Effect of Surface Evaporation and Slab Thickness on the Scaling Resistance of Concrete Containing Fly Ash

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Abstract

Laboratory tests (conducted in accordance with ASTM C672) frequently indicate that concrete containing fly ash may be susceptible to scaling. Based on this concern, a few northern USA states restrict the use of fly ash during the late-fall pavement construction season. However, a survey of twelve northern states revealed that scaling is rarely observed in actual pavements. In an attempt to develop a more clear understanding of the potential reasons for the apparent discrepancy between the scaling resistance of laboratory concretes and field concretes, scaling studies were conducted on concrete containing 20 percent of a Class C fly ash. The main variables in the study were the surface water evaporation rate (water loss was ranged from 0 to 4.5 kg/m^2) and the thickness of the slab specimen (55 mm to 245 mm). The selected ranges of test variables were intended to represent moisture and temperature conditions that are likely to be encountered in the field. In addition to monitoring the mass of material lost from the surface due to scaling, the temperature gradient that developed inside the specimen during freezing was measured. In addition, scanning electron microscopy was performed to assess differences in porosity of the near surface concrete. The results indicate that ASTM C 672 is too severe when compared to the environmental conditions that are likely to be encountered in the field.

Research Background

In many snow-belt states, including Indiana, current concrete pavement specifications restrict the use of fly ash during the late fall construction season (typically between October 15 to April 1). This limitation significantly increases the cost of projects and occasionally results in cement shortages during the transition from cement-fly ash to cement only mixtures. Moreover, many of the states also imposed a maximum allowable replacement level of cement by fly ash (typically 18-35%) for concrete pavements. One reason for this limitation is the slow strength gain that may occur when fly ash is used. In addition, this limitation is intended to address two durability concerns due to freezing and thawing (F-T) damage and scaling.

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An earlier study (Krishnan, 2002), conducted on several potentially slow strength-gaining mixtures, showed that F-T durability was not a concern for concrete containing fly ash when tested in accordance with ASTM C 666 procedure A. A durability factor of more than 80% was observed for all mixtures, irrespective of fly ash type or source. However, the laboratory mixtures containing fly ash scaled more in comparison to the plain cement concrete for two different slumps and all different curing regimes studied.

Unlike the laboratory results that frequently show scaling, there are no major documented cases of field scaling of concrete pavements containing fly ash (up to 20-30% replacement), irrespective of the construction season (Thomas, 1997). Therefore, it is important to develop an improved understanding of the parameters influencing the scaling resistance of concrete containing fly ash, especially for low temperature-cured concrete in the laboratory. It is also important to determine the reasons for the discrepancy observed between laboratory and field scaling performances and to assess whether this is an artifact of the testing procedure.

Introduction

Scaling of concrete in the presence of a de-icing salt solution is mainly described as a delamination of surface layers of concrete due to high degree of saturation generated during freezing and thawing. This not only makes the concrete aesthetically unattractive, but it creates unsafe riding surfaces and increases the susceptibility of the bulk of concrete to water and ion ingress.

Detailed information regarding field scaling performance of concrete was collected with the help of an extensive literature review and telephone survey. Based on this information and additional laboratory studies, five main parameters were identified which can be considered responsible for the observed discrepancy between laboratory and field performance of concrete. This paper mainly discusses two such parameters: rate of early age evaporation and temperature profile along the depth of the specimen during freezing and thawing. Additionally, a microstructural study was performed to compare bulk and surface porosities of concrete.

Survey of Field Performance of Concrete Containing Fly Ash in Different States Relating to Issues of Scaling

It is well known that scaling is highly dependent on local environmental conditions including minimum air temperature, frequency of precipitation and the number of freeze-thaw cycles (Studer, 1993 and Jacobsen et al., 1997). Therefore, it is important to collect information about the field performance of pavements located in similar environments. A telephone survey was conducted to collect information regarding the use of supplementary materials in late fall construction season, from twelve states neighboring Indiana. The states were chosen based on climatic and geographical similarities (Figure 1). Most of the states selected for the survey are located at the same or at higher latitudes than Indiana. Additionally, the state of Kansas was selected due to some reported scaling problems.

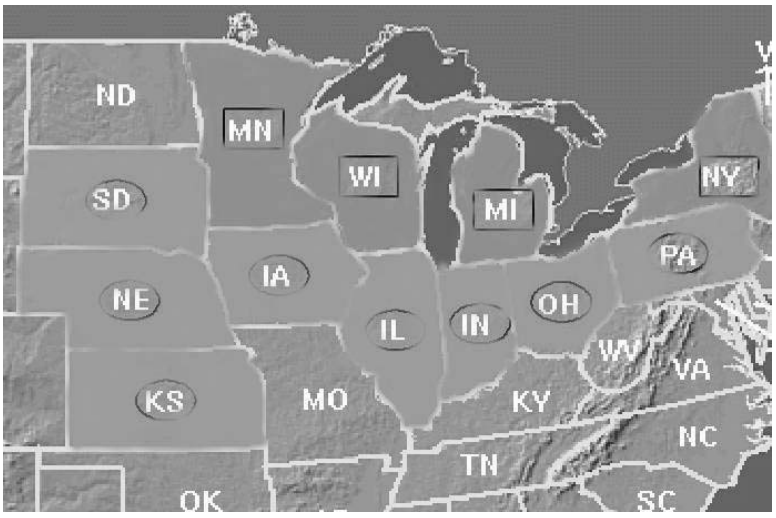


Figure 1. States selected for scaling problem survey

A brief summary of all the information collected in the phone survey is shown in Table 1. Additionally, any specific measures taken by the states for construction during late fall (i.e., low temperature season) are also reported. This table is not a complete list of all the details on state practices with respect to scaling. However, this table provides a general overview which shows that most of the states that had the potential of having some information about scaling were contacted and hence, the information collected should give a good "average" indication of the problem.

Table 1. Summary of information on scaling obtained from 12 states surrounding Indiana

State**	Restriction on use of fly ash/slag	Scaling problem due to fly ash (reasons for general scaling)	Pavement surface treatments for late fall
Indiana	Yes (Oct. 15th- April 1st)	None	Normal curing compound
Illinois	No (removed since 2002)	None	Application of 2 coats of linseed oil
Iowa	No (removed since 1997)	None (one problem mainly due to finishing issue)	Normal curing compound
Kansas	No	None (some problems with high volume slag concrete)	Normal curing compound
Nebraska	No	None	No salt application until 6 months after const.
South Dakota (Class F)	No (replacement of 18% only)	None	Normal curing compound
Wisconsin (Class C)	No (removed since 1994)	None (one major problem with high vol. slag concrete constructed in summer)	Normal curing compound
Minnesota	No	None (in 1998 one major problem due to aggregates)	Application of 2 coats of linseed oil, during late fall replacement of fly ash 1:4/3rd
Michigan (Class F)	Yes (Oct. 1st – April 1st)	None (some problems due to improper curing)	Normal curing compound
Ohio	Yes (Oct. 15th - April 1st)	None (one problem on bridge deck with fly ash)	Normal curing compound
Pennsylvania (Class F)	No	None	Linseed oil was being used but not any more
New York (Class F)	No	Yes (one major problem in fall 2003)	Normal curing compound

**Information obtained from individuals of various agencies of each state in February 2004 and from ACPA (pavement.com) website. Unless specified discussion includes class F and C both fly ash.

In summary, Table 1 shows that in general only a few problems of scaling of concrete containing moderate (up to 30%) amounts of fly ash were actually observed in the field. In cases where problems occurred they were mostly attributed to poor construction practices or high volume replacement of cement by supplementary materials. Another important finding of this survey is that when scaling was observed, it was mostly observed in the thin slabs and bridge decks (high slump mixes), not in slip formed pavements. This is similar to prior laboratory observations (Krishnan, 2002; Neuwald et al., 2003). This implies that pavement thickness and construction procedures would have strong influence on scaling resistance. Based on other preliminary studies and above information, it was hypothesized that early age evaporation in fresh concrete and temperature profile in hardened thick pavements are significant parameters, that can make actual pavements more scaling resistant than standard laboratory specimens. This hypothesis was confirmed with the help of relevant scaling studies and microstructural analysis, as described below.

Influence of Early Age Evaporation on Scaling and Surface Porosity

The porosity of the concrete surface layer depends on the cumulative effect of bleeding and evaporation. Specimens with higher amounts of bleeding and lower evaporation loss can develop highly porous surface layers due to the high localized w/cm. The rate of evaporation in the field can be much higher due to effect of wind and solar radiations than that in the corresponding laboratory specimens. This can create significant differences in surface porosity of types of concrete. To understand the role of surface pore structure and porosity in scaling mechanism, specimens exposed to different severities of evaporation were studied.

Table 2. Mixture proportions used for the described study

Cement	Fly Ash	Water	F.A. (SSD)	C.A. (SSD)	Water Reducer (WRA)	Air Entrai-ning Agent	Slump	Fresh Air (%)
244.4 kg/m^3 (412 lb/yd^3)	61.1 kg/m^3 (103 lb/yd^3)	134.1 kg/m^3 (226 lb/yd^3)	881.0 kg/m^3 (1485 lb/yd^3)	987.8 kg/m^3 (1665 lb/yd^3)	450 ml	79 ml	25 ± 5 mm (1”±0.2”)	6.5 ± 0.3

Specimen Preparation and Experimental Procedure. Concrete mixtures with the proportions shown in Table 2 were used to prepare three slab specimens with dimensions of 380 mm x 190 mm x 75 mm. Further details of the materials and detailed mixing procedures and specimen preparation can be found elsewhere (Neuwald et al., 2003; Mehta, 2004). After finishing, all specimens were weighed and the initial mass was recorded. After weighing, one of the slabs was stored under the plastic cover until the time at which it was demolded (24 ± 2 hours after casting).

The other two specimens were placed in an environmentally controlled chamber for 6 hours. Fans within the chamber aided in the evaporation of surface bleed water. One specimen was subjected to an average wind velocity of 27.3 kph (17 mph) and the other to 14.5 kph (9 mph) over the top surface. Details of specimen and water loss are given in Table 3. After 6 hours, the specimens were removed from the environmental chamber and placed under a plastic sheet until they were demolded (at 24 ± 2 hours).

At the time of demolding each slab was weighed again and cut in half using a diamond bladed saw to create two 75 mm x 190 mm x 250 mm test specimens. These specimens were then placed in a moist curing room (98 ± 2% RH), for two more days, after which they were kept for 3 more days in a constant humidity room (50 ± 5% RH) for drying. One half of each slab was used to perform standard scaling tests and the other half was used to prepare two Scanning Electron Microscopy (SEM) specimens for microstructural study.

Table 3. Mass of specimens before and after evaporation

Specimen ID	Size of the specimens (mm)	Wind speed at surface (kph)	Initial Mass (kg)	Final Mass (kg)	Loss of water in 24 hrs. (kg)	Loss per area (kg/m^2)	No. of SEM specimens
3-3-ah (env. chamber)	250 x 190 x 75	27.3	31.59	31.16	0.43	4.53	2
3-3-am (env. chamber)	250 x 190 x 75	14.5	33.74	33.32	0.42	4.47	1
3-3-an (plastic cover)	250 x 190 x 75	0	31.96	31.97	-0.01	--	2

Notation "3-3" represents moist curing and drying duration, respectively. Additionally, the specimens were given the following suffixes: "ah" - high evaporation, "am" - medium evaporation, and "an" - no evaporation.

Scaling tests were performed on these specimens, as per ASTM C 672. Further test details including typical F-T cycles in the chamber, can be found elsewhere (Neuwald et al., 2003; Mehta, 2004).

Results from Scaling Study of Evaporation Samples. The results of scaling studies for specimens exposed to different wind speeds (i.e., evaporation rates) at early ages are shown in Figure 2. It can be seen that with increase in wind speed, the total scaled mass decreased significantly. This indicates that for very short moist curing and drying periods (i.e., at very early ages, less than 10 days), the amount of moisture in the surface layer and the degree to which it controls microstructure in the surface region is an important parameter influencing scaling.

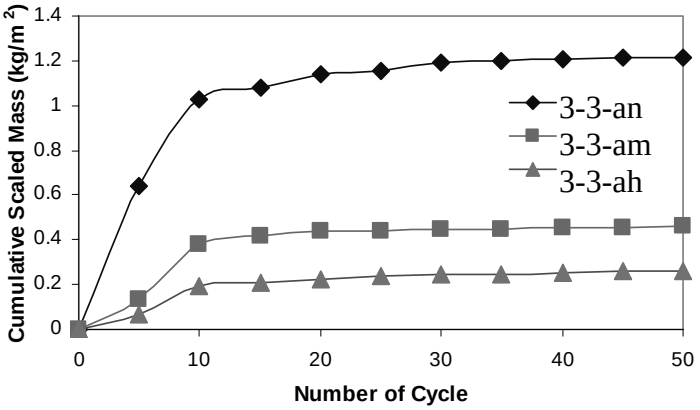
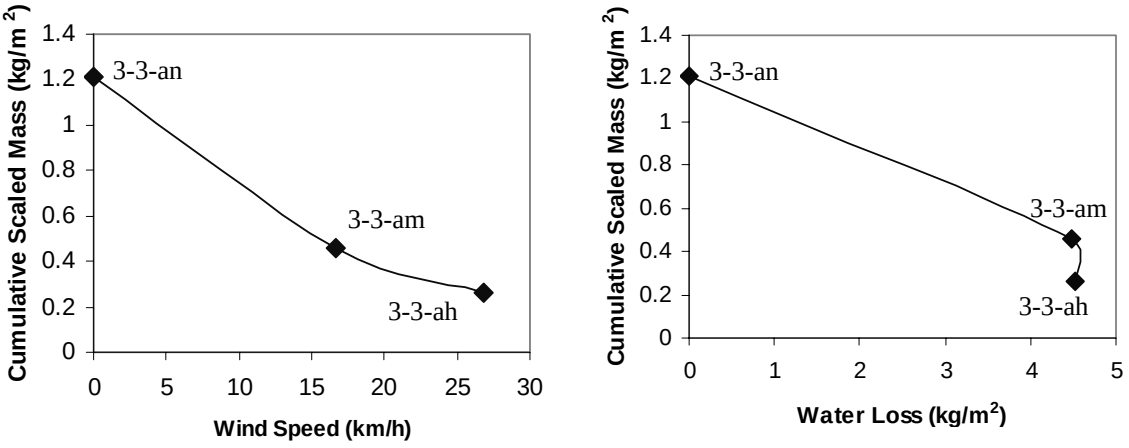


Figure 2. Total mass scaled for samples exposed to different wind velocities

Figures 3(a) and (b) show cumulative scaled mass versus wind velocity and versus total water loss, respectively. From Figure 3(b) it seems that the rate of evaporation would have exceeded the bleeding rate for the specimen 3-3-ah, subjected to 27.3 km/h wind speed (as indicated by the vertical drop in the trend line), while that may not be the case for specimen 3-3-am, subjected to 14.5 km/h wind speed. It can be hypothesized that in specimen 3-3-ah high wind speed could have caused water loss resulting in the generation of higher capillary stresses which would result in denser microstructure. Therefore, water loss being the same, lower scaling was observed in the specimen 3-3-ah compared to specimen 3-3-am. Therefore, the effect of evaporation might provide a reasonable explanation for the absence of scaling in the actual pavements at early or later ages. The following section investigates the density of the surface layer using Scanning Electron Microscope (SEM)



(a) (b)

Figure 3. (a) Scaled mass for different wind speeds and (b) scaled mass for different total water loss

Microstructural Study of Evaporation Samples. A series of 25 x 25 x 25 mm SEM specimens (two for each evaporation rate) were prepared. The details of specimen preparation can be found elsewhere (Neuwald et al., 2003; Mehta, 2004). The specimens were examined in a SEM operated in backscatter mode, to study the surface characteristics. Images of microstructure at successive depths were collected and analyzed to obtain porosity gradients. At least 10 images were collected at each depth. The reported porosities are average values from the 10 images. The values of individual porosities were normalized against the minimum (or bulk porosity) obtained from SEM images collected at mid depth of the specimens. These normalized porosities are plotted in Figure 4. Surprisingly, for all three cases, the ratio of surface-to-bulk porosity was almost in the same range.

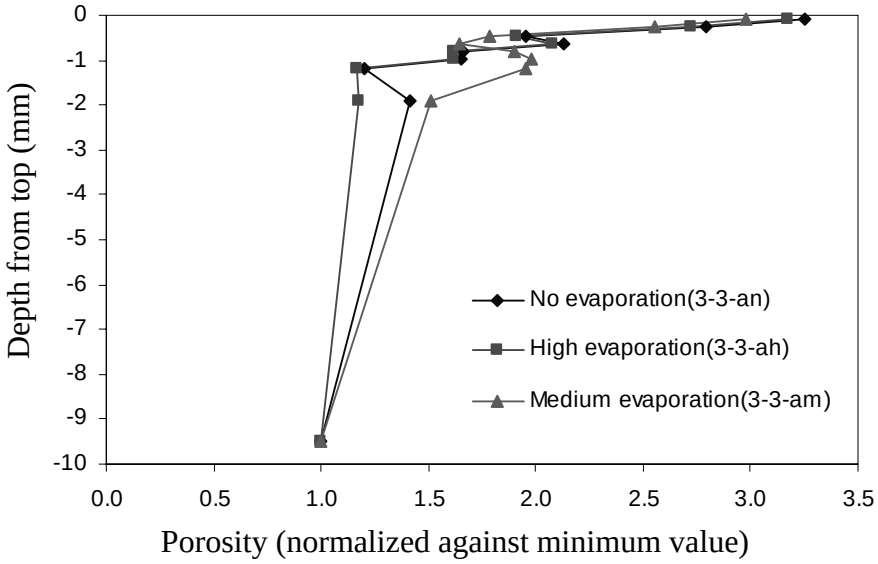


Figure 4. Porosity gradient for evaporation specimens, normalized against minimum value

During image acquisition it was observed that a higher amount of cracking was presented in the samples subjected to high evaporation, while minimal or no cracking was observed in the specimen without any evaporation losses. The crack widths were found to be higher for the sample 3-3-ah than for sample 3-3-am. Since all of these specimens were exposed to similar sample preparation procedures, it can be said that these cracks would not have formed during oven drying or any other sample preparation procedures. In addition, these cracks are only visible in the surface region of the specimen. Thus, it can be said that these cracks are most likely plastic shrinkage cracks formed during evaporation of water from the surface. To confirm these observations and to find true capillary porosity the following procedure was adopted.

The images obtained from the three specimens (typical images are shown in Figure 5) were segmented at a lower brightness threshold value (60 to 65) to distinguish the distinct features. It can be easily seen that cracks are more pronounced in the case of specimen 3-3-ah than in the specimen 3-3-am. Moreover,

the matrix in both of these specimens is comparatively denser, while in the case of specimen 3-3-an, no cracks are observed and the matrix has more distributed pores (capillary porosity). It is believed that higher capillary porosity and lower tensile strength of this matrix is responsible for higher F-T and scaling damage. Thus, although total porosity was similar for all the three specimens, the porosity in 3-3-ah and 3-3-am specimens can be attributed in large parts to cracking. If the porosity is related to strength, it would seem likely that the strength of the matrix in the surface is less when evaporation is limited, therefore scaling performance is likely be worse. To eliminate the effect of plastic shrinkage cracking and localized differences in air voids, porosities of the images were obtained by eliminating these features with different filters.

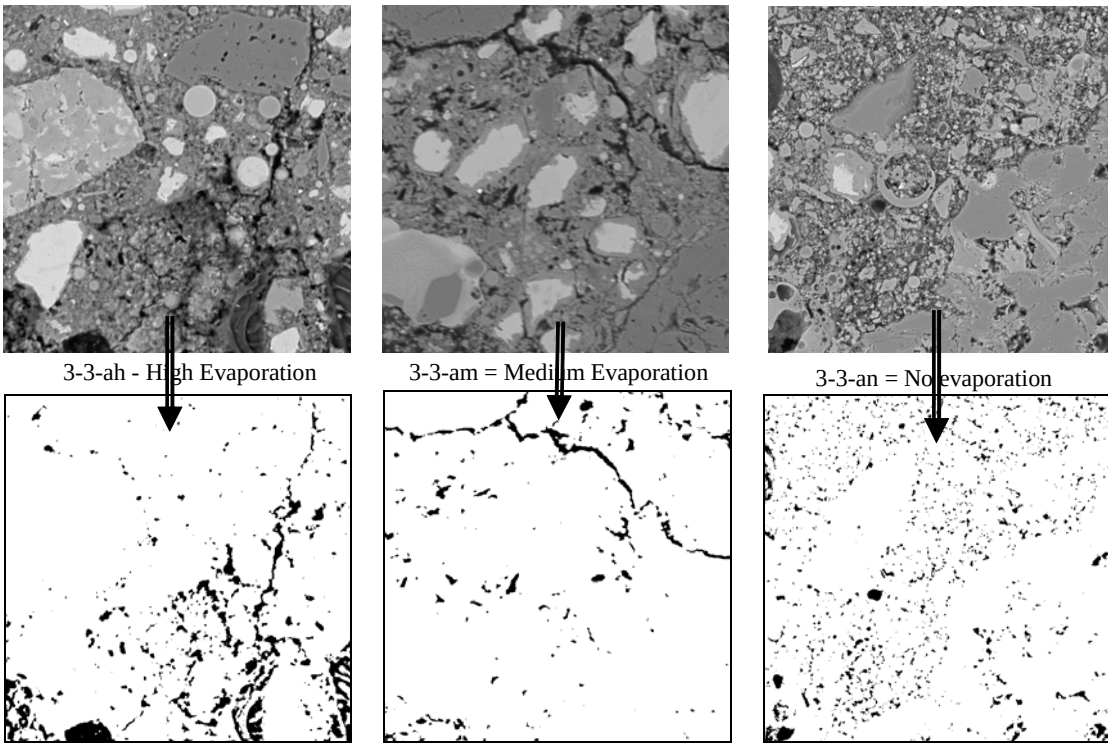


Figure 5. Segmentation of images at lower threshold

These modified porosity gradients (i.e., porosity after accounting for the effects of cracks) for 3-3-an and 3-3-ah specimens are plotted in Figure 6.

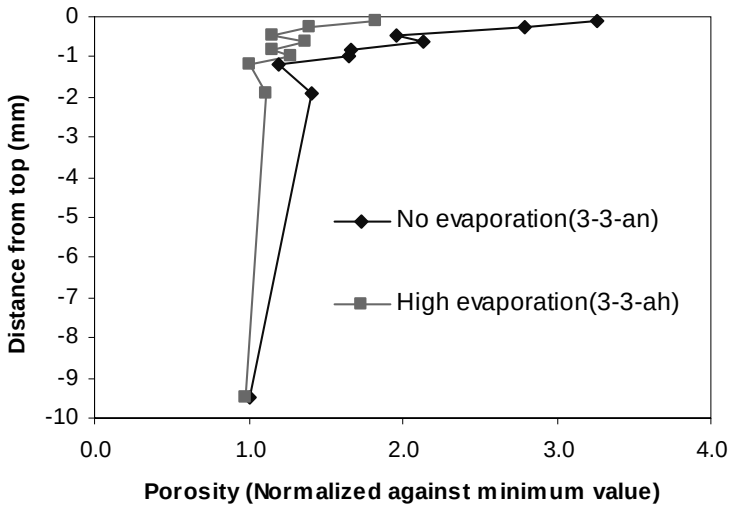


Figure 6. Modified porosity gradients for high and no evaporation specimens

Figure 6 shows that the surface capillary porosity of specimen 3-3-an is almost twice the capillary porosity of the specimen 3-3-ah. Young field concrete is normally exposed to high rates of evaporation than regular laboratory specimens. This will result in removal of excess water from the surface and will reduce potential for scaling damage in the field as compared to laboratory specimens.

Influence of Size of the Specimen on Minimum Surface Temperature, Rate of Freezing and Scaling

The size of specimens used in the laboratory study (75 mm x 190 mm x 250 mm) is considerably smaller than an actual pavement section. During the preliminary phase of this research, it was shown that large thermal mass and single direction heat flow could change scaling behavior. For large size specimens, the rate of freezing and minimum surface temperature observed are different from that observed in the corresponding small specimens even at the same ambient temperature (Mehta, 2004). Therefore, further study was conducted with different sizes (variable depths) of specimens to determine the influence of size of specimen on rate of freezing and scaling. The specimen thicknesses were selected from 75 mm (typical laboratory specimen) to 245 mm (typical concrete pavement). To generate realistic single direction heat flow as observed in large pavement section, 50 mm think insulation was used on all the sides except the top of each specimen.

Specimen Preparation and Experimental Procedure. For this study, two molds were used to prepare six specimens to simulate laboratory and field conditions. Each wooden mold of 300mm x 300 mm x 900 mm internal dimension was partitioned vertically (using 50 mm thick Styrofoam^{TM} sheets) to create a total of three slabs. The area of the each slab was 11" x 11" (0.078 m^2), which is much higher than minimum area (75 in^2 or 0.048 m^2) specified by ASTM C 672. A wooden pole was

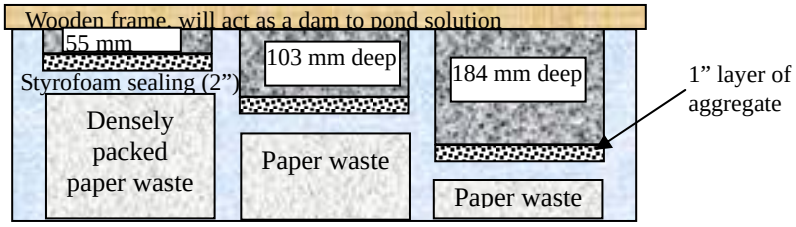
installed at the center of the each slab and thermocouples were attached to it at various depths. Figure 7 shows both molds with partitions and thermocouples pole installed. To create slabs with different thicknesses (ranging from 55 to 245 mm), paper waste was used to fill up the bottom portions of the molds so that the top of all the slabs was at the same elevation, as shown in the section in Figure 8.



Figure 7. Partitioned mold for size effect study

After partitioning, all joints were sealed using duct tape. Three to nine thermocouples (depending on the depth of the slab) were attached to each central pole using duct tape to obtain the temperature profile at various locations within the slab. All the thermocouple wires were "channeled" out from the mold and into one corner of each slab. Details regarding the number and position of thermocouples for specimens of various depths are shown in Table 4. The depth of the each partition was kept 1" deeper than the specified specimen depth mentioned in the Table 4. The bottom 1" of each slab was filled with coarse aggregates (cooled to 1°C) to simulate boundary conditions (aggregate base) at the bottom of a field slab during late fall construction. Form release agent was applied on all sides of the formwork. Figure 8 shows one of the molds, in its final stage before casting the concrete.





Cross section of the mold

Figure 8. Final mold before mixing, with 1" thick base of aggregates

The mixture proportions shown in Table 2 were also used in this study. All aggregates were stored in a 1°C room for 48 hours prior to mixing. The details of the mixing, casting and finishing procedure can be found elsewhere (Mehta, 2004). Slabs were stored in the cold room (1°C), until they achieved maturity equivalent to 550 psi, at which point they were moved to the F-T chamber for 50 cycles of freezing and thawing with salt solution on the surface. Temperature data was collected continuously throughout the test; two additional thermocouples were placed to measure the room temperature.

Table 4. Summary of specimens and results of size effect study

Depth of specimen (mm)	No. and positions of thermocouples from top (mm)	Minimum temp. at 2 mm (°C)	Maximum temp. at 2 mm (°C)	Avg. rate of freezing (°C/hr)	Scaling results (kg/m^2)
55	5 (2, 8, 20, 40 and 50)	-11.5	15.2	-2.0	0.25
81	3 (2, 30 and 75)	-10.1	15.1	-1.88	0.15
103	5 (2, 10, 30, 60 and 100)	-8.6	12.5	-1.58	None observed
130	3 (2, 60 and 125)	-7.2	12.0	-1.43	None observed
184	3 (2, 75 and 180)	-6.9	11.0	-1.38	None observed
245	8 (2, 8, 20, 40, 75, 125, 180 and 240)	-6.6	11.3	-1.35	None observed
Room temp.	2 (near surface of the each specimen)	-15.9	22.4	-2.95	-----

Results and Data Analysis - Laboratory Study. Figure 9 shows the temperature profiles (2 mm below the surface) for all six lab specimens along with the temperature of the F-T room. Minimum and maximum temperatures for all these slabs, along with computed average rate of freezing, are given in Table 4. The scaling results after application of 50 F-T cycles for all the slabs are also given in the same Table.

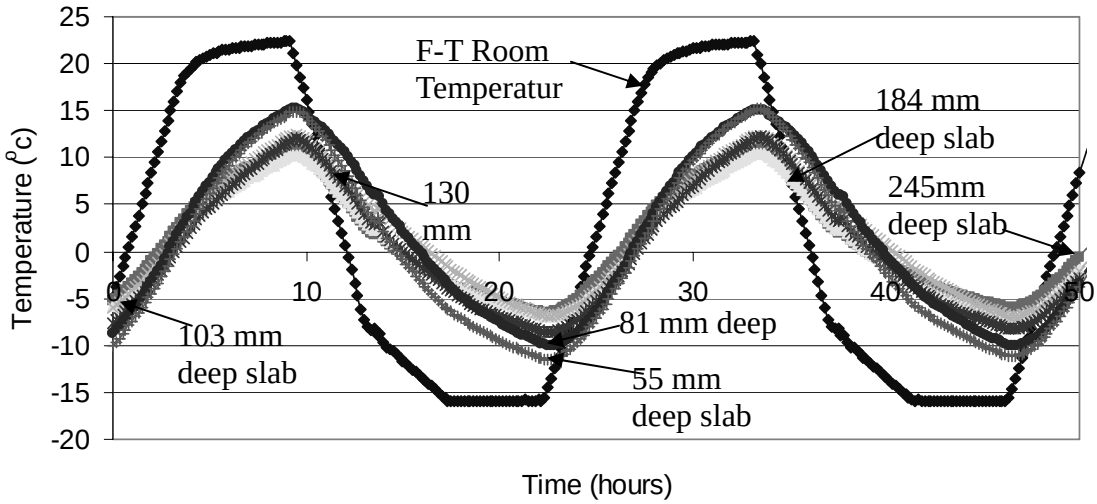


Figure 9. F-T cycle temperatures (room and 2 mm below surface of all six specimens)

It can be seen that for specimens with depths ranging from 55 mm to 245 mm, the minimum temperature of the surface region ranges from -11.5 to -6.6°C for ambient minimum temperature of -15.9°C. This clearly indicates the difference between surface and air temperature is largely dependent on thermal mass and increases with the increase in thickness of the specimen. Moreover, results show that scaling (very minor) was only observed for the specimens in which surface temperature dropped below than -10°C. These results confirm the finding of Lindmark (1999) that scaling of the concrete is highly dependent on the minimum temperature that the surface attains, and the duration of time for which it attains this temperature. Therefore, since the size of the pavement being very large in comparison to the laboratory specimen, chances of scaling will be reduced in field in each case when the minimum surface temperature stay above -10°C.

One more important observation was made from analysis of the temperature data from these slabs. Figure 10 shows the temperature profile for thermocouples placed in 81 mm(thinner-laboratory size) and 245 mm (thicker- pavement size) thick slabs at 2 mm and 75 mm from the surface for each specimen, along with the temperature profile of the F-T room.

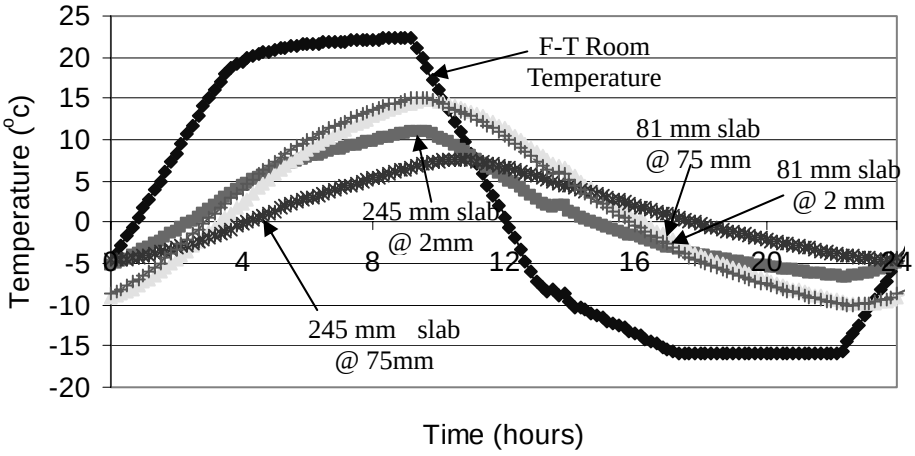


Figure 10. Thermal massing effect of large size specimens

From Figure 10 it is evident that for a thinner (81 mm) specimen the rates of freezing at 2 mm and 75 mm are the same, while for a thicker (245 mm) specimen rates of freezing at 2 and 75 mm are significantly different. Therefore, in the thicker specimen, a different rate of freezing is observed in the surface region for same boundary conditions. In the thicker specimen the freezing front moves down slowly from top towards bulk of the specimen. This could be another reason why scaling is observed in the laboratory specimens, while field specimens of similar concrete do not scale.

It has been observed that the presence of excess surface water on the surface is essential to cause scaling problem. Verbeck and Klieger (1957) found that when samples were frozen in a damp condition, i.e., with no liquid present on the surface, there was no scaling. Similar observation was made by Lindmark (1999). This is one of the very few phenomena that has been observed and accepted by all researchers who studied scaling. Fagerlund (1977) proposed that, in sound concrete, moisture uptake during freezing and increased degree of saturation is the major cause of scaling.

Based on above observations, in the case of thinner specimen, identical rates of freezing of bulk and surface regions may lead to higher moisture uptake and saturation of the entire cross-section including surface. On the other hand, for thicker specimens, the surface freezes much faster then the bulk of the concrete. This phenomenon, even in the presence of salt solution, provides less time for water uptake. Moreover, freezing will progress downward with time, which can cause moisture movement further downward and away from the surface. Thus, chances of having a high degree of saturation in the surface region, and thereby generating detrimental forces, are much lower for thicker specimens than for thin specimens. In summary, the change in rate of freezing is one another important parameter that can help in resolving the discrepancy between laboratory and field scaling performance of concrete.

Summary of Research in Regard to Apparent Discrepancy between Laboratory and Field Scaling Results

In summary, it can be said that, based on the literature review and survey, scaling of concrete pavement is a rare phenomena in practice for low replacement values of Supplementary Cementitious Materials (SCM). The laboratory procedure (ASTM C 672) is too severe to evaluate the scaling performance of field concrete. The major reasons which could lead to discrepancy between laboratory and field scaling results include:

- Early age evaporation in the field which reduces surface porosity and ultimately makes field concrete more resistant to scaling.
- Differential rates of freezing likely to be present in the large and thick pavement sections, reduces potential for scaling.

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