 6 ±1½ %, (2) a minimum specific surface area of 600 in$^2$/in$^3$, and (3) a maximum spacing factor of 0.008-in (200 µm). The precedent for these guidelines is the results of numerous laboratory freeze/thaw studies over the years.

As discussed in the present report, there is a significant body of evidence to suggest that the laboratory-derived guidelines do not apply in many cases to concrete pavements subjected in service to natural freeze/thaw cycles. Of particular interest to ODOT are the findings of the present investigation which show that the air void system in some of the pavement concretes on the DEL-23 project and the HAN-75 fall far short of the recommended guidelines; yet the concretes show no freeze/thaw damage after exposure times up to 15 years. Other ODOT and industry studies cited in the present report also support this conclusion.

The following significant observations and conclusions are offered as regards the findings of the air entrainment/durability studies of the DEL-23 and HAN-75 pavement cores. The study examined six cores from the DEL-23 project and seven cores from HAN-75. None of the thirteen cores show any evidence of freeze/thaw damage in any form, including (1) scaling of the wearing surface, (2) classic freeze/thaw cracking distress, or (3) D-Cracking distress.

**ODOT Pavement Concrete Service Conditions and Properties**

1. The DEL-23 pavements have been in service since 1996. The HAN-75 pavements were placed in 1989-1990. Both have experienced salt applications and freeze/thaw cycles in service.
2. The concretes on these projects are air entrained, and are of good quality from the point of view of (1) water to cementitious material ratio (w/cm), (2) quality of the aggregates, and (3) strength.

3. The estimated w/cm of the DEL-23 concretes ranges from 0.30 to 0.40. The w/cm of the HAN-75 concretes is estimated at 0.40.

4. The coarse aggregates in the concretes from both projects are 1-inch maximum size crushed limestones that show no evidence of freeze/thaw damage in these concretes. The DEL-23 aggregate was specifically chosen for this Test Road because of its good service record.

5. The one year compressive strength of the DEL-23 pavement concrete measured on job-cylinders is around 8000 psi. The compressive strength measured on cores taken from the HAN-75 project in 2004 showed an average compressive strength of 8270 psi, with a range of 6880 psi to 10,500 psi.

6. The total air-void content of the pavement cores ranges from 2.2 % to 8.9 %. Five of the thirteen cores have a total air void content under the ODOT allowable minimum of 4 %. The “good” reference concrete from the HAN-75 project (Core HAN-17) has an air content of 3.2 percent.

7. The specific surface area of the air void systems ranges from 268 in$^2$/in$^3$ to 754 in$^2$/in$^3$. Ten of the thirteen cores have a specific surface area under the historical industry recommended minimum of 600 in$^2$/in$^3$. The lowest value of specific surface area was measured on the HAN-17 core.

8. The air void spacing factor of the pavement concrete cores ranges from 0.0055-in (140 µm) to 0.0218-in (550 µm). Seven of the thirteen cores have a spacing factor greater than the industry recommended maximum of 0.008-in (200 µm). The highest value of spacing factor was measured on the HAN-17 core.
Factors Affecting the Freeze/Thaw Resistance of ODOT Pavement Concretes

1. The acceptable freeze/thaw resistance of these pavement concretes despite lacking features of the historically recommended air-void system is attributed to (1) the likelihood that the concretes did not reach a level of critical moisture saturation relative to the freeze/thaw exposure conditions that were experienced, (2) the low w/cm of the concretes, (3) the concretes all contain some level of air entrainment, and (4) less severe freeze/thaw conditions in the field relative to those experienced by laboratory specimens.

Critical Moisture Saturation of the Pavement Concretes

1. Critical moisture saturation is the saturation level at which the volume increase accompanying the liquid water to ice conversion can no longer be accommodated without damage in the concrete. There is evidence that what constitutes critical saturation in laboratory freeze/thaw specimens differs from critical saturation in concrete pavements in service.

2. The likelihood that the pavement concretes do not typically become critically saturated with water in service is attributed to (1) the pavements usually experience periods of air-drying prior to the first freezing event, (2) the low permeability of the concretes (low w/cm) restricts the rate of moisture movement into the pavements, (3) the pavement thickness (8-in to 11-in.) also limits the movement of moisture into the pavement slabs.

Water to Cementitious Material Ratio

1. The low w/cm (0.30 to 0.40) has a favorable influence on the freeze/thaw durability of the pavement concretes from several points of view including (1) reducing the permeability of the concrete, (2) reducing the capillary porosity of the cement paste phase, and (3) increasing the tensile strength of the concrete.
2. At a w/cm below 0.45 the permeability of the cement paste phase is very low, leading to a low rate of moisture diffusion through the paste (see Figure 2).

3. At a w/cm below 0.40 the reduced amount of capillary porosity in the cement paste translates to a reduced amount of freezable water in the concrete.

4. A higher tensile strength translates into an ability of the concrete to resist the stresses associated with freezing and thawing events when they do arise.

**Entrained Air Contents Below the Historically Recommended Minimum Amount**

1. It is widely recognized that “some” level of air entrainment, even if lower than the recommended minimum affords a level of protection against freezing and thawing not provided by non air entrained concrete, which contains mostly entrapped air voids greater than 1 mm in diameter.

2. The air void spacing factor is still a useful parameter for assessing freeze/thaw durability. The industry recommended maximum air void spacing factor of 0.008-in (200 µm) can be thought of as a conservative guarantee that most concretes will be protected against almost any type of freeze/thaw exposure (if the w/cm is low enough). It is suggested by the present study and by others that some “low-air” concretes of otherwise good quality do not need such a high degree of protection. The critical spacing factor for ODOT pavement concretes (with a w/cm typically around 0.40) may be as high as 0.02-in (500 µm).

**Freeze/Thaw Conditions: Laboratory vs. Field Exposure**

1. Measurements made in previous studies have shown that the rate of freezing and thawing is significantly higher in standard laboratory tests on concrete prisms relative to those experienced by concrete pavements in the field (12 C per hour vs. 2 C per hour per Reference No. 1).
2. When a slower rate of freezing and thawing is used in laboratory tests\(^\text{(1)}\) the critical air-void spacing factor of the concrete can be significantly higher than 0.008-in (200 \(\mu\text{m}\)) and still provide protection.

**D-Cracking Issues**

1. Consideration must still be given to selecting coarse aggregates for ODOT pavement applications that have a good service record as regards the D-Cracking problem. Even an air void system that meets historical industry standards can not protect the concrete from this type of freeze/thaw distress, which is an aggregate issue.

**RECOMMENDATIONS**

1. ODOT’s current requirement of 6 \(\%\) \(\pm\) 2 \(\%\) air content for pavement concretes should be continued. For the type of concrete used in this application (typically ODOT Class C) this practice has consistently afforded adequate protection to the cement paste phase under Ohio’s freeze/thaw conditions.

2. The failure to consistently achieve a minimum air content of 4 \(\%\) in ODOT pavement concretes is very likely related to the difficulty, also experienced by others, of creating normal levels of air entrainment in stiff, low-slump concretes. Some research on this issue could be considered.

**IMPLEMENTATION POTENTIAL**

ODOT pavement engineers can be made aware of the findings of the present study as regards the requirements for air entrainment in pavement concretes. Consideration can be given to the development of new procedural guidelines which describe the steps to take in those instances where air content measurements on ODOT pavement projects fall short of the current target minimum value of 4 percent. These steps would include (1) verification that the concrete contains
some level of intentionally entrained air, and (2) verification that the water to cementitious material ratio of the concrete is sufficiently low.

**REFERENCES**


Table 1. Coring Sites and Properties of the DEL-23 Test Road Cores Examined at Lankard Materials Laboratory.

<table>
<thead>
<tr>
<th>Core Identification Number</th>
<th>Coring Site</th>
<th>Pavement Test Section Number</th>
<th>Cementitious Material Cement/FlyAsh, lb/yd$^3$</th>
<th>Concrete Density$^{(a)}$, lb/ft$^3$</th>
<th>Concrete Compressive Strength$^{(b)}$, psi</th>
<th>Total Air Content of the Concrete$^{(c)}$, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>ML-1</td>
<td>Mainline</td>
<td>390206</td>
<td>750/113</td>
<td>146.7</td>
<td>7920</td>
<td>2.9</td>
</tr>
<tr>
<td>ML-2</td>
<td>Mainline</td>
<td>390206</td>
<td>750/113</td>
<td>147.8</td>
<td>7920</td>
<td>2.3</td>
</tr>
<tr>
<td>ML-3</td>
<td>Mainline</td>
<td>390206</td>
<td>750/113</td>
<td>140.4</td>
<td>7920</td>
<td>7.3</td>
</tr>
<tr>
<td>ML-4</td>
<td>Mainline</td>
<td>390205</td>
<td>510/90</td>
<td>147.3</td>
<td>8120</td>
<td>2.7</td>
</tr>
<tr>
<td>LCB-4</td>
<td>Lean Concrete Base Under ML4</td>
<td>390205</td>
<td>160/48</td>
<td>ND</td>
<td>ND</td>
<td>6.3</td>
</tr>
<tr>
<td>R-810</td>
<td>Southbound Ramp</td>
<td>390810</td>
<td>350/120</td>
<td>140.8</td>
<td>4880</td>
<td>6.5</td>
</tr>
</tbody>
</table>

(a) Water-saturated density = unit weight of fresh concrete.

(b) Measured on job cylinders at an age of one year.

(c) Measured per ASTM C 457.
Table 2. Coring Sites and Properties of the HAN-75 Pavement Cores Examined at Lankard Materials Laboratory.

<table>
<thead>
<tr>
<th>Core Identification Number</th>
<th>Core Location</th>
<th>Coring Site (Station)</th>
<th>Concrete Density (a), lb/ft³</th>
<th>Concrete Compressive Strength (b), psi</th>
<th>Total Air Content of the Concrete (c), %</th>
</tr>
</thead>
<tbody>
<tr>
<td>HAN-15 Shoulder 776+45</td>
<td>Shoulder</td>
<td>144.2</td>
<td>6880</td>
<td>8.9</td>
<td></td>
</tr>
<tr>
<td>HAN-16 Shoulder 774+56</td>
<td>Shoulder</td>
<td>150.2</td>
<td>10,500</td>
<td>2.2</td>
<td></td>
</tr>
<tr>
<td>HAN-18 Shoulder 770+66</td>
<td>Shoulder</td>
<td>147.2</td>
<td>7520</td>
<td>4.4</td>
<td></td>
</tr>
<tr>
<td>HAN-6 Mainline 770+90</td>
<td>Mainline</td>
<td>ND</td>
<td>ND</td>
<td>5.9</td>
<td></td>
</tr>
<tr>
<td>HAN-17(d) Mainline 771+90</td>
<td>Mainline</td>
<td>147.3</td>
<td>9350</td>
<td>3.2</td>
<td></td>
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<tr>
<td>HAN-19 Mainline 769+60</td>
<td>Mainline</td>
<td>144.8</td>
<td>7850</td>
<td>5.3</td>
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<tr>
<td>HAN-20 Mainline 768+50</td>
<td>Mainline</td>
<td>144.8</td>
<td>7530</td>
<td>6.7</td>
<td></td>
</tr>
</tbody>
</table>

(a) Water-saturated density = unit weight of fresh concrete (measured on the companion core).

(b) Measured on companion cores per ASTM C 42 at an age of 15 years.

(c) Measured per ASTM C 457.

(d) Core 17 was taken from a mainline pavement slab showing no distress to serve as the reference for “good” concrete.
Table 3. Parameters of the Air-Void System in the DEL-23 Test Road Cores.

<table>
<thead>
<tr>
<th>Core Identification Number</th>
<th>Coring Site</th>
<th>Cement Paste Content(^{(a)}), %</th>
<th>Air Void Parameters per ASTM C 457(^{(a)})</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Total Air Content, %</td>
<td>Percent Air Voids ≥ 1 mm</td>
<td>Specific Surface Area, (\text{in}^2/\text{in}^3)</td>
<td>Spacing Factor, inch</td>
</tr>
<tr>
<td>ML-1</td>
<td>Mainline</td>
<td>34.9</td>
<td>2.85</td>
<td>1.30</td>
<td>546</td>
<td>0.0127</td>
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<tr>
<td>ML-2</td>
<td>Mainline</td>
<td>32.4</td>
<td>2.28</td>
<td>1.21</td>
<td>594</td>
<td>0.0125</td>
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<tr>
<td>ML-3</td>
<td>Mainline</td>
<td>34.8</td>
<td>7.34</td>
<td>2.16</td>
<td>754</td>
<td>0.0060</td>
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<tr>
<td>ML-4</td>
<td>Mainline</td>
<td>29.5</td>
<td>2.69</td>
<td>1.13</td>
<td>644</td>
<td>0.0103</td>
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<tr>
<td>LCB-4</td>
<td>Lean Concrete Base Under ML4</td>
<td>18.0</td>
<td>6.33</td>
<td>3.37</td>
<td>287</td>
<td>0.0099</td>
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<tr>
<td>R-810</td>
<td>Southbound Ramp</td>
<td>22.7</td>
<td>6.53</td>
<td>2.73</td>
<td>486</td>
<td>0.0071</td>
</tr>
</tbody>
</table>

(a) Minimum length of traverse of ≥ 95 inches; minimum number of stops of ≥ 1425; minimum traversed area of ≥12 \(\text{in}^2\).
Table 4. Parameters of the Air-Void System in the HAN-75 Pavement Cores.

<table>
<thead>
<tr>
<th>Core Identification Number</th>
<th>Coring Site</th>
<th>Cement Paste Content(^{(a)}), %</th>
<th>Air Void Parameters per ASTM C 457(^{(a)})</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Total Air Content, %</td>
</tr>
<tr>
<td>HAN-15 Shoulder</td>
<td>25.7</td>
<td>8.92</td>
<td>2.61</td>
</tr>
<tr>
<td>HAN-16 Shoulder</td>
<td>29.0</td>
<td>2.15</td>
<td>1.18</td>
</tr>
<tr>
<td>HAN-18 Shoulder</td>
<td>27.9</td>
<td>4.36</td>
<td>1.79</td>
</tr>
<tr>
<td>HAN-6 Mainline</td>
<td>25.9</td>
<td>5.93</td>
<td>2.12</td>
</tr>
<tr>
<td>HAN-17(^{(b)}) Mainline</td>
<td>26.8</td>
<td>3.21</td>
<td>2.05</td>
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<tr>
<td>HAN-19 Mainline</td>
<td>27.4</td>
<td>5.33</td>
<td>1.63</td>
</tr>
<tr>
<td>HAN-20 Mainline</td>
<td>25.6</td>
<td>6.74</td>
<td>2.29</td>
</tr>
</tbody>
</table>

\(^{(a)}\) Minimum length of traverse of ≥ 95 inches; minimum number of stops of ≥ 1425; minimum traversed area of ≥ 12 in\(^2\).

\(^{(b)}\) Core 17 was taken from a mainline pavement slab showing no distress to serve as the reference for “good” concrete.
Figure 1. Length Change of Concrete Prism Specimens at 300 Slow Freeze/Thaw Cycles (2 C/hr) as a Function of Air Void Spacing Factor. The w/cm of the Concrete is 0.5. The Prisms are 100 mm x 100 mm x 250 mm. (Reference No. 1).
Figure 2. The Relationship Between Permeability and Water-Cement Ratio (w/cm) of Mature Portland Cement Paste (Reference No. 3).