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Examining the frost resistance of high performance concrete

W. Micah Hale [a,*], Seamus F. Freyne [b], Bruce W. Russell [c]

[a] Department of Civil Engineering, University of Arkansas, Fayetteville, AR 72701, USA
[b] Civil and Environmental Engineering Department, Manhattan College, Bronx, NY 10471, USA
[c] School of Civil Engineering, Oklahoma State University, Stillwater, OK 74078, USA

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ABSTRACT

The experimental program investigated the need for air entrainment in high performance concrete (HPC). Concrete mixtures with varying water to cementitious material ratios (w/cm) were subjected to ASTM C 666 (Procedure A). The variables for the mixtures were total air content and w/cm. The targeted total air contents for the mixtures were 2% (non-air entraining agent), 4%, and 6%. The w/cm ranged from 0.26 to 0.50. The 56 day compressive strengths varied from 41 to 96 MPa (6000–13,900 psi). The freeze-thaw tests continued until the specimen deteriorated, or until the specimen achieved 300 freeze-thaw cycles. For the materials used in the study, the research results show non-air entrained mixtures with w/cm less than 0.36 can be developed that have adequate frost resistance. The results also show for the mixtures developed in the study that a total air content of 4% is adequate to provide frost resistance for mixtures with a w/cm between 0.36 and 0.50.

1. Introduction

The increased strength and durability of high performance concrete (HPC) makes it very appealing to the prestressed concrete industry, particularly in bridge girders. Due to its increased strength and durability, HPC can reduce the number of girders, increase bridge spans, decrease bridge depth, and improve bridge durability [1]. Many state departments of transportation (DOT) require entrained air in bridge girders. However, air entrainment may negate some of the benefits of HPC by reducing the concrete strength. Many researchers are questioning the need for air entrainment in HPC [2–8]. A goal of the research program was developing non-air entrained concrete mixtures that are resistant to freezing and thawing cycles. The researchers realize the importance of the air void system of hardened concrete, however for the purposes of this research program, only the air content of the fresh concrete was measured and the concrete's resistance to ASTM C 666. Many concrete testing agencies and state DOTs do not have the capabilities to assess the hardened air void system, therefore the research program focused on developing HPC mixtures that had durability factors of 60 or greater (as measured by ASTM C 666).

Entrained air is required to ensure the frost resistance of some concretes that are subjected to freezing and thawing. Entrained air is stabilized in concrete through the use of air-entraining admixtures (AEA). Current building codes require varying amounts of entrained air depending on the severity of the exposure. Entrained air voids provide small air pockets where water can expand when freezing and where water pressure can be relieved as freezing occurs. There may be as many as 300 billion entrained air voids in a cubic yard of concrete with a total air content of 4–6% by volume [9]. The voids generally have a diameter of about 0.05 mm and are uniformly distributed throughout the concrete [10]. Entrained air voids are typically spaced within 0.2 mm of each other [11]. Without these voids, continuous freeze-thaw cycles will eventually degrade and damage the concrete. A total air content between 4% and 8% is generally considered adequate to provide resistance to the freezing and thawing action [12].

The experimental program was designed to achieve two objectives. The first objective was to determine if air entrainment is necessary for frost resistance in HPC. The second objective was to determine the maximum w/cm where air entrainment is not needed. Concrete mixtures with varying w/cm and total air contents were subjected to ASTM C 666 (Procedure A).

2. Literature review

The use of HPC in exterior structures has increased in recent years [13]. The durability and permeability of normal strength concrete (NSC) has been thoroughly studied over the past century, but the engineering properties of HPC have not been studied to the same extent. To improve the frost resistance of NSC, an air-entraining agent is added to the concrete mixture. While entrained air increases frost resistance, it also decreases concrete strength. For this reason air entrainment is not commonly used in HPC,

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[*] Corresponding author.
E-mail address: micah@uark.edu (W. Micah Hale).

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and researchers are questioning the need for air entrainment in HPC [2–8]. Many of these researchers have concluded that the low permeability of HPC due to its decreased w/cm improves its frost resistance [2,5,6,8,14]. Accordingly, several researches have developed frost resistant non-air entrained HPC mixtures [2,7,14–16]. Despite these indicators, most researchers still recommend the use of air entrainment [2,6,8,14,17,18].

2.1. Freeze-thaw mechanism

It is common knowledge that pure water freezes at 0 °C (32 °F) under normal atmospheric pressure. When water freezes there is a 9% increase in volume as water turns to ice. However, water that is trapped within the capillary pores of concrete does not necessarily freeze at 0 °C. The temperature at which water freezes in capillary pores is a function of the size of the pores and pore chemistry. As pore sizes decrease, the temperature required to freeze the water also decreases. For example, in pores with a diameter of 10 nm, the water will not freeze until –5 °C (23 °F), and for pores with a diameter of 3.5 nm, the water will not freeze until −20 °C (−4 °F) [12].

While the freezing of water damages the concrete paste, it is not the main contributor to the freezing and thawing deterioration of concrete. The primary damage is caused by the increase in hydraulic pressure within the pore spaces. As water freezes within a capillary pore, the ice that is formed compresses the unfrozen water within the pore. If the water can escape into an unoccupied void, the hydraulic pressure is relieved. However, if the distance to a void is too great and the hydraulic pressure cannot be relieved, the water pressure will expand the pores causing tensile stresses in the surrounding concrete paste. In saturated concrete, the tensile stresses may eventually exceed the tensile capacity of the paste and cracking will occur. Entrained air is added to the concrete to provide the voids necessary to relieve the hydraulic pressure [12].

2.2. Air content

If exposed to freezing and thawing cycles, NSC requires a total air content of 4–7% [12]. Of this 4–7% air, approximately 2% is entrapped air and the remaining 2–5% is entrained air. Due to the reduced permeability of HPC, researchers have suggested that the air content of HPC can be reduced [4]. Fagerlund used a closed container model to determine the minimum air contents required for HPC to have acceptable frost resistance [14]. The model assumed a spherical void shape with solid, impermeable materials along the outside of the sphere and freezable water in the center. From his model, Fagerlund determined that an entrained air content of 0.2% would be sufficient in HPC, but in normal strength concrete 7.5% would be necessary.

Experimental results have also shown that the total air content required for HPC to possess acceptable frost resistance is less than that for NSC. Acceptable frost resistance is defined as concrete having a durability factor greater than 60 or a spacing factor less than 0.2 mm (0.008 in.) [6,7]. Several researchers have developed HPC mixtures with low air contents that demonstrated acceptable frost resistance [3,8,16,19]. However, other researchers also developed HPC mixtures with low air contents that did not have acceptable frost resistance [2,3,5,19,20].

2.3. Water to cementitious material ratio

In 1956, Hubert Woods suggested that as an alternative to air entrainment, concrete mixtures could be cast at or below a water to cement ratio (w/c) of 0.40 [21]. He reasoned that well cured concrete mixtures with w/c < 0.40 would not contain water “that would freeze under natural conditions.” He also suggested that the reduced permeability of low w/c concrete would prevent saturation of the concrete. Woods recommended experimental

Table 1
Testing matrix

Target total air content (%)	w/cm							
	0.26	0.30	0.32	0.34	0.36	0.42	0.45	0.50
2	X	X	–	X	X	X	–	X
4	X	X	X	–	X	X	X	X
6	X	X	–	–	X	X	–	X

X = indicates batching and testing of these variables.

Table 2
Fresh concrete properties

Mixture	Slump (mm)	Total air content (%)	Unit weight (kg/m^3)
26–2.4	165	2.4	2439
26–3.8	203	3.8	2392
26–5.6	108	5.6	2358
30–1.1	254	1.1	2417
30–4.5	38	4.5	2363
30–5.7	273	5.7	2342
32–4.1	165	4.1	2358
34–2.0	292	2.0	2412
36–2.6	64	2.6	2368
36–3.8	89	3.8	2352
36–6.2	51	6.2	2236
42–1.8	83	1.8	2335
42–2.2FA	51	2.2	2337
42–2.4SF	25	2.4	2304
42–4.4	95	4.4	2286
42–5.9	102	5.9	2228
45–4.1	140	4.1	2247
50–0.9	159	0.9	2297
50–1.5FA	203	1.5	2279
50–2.2SF	83	2.2	2247
50–3.6	241	3.6	2164
50–6.6	254	6.6	2137

25.4 mm = 1 in.
16.01 kg/m^3 = 1 lb/ft^3.

Table 3
Hardened concrete properties

Mixtures	28 day compressive strength (MPa)[a]	56 day compressive strength (MPa)[a]	Freeze-thaw durability factor[b]
26–2.4	84.1	89.4	97.5
26–3.8	77.7	83.4	97.7
26–5.6	72.8	77.8	99.3
30–1.1	84.1	93.8	100.6
30–4.5	68.7	75.8	98.9
30–5.7	70.8	76.0	95.6
32–4.1	66.6	73.7	94.4
34–2.0	70.7	77.2	94.2
36–2.6	63.3	66.3	77.6
36–3.8	57.5	62.3	94.4
36–6.2	53.1	58.3	100.9
42–1.8	59.9	62.4	20.8
42–2.2FA	59.9	62.7	30.5
42–2.4SF	53.6	56.8	13.4
42–4.4	44.6	47.3	100.2
42–5.9	42.1	46.3	93.2
45–4.1	42.1	48.1	91.3
50–0.9	42.9	48.2	17.3
50–1.5FA	50.8	54.3	21.5
50–2.2SF	42.1	44.0	22.4
50–3.6	43.7	46.6	91.3
50–6.6	38.3	42.4	93.1

[a] Average compressive strength of three tests.
[b] Average durability factor of four specimens.