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A method for assessment of the freeze–thaw resistance of preformed foam cellular concrete

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Abstract

The growing use of cellular concrete for building materials and geotechnical fills brings forth the question of suitable durability and performance standards. Of particular importance is the performance of cellular concrete in freezing and thawing environments. Since the macrostructure of cellular concrete or cellular control low-strength material is not like that of normal-weight concrete, a modified procedure is needed to specify the required characteristics of cellular concrete that lead to freeze–thaw durability. This research investigated the freeze–thaw durability of cellular concrete and developed a modified freeze–thaw test procedure, based on ASTM C666. Physical properties related to freeze–thaw durability were measured for each mixture and compared to the initial properties. As a result of these comparisons, recommendations are made regarding the production of freeze–thaw-resistant preformed foam cellular concrete exposed to freeze–thaw environments. The results of the study show that depth of absorption was a key predictor in developing freeze–thaw-resistant concrete. Compressive strength, depth of initial penetration, absorption and absorption rate are the important variables in producing cellular concrete that is resistant to cycles of freezing and thawing. Density and permeability were shown not to be significant variables.

Keywords: Concrete; Characterization; Durability; Mechanical properties; Freezing and thawing; Fly ash

1. Introduction

Cellular concrete is composed of cementitious mortar surrounding disconnected random air bubbles, with the air typically occupying more than 50% of the volume. The air bubbles are a result of gas formed within the mortar or foam introduced into the mortar mixture. The preformed foaming agents used in this study are designed to attract the cement particles into the aerosol foam network. The cement grains in this type of system collect on the surface of the bubble films in very close proximity. As the hydrate rims develop around each cement grain and due to their relative proximity to other cement grains, a hydrated portland cement paste is formed around each entrapped preformed air bubble. Incorporating the spherical air voids into the mortar matrix provides lighter weight, higher insulating values, and lower strengths when compared to normal-weight concrete. The unique properties of cellular concrete make it a suitable material for sound barriers and fire walls, structural backfill, foundations, building panels, lightweight base or geotechnical fill and mine fill applications.

These applications utilize the lighter weight, lower strength, superior fire protection or insulating ability of cellular concrete. Other applications utilize the material's ability to absorb energy; these applications include vehicle arresters on airport aprons, mine plugs, ballistic range targets, and roadway crash barriers.

2. Research significance

Cellular concrete is a relatively new construction material when compared to reinforced or plain normal-weight concrete. The major factor limiting the use of cellular concrete in applications where durability is a concern is

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the lack of information and design guidance regarding the acceptable performance of the material. For commonly used construction materials, such as normal-weight concrete, material durability is a well-researched and documented topic. Testing standards and performance criteria exist for normal-weight and lightweight concrete, giving both specifiers and designers tools to specify product performance. This is not the case for cellular concrete. When considering the potential uses of cellular concrete, one of the primary durability issues is resistance to freeze–thaw cycling. Testing and specifying cellular concrete's ability to resist freeze–thaw cycling is essential to its durable and economic use. This study addresses the evaluation of freeze–thaw durability of cellular concrete and controlled low-strength material. To address these cellular concrete durability questions, mixture formulations, which ranged in physical properties and intended use, were tested using a modified freeze–thaw testing protocol. The results provide guidance for testing and designing cellular concrete that is durable in freeze–thaw environments.

3. Background

The freeze thaw resistance of cellular concrete is a relatively recent topic in the scientific literature. The most comprehensive studies have been conducted and reported by Japanese researchers. Kamada et al. [1–3] have developed and summarized freeze–thaw deterioration models for both cellular concrete and autoclaved aerated concrete. The water in cellular concrete is largely free water or absorbed water, as opposed to capillary water. Since the voids are much larger than those in normal-weight concrete, the depth of saturation and the volume of water can be much greater in cellular concrete than in normal-weight concrete for the same time of exposure to moisture. This leads to a larger surface zone with higher water content and subsequent volume change in freezing temperatures, than the relatively dryer inner zone. The differences between cellular concrete and normal-weight concrete lead to a pronounced two-phase freeze–thaw deterioration: one phase through classic expansive forces from restrained freezing water [7] and another phase from differential forces between the saturated surface zone and the unsaturated inner zone [1]. It is not the purpose of this paper to develop additional theory on the mechanism of freeze–thaw deterioration of cellular concrete, but rather to present a method of evaluating cellular concrete mixture designs for freeze–thaw resistance.

4. Testing protocol

4.1. Existing test methods

Several types of freeze–thaw testing procedures have been used to evaluate cellular concrete. These include the critical degree of saturation test [4,5], the top surface freezing test [1], and modified versions of ASTM Standard C666, "Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing" [6]. The critical degree of saturation test measures the level of water saturation at which deterioration occurs. This level is compared to the expected ambient water saturation level to determine the relative freeze–thaw resistance of the cellular concrete. Basic test procedures include bringing multiple samples to different degrees of saturation, freezing and thawing the samples for a predetermined number of cycles, and observing any deterioration in the samples.

The top surface-freezing test models the internal cracking failure observed in cellular concrete walls exposed to temperature gradients. Test procedures for the cracking test involve simulating a temperature gradient varying from below freezing to above freezing temperatures in a cylindrical specimen. Performance is measured by determining the time necessary to cause a crack in the specimen. When the water content reaches a value greater than the critical degree of saturation, freezing pressures crack the specimen.

ASTM Standard C666 is a test procedure that determines the ability of normal-weight concrete to resist rapid cycles of freezing and thawing [6]. The test procedure involves freezing and thawing specimens while monitoring the mass loss and natural frequency of the specimens during testing. Method A consists of freezing and thawing specimens in water. Method B consists of freezing specimens in air and thawing them in water. ASTM Standard C666 produces microcracking and a scaling-type failure when performed on cellular concrete [1–3].

4.2. Modified test method

A modified testing procedure was developed based on the results of Senbu and Kamada [2] and Roulet [5] and the most common and critical failure modes of cellular concrete. The most important failure modes include surface scaling and spalling because cellular concrete absorbs water from the surface. The top surface freezing test only provides information for a specific type of splitting failure [3]. While the critical degree of saturation test and the top surface-freezing test provide important research information, they do not provide a full measure of freeze–thaw durability.

A modification of ASTM Standard C666 Method B was chosen as a representative freeze–thaw test due to the absorption and failure characteristics of cellular concrete. Modifications to this procedure take into consideration the freeze–thaw failure mechanisms and properties critical to freeze–thaw performance. In normal-weight concrete, failure occurs from the freezing of water in capillary voids, whereas in cellular concrete, failure occurs from the freezing of water in larger air voids [2]. Deterioration is not possible in cellular concrete if the air voids are not sufficiently saturated with water. ASTM Standard C666 provides no provisions for normalizing the moisture content of specimens. Moisture content at the time of freezing is an important parameter governing cellular concrete freeze–thaw behavior. A saturation procedure to normalize the moisture content was used to account for natural absorption characteristics.

For the modified test procedures, specimen dimensions are in accordance with the specifications of ASTM Standard C666. The cellular concrete beams were removed from their molds and cured at 23 °C and 97% relative humidity for 28 days. After 28 days, each beam was weighed immediately after removal from the curing chamber and subjected to a saturation procedure. The saturation procedure consisted of submerging the specimens under 2 cm of water at 4 ± 1.7 °C. After 1 h, the weight of each beam was determined by drying the excess water from the surface and weighing. The beams were resubmerged and the SSD weight was obtained at 24-h intervals until the weight gain was less than 1% from the previous reading or for a maximum of 28 days.

Freeze–thaw cycling was performed following the curing and saturation procedure. The cycling procedure consisted of freezing the beams in air at a temperature of -18 ± 4 °C and thawing submerged in water at 10 ± 2 °C. The higher thawing temperature, from that used in ASTM C666, was used because of the high thermal resistance of cellular concrete. In cellular concrete the thawing in water also acts to accelerate the test, keeping the specimen saturated. As the specimen deteriorates, it may absorb more water and accelerate the deterioration. A thermocouple was inserted into a control beam to continuously monitor the internal specimen temperature. Two cycles were conducted per day. The average freezing time was 9 ± 1.0 h, and the average thawing time was 1.5 ± 0.5 h.

Three parameters were monitored throughout the freeze–thaw test in order to quantify the cellular concrete's freeze–thaw performance. Natural frequency and mass loss were measured every 10 cycles for 150 cycles. Compressive strength was measured after 10, 30, 50, 70, 90, and 150 cycles. Natural frequency was determined using the impulse excitation technique according to ASTM Standard C215, ‘‘Fundamental, Transverse, Longitudinal, and Torsional Frequencies of Concrete Specimens’’ [7]. Mass loss was determined by weighing the beams in the SSD condition. After a specified number of cycles, 5-cm cubes were cut from the companion beams subjected to the identical freeze–thaw cycles. Two cubes were taken for each compressive strength test. Each cube contained two exterior faces of the specimen.

5. Test parameters

The testing matrix and mixture designs vary density, compressive strength, and absorption. Table 1 summarizes the mixture proportions. For comparison purposes, the mixtures evaluated in this study are divided into two groups, designated herein as Group I and Group II. Density is held nearly constant in each group. The differing properties were obtained by adding varying amounts of ASTM C618 Class F fly ash to the mixtures. The fly ash is mostly an aggregate in these mixtures. Since it has a similar size to portland cement the mortar properties are similar for foaming applications. The strength contribution is small compared to the portland cement as there is not sufficient calcium to react the fly ash to its pozzolanic potential.

Table 1
Summary of mixture proportions per cubic meter and per laboratory batch

Mass per cubic meter (kg or kg/m^3)								
Mix code	Density	Cement	Water	Fly ash	Sand	Foam	Foam	w/c
Group I—low density								
M1	629	420	168	0.0	0.0	39.4	B	0.40
M2	631	411	186	0.0	0.0	38.5	A	0.44
M6	678	149	190	302	0.0	35.8	A	0.42
M3	497	311	141	0.0	0.0	44.3	A	0.45
Group II—high density								
M4	1396	57	163	268	885	20.0	A	0.50
M5	1338	57	484	787	0.0	8.2	A	0.57
M7	1304	149	469	676	0.0	10.2	A	0.57

Group I mixtures include mixtures M1, M2, M3, and M6. The measured wet densities for Group I mixtures M1, M3, and M6 ranged from 629 to 678 kg/m^3. Mixture M3 is an ultra lightweight mixture with a density of 497 kg/m^3. Comparisons made between Group I mixtures evaluate the following effects:

1. Effect of different formulation of preformed foam by comparing mixtures M1 and M2.
2. Effect of higher permeability and absorption by comparing mixtures M2 and M6.
3. Effect of lower density by comparing mixtures M2 and M3.

Group II mixtures included mixtures M4, M5, and M7. Measured wet densities for Group II mixtures ranged form 1304 to 1396 kg/m^3. Different variables are evaluated for Group II mixtures since mixtures of this type are usually used as controlled low-strength material (CLSM). Typically, CLSM mixtures have low cement contents, relatively high densities, lower strengths, and use significant amounts of fly ash and/or sand as filler. Comparisons made with Group II mixtures establish the following effects:

1. Effect of using fly ash and sand as filler material by comparing mixtures M5 and M4.
2. Effect of cement content by comparing mixtures M5 and M7.
3. Effect of density by comparing Group I and Group II mixtures.

6. Research results

The hardened concrete properties of each mixture were determined using concrete specimens cured at 23 °C at

Table 2
Summary of hardened cellular concrete properties

Mix code	Surface saturated dry specific gravity	Oven-dried specific gravity	Initial moisture content (% vol.)	Initial depth of water penetration (mm)	24-h/28-day absorption (% vol.)	28-Day compressive strength (MPa)	Permeability (cm/s)
Group I—low density							
M1	0.62	0.46	15.5	3.5	16/23	1.77	< 1.00e − 7
M2	0.63	0.47	15.9	3.3	15/23	2.07	< 1.00e − 7
M3	0.49	0.37	12.2	4.2	15/24	1.09	< 1.00e − 7
M6	0.66	0.45	21.1	>50.0	36/49	0.71	0.58e − 5
Group II—high density							
M4	1.50	1.23	24.7	44.5	26/32	0.25	3.76e − 5
M5	1.37	0.88	49.1	>50.0	45/51	0.23	2.56e − 5
M7	1.32	0.87	51.5	>50.0	46/50	1.10	0.53e − 5

97% relative humidity for 28 days. Table 2 summarizes the results of tests for all mixtures evaluated in the study. The "initial moisture content" was the moisture content after the saturation procedure before the start of freeze–thaw testing.

Depth of water penetration, 24-h and 28-day water absorption, and constant-head water permeability measured the water absorption and transport properties. The depth of water penetration and the water absorption were determined by ASTM C796 [6] using a red dye. The compressive strength was determined according to ASTM C495 [6]. Freeze–thaw deterioration of the mixtures was monitored using relative dynamic modulus, relative mass, and relative compressive strength. Relative dynamic modulus was calculated using the natural frequency data obtained from nondestructive frequency testing according to ASTM C215 [6]. The permeability was measured using a constant-head permeameter on 10-cm-diameter specimens over a 7-day period. Relative dynamic modulus and mass were determined using Eq. (1).

$$M_c = (m_c^2/m_o^2) \times 100 \tag{1}$$

where M_c is the relative value after c cycles of freezing and thawing, m_c is the measured value after c cycles of freezing and thawing, and m_o is the measured value at 0 cycles.

Fig. 1 shows the performance of the Group I low-density mixtures, M1, M2, M6, and M3. Mixtures M1, M2, and M3 had strengths greater than 1 MPa at 28 days and low absorptive qualities (depth of water penetration, 24-h and 28-day absorption, and permeability) as shown in Table 2. These mixtures showed excellent freeze–thaw resistance through 300 cycles. The 24-h absorption of these mixtures averaged 67% of the 28-day absorption, as compared to an average of 86% for the high-density mixtures, M4, M5, and M7.

The depth of water penetration after 28 days was less than 5 mm for these cellular concrete mixtures. In addition,

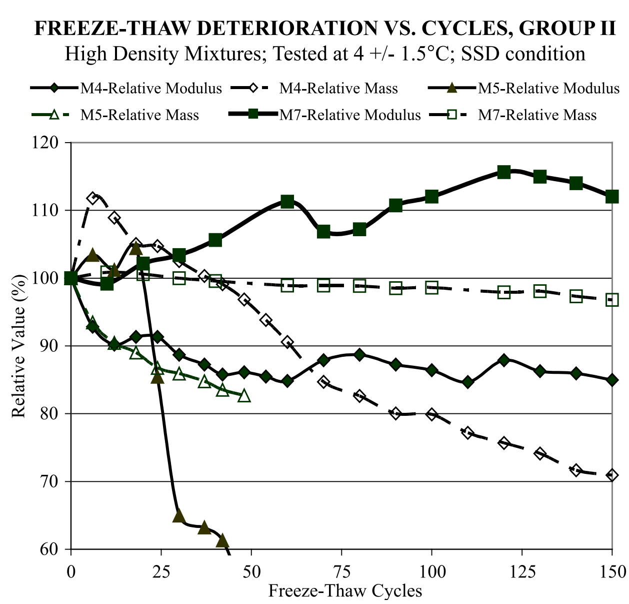

Fig. 1. Freeze–thaw deterioration data for Group I mixtures.

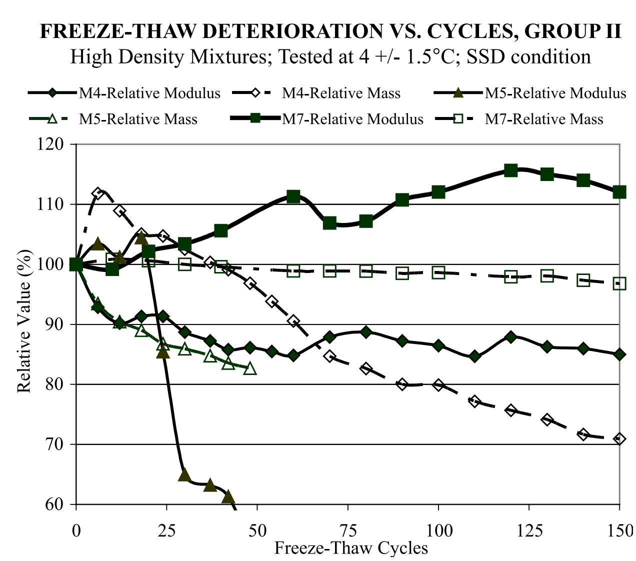

Fig. 2. Freeze–thaw deterioration data for Group II mixtures.

Table 3
Compressive strength of cellular concrete after cycles of freezing and thawing

Cycles	Low-density cellular concrete (MPa)				High-density cellular concrete (MPa)		
	M1	M2	M3	M6	M4	M5	M7
0	1.77	2.07	1.09	0.73	0.25	0.23	1.12
10	1.76	1.98	1.07	0.80	0.11	0.22	1.23[a]
30	1.54	2.17	1.43	0.85	0.13[a]	0.20	1.34[a]
50	1.91	2.05	1.50	0.85	n/a	0.08	1.34[a]
70	1.55	2.10	1.43	0.84	0.13	n/a	1.43
90	1.90	1.92	1.44	1.09	n/a	n/a	1.60
150	1.82	1.96	1.36	1.22	0.12	n/a	1.50

n/a: test specimen did not have the integrity to be tested.
[a] Linear interpolation from alternative testing schedule.

these mixtures were portland cement pastes using two different foaming agents. Mixture M6, which had a slightly lower compressive strength and much higher absorptive properties, deteriorated rapidly. Mixture M6 had the same density and w/c ratio as mixtures M1 and M2, but used one third as much portland cement and 2/3 fly ash as the cementitious material. The strength development on this mixture was much slower and its 24-h absorption was more than 36% by volume. It lost more than 25% of its dynamic modulus in the first 25 cycles of freezing and thawing, as shown in Fig. 1. During the testing, mixture M6 absorbed 80% of its dry mass in water. The marginal performance of mixture M6 was primarily due to its low early-age strength and high absorption.

Fig. 2 shows the performance of the high-density cellular concrete mixtures M4, M5, and M7. Mixture M7 performed well with relatively high durability factors as compared to mixture M4 or M5. Mixtures M4 and M5 are low-cement-factor mixtures with high density with similar depth of penetration and permeability. The primary difference between mixture M7 and mixtures M4 and M5 is the higher compressive strength, as shown in Table 2. Mixtures M5 and M7 have nearly identical absorption and density.

Compressive strength changed significantly during the course of the freeze–thaw test regime. Table 3 shows the results of the compressive strength tests after cycles of freeze–thaw exposures. The high-density, low-strength mixtures, M4 and M5, had a rapid deterioration of strength that coincided with the decrease in relative modulus.

Compressive strength appears to be the primary variable indicated by the data for producing cellular concrete that is resistant to cycles of freezing and thawing. However, absorption, rate of absorption, and depth of penetration clearly play a role in the durability of cellular concrete. Density and permeability did not appear to be significant variables in this study. Cellular concretes with 28-day compressive strengths higher than 1 MPa were observed to be durable in cycles of freezing and thawing. Mixtures with compressive strengths below 1 MPa and with high absorptive properties are not resistant to cycles of freezing and thawing. The 24-h absorption test or depth of penetration appears to be a better indicator of detrimental absorption of water than permeability. However, mixture M7 shows that absorption or depth of penetration cannot be used as sole indicators of freeze–thaw resistance.

7. Summary and conclusions

The results of this study show that the modified freeze–thaw procedure can differentiate levels of freeze–thaw resistance for varying mixture designs. Strength, depth of initial penetration, absorption, and absorption rate were found to relate with the freeze–thaw durability. However, some mixture formulations may have high water absorption and transport properties and still exhibit good freeze–thaw durability, such as mixture M7 in this study. Low-density mixture designed with an initial absorption less than 16% provided good freeze–thaw resistance as measured by the presented test procedure. In both high- and low-density preformed foam cellular concrete, a minimum compressive strength of 1 MPa was observed in the freeze–thaw-resistant specimens. Additional testing is needed to create a larger statistical database to evaluate the sensitivity and variability of the modified test procedure.

References

[1] E. Kamada, Y. Koh, M. Tapata, Frost deterioration of cellular concrete, in: T. Sneck, A. Kaarresalo (Eds.), Third International Conference on the Durability of Building Materials and Components, VTT Symposium 50, Espoo, Finland, vol. 3 (1984 August), pp. 372–382.
[2] O. Senbu, E. Kamada, Mechanism and evaluation method of frost deterioration of cellular concrete, durability of building materials and components, in: J.M. Baker, P.J. Nixon, A.J. Majumdar, H. Davies (Eds.), Proceedings of the Fifth International Conference, 1990 November, pp. 241–246.
[3] O. Senbu, E. Kamada, Mechanism of frost deterioration of ACC, advances in autoclaved aerated concrete, in: F.H. Wittmann (Ed.), Proceedings of the Third RILEM International Symposium on Autoclaved Aerated Concrete, 1992 October, pp. 153–156.
[4] RILEM Technical Committees 78-MCA and 51-ALC, in: S. Aroni, et al. (Eds.), Autoclaved Aerated Concrete: Properties, Testing, and Design: RILEM Recommended Practice, E & F. N. Spon, London, UK, 1993.
[5] C.A. Roulet, in: F.H. Wittmann (Ed.), Expansion of Aerated Concrete due to Frost—Determination of Critical Saturation, Autoclaved Aerated Concrete, Moisture and Properties, Elsevier, New York, 1983, pp. 157–169.
[6] American Society of Testing and Materials, Annual Book of ASTM Standards, ASTM, West Conshohocken, PA, 1998.
[7] M. Eglinton, in: P.C. Hewlett (Ed.), Lea's Chemistry of Cement and Concrete, 4th ed., Arnold Press, London, 1998, pp. 299–342, Chapter 7.