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Cohesive fracture and probabilistic damage analysis of freezing–thawing degradation of concrete

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HIGHLIGHTS

- Degradation of concrete due to freeze/thaw action is characterized by cohesive fracture test.
- The relationship between damage and the number of F/T cycles is established using the nonlinear regression analysis.
- Probabilistic damage model is established to predict the cyclic freeze/thaw life of concrete.

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ABSTRACT

The durability of concrete with low-degradation aggregates due to cyclic freezing and thawing effect is experimentally studied by characterizing the variance of fracture energy with respect to the number of freeze/thaw (F/T) cycles. Cohesive fracture test is conducted for notched concrete beams subjected to different F/T cycles, and the fictitious crack model-based approach is employed to calculate the fracture energy from the testing data. The relationship between the relative fracture energy and the number of F/T cycles is established using the nonlinear regression analyses. Based on the three-parameter Weibull distribution model, the probabilistic damage analysis is conducted, and the life distribution diagrams are produced according to the probability of reliability/survival concept. The relationships between the life (i.e., the number of F/T cycles) and damage parameter for different probabilities of reliability are obtained, from which the service life of concrete due to cyclic freezing and thawing actions can be determined at any given reliability index. The validation and accuracy of the present models are demonstrated through comparisons between the predicted data by the present models and the test data. The present probabilistic damage model can serve as a reference for maintenance, design and life prediction of concrete structures with low-degradation aggregates in cold regions subjected to cyclic freezing and thawing actions.

1. Introduction

Significant transportation infrastructure in North America is located in regions with severe environmental conditions, where alternate freezing and thawing can seriously affect the material and structural integrity. The durability of Portland cement concrete (PCC) has long been identified as a concern by transportation communities across the United States. Degradation of aggregates in concrete can be caused by erosion or fracture, and both cementitious materials and aggregates age over time. The erosion process produces a material of poorer quality compared to the parent aggregate. Degradation becomes more pronounced in marine basalt materials [1]. In marine basalt materials, aggregates can degrade into plastic fines. Failure of aggregates in a bituminous matrix may be caused by inferior mineral content and is manifested first by softening of the mixture followed soon afterward by actual disintegration of the matrix. Basalt rock of the Eocene age and gravels associated with the Eocene basalt are most apt to exhibit this harmful degradation. Though aggregate degradation of marine basalt materials is well recognized and understood, very limited information can be found in the literature on the long-term performance of concrete made with low-degradation aggregates.

Durability degradation due to cyclic freezing and thawing is one of the major damage aspects in cementitious materials and structures in cold regions. The basic mechanisms of this type of frost damage in cement-based materials were first studied by Powers and his co-workers [2–4]. During the cyclic freezing and thawing actions, the concrete is subjected to loading in the freezing period and undergoes unloading in the thawing process. From the kinetic point of view, the damage of concrete under successive freeze/thaw (F/T) cycles is due to hydrostatic and osmotic pressure, which

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is a pure physical process [3]. In this sense, freezing–thawing damage of concrete can be viewed as a type of fatigue damage accumulation of the internal hydrostatic pressure and osmotic pressure acting on concrete [5]. Because of the heterogeneous nature in material components as well as the inherent variability in material properties of concrete, probabilistic approaches are usually utilized to include the uncertainty of various parameters in a consistent manner. Thus, probabilistic modeling of the deterioration mechanisms in concrete structures has gained more and more applications during the past few years [6,7]. It is thus feasible to use probabilistic model-based service life design methodologies for structural evaluations.

The ability to assess with confidence the potential freezing and thawing durability of concrete is important for long term evaluations of in situ concrete [8]. In the literature, the deterioration of concrete in rapid freezing and thawing testing (ASTM C666 procedure A or B) is normally measured as changes of geometrical and material properties after different amounts of F/T cycles, such as variations of length [9], resonance frequency and its corresponding relative dynamic modulus [8,10–12], and electrical resistivity change [13–15]. Alternatively, as a characteristic material property, the specific fracture energy has proved to be a useful parameter for design with concrete and cementitious materials [16–19]. However, to the authors' best knowledge, none of existing studies has been conducted to explore the degradation of fracture energy for concrete structures due to F/T cycles.

In this study, the long-term performance of concrete with a specified low-degradation aggregate due to freezing and thawing effect is experimentally studied by characterizing the variance of fracture energy with respect to the number of freeze/thaw (F/T) cycles. Based on the three-parameter Weibull distribution model, a probabilistic damage model is proposed in terms of the varying fracture energy with respect to different F/T cycles, and the cyclic F/T life (in the term of the number of F/T cycles) distribution diagrams are produced according to the probability of reliability/survival concept. The relationships between the cyclic F/T life and damage parameter for different probabilities of reliability are explicitly established, from which the service life of concrete with the considered low-degradation aggregates due to cyclic freezing and thawing actions can be determined at any given reliability index.

2. Materials and experimental procedure

2.1. Materials and mix design

In this study, the cement used is Portland cement (Type I–II). Coarse low-degradation (LD) aggregates were provided by Washington State Department of Transportation (WSDOT), and the specific gravity and water absorption of coarse aggregate alone is 2.68 and 1.2%, respectively. The specific gravity of fine aggregates is 2.65. According to the aggregate degradation review conducted by KBA, Inc. [20], aggregates with a degradation factor less than the critical value of 35 are commonly considered as a low-degradation (LD) one. In this study, the identified LD aggregate sources with a degradation factor of 31 was used. The degradation factor for the LD aggregates considered in this study was obtained by the WSDOT using the WSDOT Test Method T 113. The gradations of the coarse LD aggregates and fine aggregate are presented in Table 1.

The mix design employed in this study was based on the WSDOT guidelines for a 27.6 GPa (4000 psi) mix (WSDOT Concrete Mix Performance Guideline (4000D)), which is summarized in Table 2.

Table 1
Coarse aggregate gradations (sieve analysis).

Sieves	LD aggregate Cumulative % passing	Fine aggregate Cumulative % passing
1/2″	100	–
3/8″	98.5	100
1/4″	67.8	99.5
#4	37.3	97.7
#8	3.0	84.3
#16	0.4	61
#30	–	42.2
#50	–	17.7
#100	–	4.1
#200	–	2.2

2.2. Sample preparations

In accordance with ASTM C192/C192 M, the fresh concrete was cast in oiled wood molds to form prisms with 76.2 × 101.6 × 406.4 mm (3 × 4 × 16 in.), prisms with 101.6 × 101.6 × 406.4 mm (4 × 4 × 16 in.) and cylinders with 152.4 mm (6 in.) (diameter) × 304.8 mm (12 in.) (height) were, respectively, cast for the flexural strength and compression strength tests. Immediately after the casting, all the samples were externally vibrated for approximately 15 s and finished using a metal trowel. All specimens were demolded after 24 h and then cured in lime-saturated water at room temperature for at least 28 days before subsequent tests.

2.3. Freezing–thawing experimental program

Test Method for Resistance of Concrete to Rapid Freezing and Thawing (ASTM C 666), Procedure A, which was designed to provide an indication of the potential durability of concrete in a freezing and thawing environment, was adopted in this study to condition all the samples. It provides a relative assessment of the frost resistance of concrete after a given number of F/T cycles, compared to the initial condition of the specimens. The F/T machine used in this study consists of 18 containers, in which 17 samples can be subjected to specified F/T cycles, together with a particular container for the control sample, which controls to produce continuously and automatically reproducible cycles with the specified temperature (see Fig. 1). An "S" shape stainless steel wire with diameter of 2.0 mm (3/32 in.) is placed in the bottom of the containers before the samples laying into them, so that: (1) each sample will be always completely surrounded by enough water while it is being subjected to cyclic freezing and thawing actions and (2) the temperature of the heat-exchanging medium will not be transmitted directly through the bottom of the container to the full area of the bottom of the samples. During the conditioning period, each group of samples were kept to exchange their conditioning positions in the freeze–thaw machine in certain sequences such that all samples in the same group were conditioned as much consistently and evenly as possible.

According to ASTM C666, Procedure A, the temperature range of every freezing and thawing cycle in this study was set to cycle between −17.8 °C (0°F) and 4.4 °C (40°F) as specified in ASTM C666. The difference between the temperatures at the center of a specimen and that at its surface was continuously monitored and controlled, not to exceed 10 °C (50°F). Usually, the temperature range in the samples was from −17.8 °C (0°F) to 4.4 °C (40°F) with an error of less than 1.11 °C (2°F) and a cycle frequency of 6–8 cycles per day. Whenever the temperature reaches either lower than −19.4 °C (−3°F) or higher than 6 °C (43°F), the F/T machine was turned off and the control sample was replaced by a new one to help maintain the temperature in the standard range.

2.4. Cohesive fracture test

The determination of fracture energy was performed following the procedure as recommended in [16,20], where a three point bending beam (3PBB) method is recommended. Before the fracture test, the conditioned samples were cut with notches at the mid-span of the sample by a diamond saw with high accuracy. In order to keep the maximum bending moment as lower as possible when the applied load reaches its ultimate value, a rather deep notch is recommended [16]. In this study, the depth of the notch was adopted as the half of the depth of the sample. After the cut, the mass of each notched sample was then measured by a digital scale with res-

Table 2
Existing WSDOT mix designs.

Mixtures	Cement kg/m^3 (lb/yd^3)	19 cm (3/4″) Aggregate kg/m^3 (lb/yd^3)	Sand kg/m^3 (lb/yd^3)	Water/cement ratio
LD-WSDOT	334.6 (564)	1085.8 (1830)	753.5 (1270)	0.48