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Evaluation of freeze–thaw damage in concrete by ultrasonic imaging

M. Molero [a,*], S. Aparicio [a], G. Al-Assadi [b], M.J. Casati [c], M.G. Hernández [a], J.J. Anaya [a]

[a] Centro de Acústica Aplicada y Evaluación No Destructiva, CAEND, (CSIC-UPM), Arganda del Rey, 28500 Madrid, Spain
[b] Departamento de Ingeniería Civil y Construcción, ETSICCP, UPM, 28040 Madrid, Spain
[c] Departamento de Vehículos Aeroespaciales, EUIT Aeronáuticos UPM, 28040 Madrid, Spain

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ABSTRACT

This work studies the use of ultrasonic imaging as an evaluation tool in concrete subjected to freeze–thaw (F–T) cycles. To evaluate the damage in this deterioration process, ultrasonic velocity and attenuation images have been generated from concrete specimens with and without air-entraining agents. Two parameters have been proposed from these ultrasonic images according to our experimental setup: the non-assessable area proportion (NAAP) and a weighted average velocity in terms of the NAAP. The proposed parameters have been compared with the recommended failure criteria of the ASTM and Rilem standards, which employ ultrasonic contact measurements. The principal advantage of the use of ultrasonic images and the proposed methodology in comparison with the ultrasonic velocity measurements by contact is the possibility of detection of incipient damage caused by accelerated freeze–thaw cycles.

1. Introduction

Freeze–thaw (F–T) damage is one of the major problems of concrete in cold climates. Cracking and spalling of concrete are the most common damages by frost action, caused by progressive expansion of the cement paste matrix from reiterated F–T cycles [1]. Several theories have been proposed to explain this type of damage, such as the hydraulic pressure [2], the osmotic pressure [3] and the micro-ice-lens model [4] among others. The damage by frost is mainly studied in a laboratory by accelerated F–T cycles. Although no evident relationship has been found between the effects induced by accelerated F–T cycles and those induced by F–T cycles under environmental conditions, researchers continue to study F–T damage using accelerated F–T cycles. Different standards have been developed to evaluate the resistance of concrete subjected to accelerated F–T cycles, such as UNE 12390-9 [5], ASTM C666/C666M-03 [6], prENV-9 [7], JIS A 1148-2001 [8], Rilem TC 176-IDC [9,10], and SS13 [11]. However, these standards differ in the testing method used and in the methodology carried out for evaluating damage in concrete specimens. Concrete resistance to F–T damage is usually evaluated and classified depending on the type of damage, whether external or internal. For instance, the standards used in [5,7,11] evaluate external damage and scaling by the loss of mass of material, whereas internal damage is usually evaluated by the ultrasonic pulse transmission time (UPTT) [9,10] and the fundamental transverse frequency measurements [6–9].

The standards that use ultrasonic non-destructive techniques to evaluate the deterioration of building materials are limited to the ultrasonic velocity measurements obtained, which are commonly performed manually. Thus, the lack of automation involves a limitation on the number of measurements performed, resulting in an expensive and unattractive method to obtain images.

Some years ago, the evaluation of concrete structures and cementitious materials by acoustic imaging, as well as the use of the attenuation and velocity measurements at each point of the material, became an attractive solution to provide the identification of irregularities and defects. For example, measurements of velocity, amplitude, and peak of frequency were used to evaluate the damage of concrete by F–T cycles in specimens along various lines [12]. However, the design of equipment to generate images that evaluate the quality and deterioration state in concrete specimens is neither direct nor obvious.

Several methods can be applied to provide high-resolution images of concrete areas, especially for detecting and locating holes, ducts, cracks, and thickness measurements, such as the synthetic aperture focusing technique (SAFT) and tomography techniques [13–15]. Recently, Chai et al. proposed a tomography technique for concrete evaluation using Rayleigh waves [16]. However, there is still a need to develop suitable systems of acoustic imaging to evaluate the deterioration of concrete structures.

The evaluation of deterioration process in cementitious materials using ultrasonic methodologies, and the development of

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[*] Corresponding author.
E-mail address: miguel.molero@csic.es (M. Molero).

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methods to generate images that allow the evaluation of material properties, are a part of the research lines of the authors [17–19]. The ultrasonic images allow the identification of irregularities and defects as well as the extraction of parameters, such as attenuation and velocity profiles, at discrete points of the material. The aim of this article is to use an automated ultrasonic imaging system, developed and patented by the authors [20], allowing the inspection of cylindrical samples of cementitious materials. In this case the system was used to evaluate the deterioration in cylindrical concrete samples subjected to F–T cycles. Two groups of concrete specimens, one of them with air-entraining agents, were subjected to accelerated F–T cycles. Ultrasonic contact measurements and automated ultrasonic immersion inspections were conducted in both groups of concrete specimens before and after the cycles. By means of the automated inspection system, ultrasonic images of velocity and attenuation were generated, allowing the comparison of degradation state in the specimens before and after the F–T cycles. Furthermore, from these ultrasonic images, two parameters were proposed to evaluate damage in the concrete specimens using the automated scanning systems designed by the authors. The proposed parameters were compared with the failure criteria of the ASTM and Rilem standards.

2. Failure criteria of standards

The frost resistance of concrete can be assessed using different criteria based on the loss of strength, weight change, dilation, fundamental frequency and ultrasonic pulse transmission time. This study addresses the failure criterion based on only the ultrasonic velocity measurement before and after the F–T cycles.

The standard ASTM C 666 [6] provides a failure criterion using the durability factor, D, which is calculated as

$$D = \frac{(\mathrm{RDME})N}{300} \tag{1}$$

where N is the number of F–T cycles necessary to reach a proposed critical value of the relative dynamic elasticity modulus (RDME; threshold, e.g., 60% according to [6]). If RDME remains higher than this critical value after ending the 300 F–T cycles, then N can be set to 300 [6]. Thus, RDME is computed as [21,22]

$$\mathrm{RDME} = \frac{V_n^2}{V_0^2} \times 100 \tag{2}$$

where V_n and V_0 are the longitudinal velocity at n and zero F–T cycles, respectively.

The Rilem recommendation [9,10] evaluates the internal damage in concrete by the relative ultrasonic pulse transmission time (relative UPTT). However, in this paper, instead of using the relative UPTT, its equivalent in velocity is used, that is, the relative velocity. This relative velocity, RV, is defined as

$$\mathrm{RV} = \left(\frac{V_n}{V_0}\right) \times 100 \tag{3}$$

According to these standards, the failure criteria to assess damage are outlined in Table 1.

The failure criteria shown in Table 1 are compared with the results obtained by the proposed ultrasonic imaging technique in Section 5.

3. Experimental design

3.1. Materials

Two groups of seven cylindrical specimens ($300 \times 150\ \mathrm{mm}^2$) were formed using HA-30 concrete, with only one group possessing air-entraining agents. The materials used were of Portland cement type CEM I 42.5R, normal river sand (0–5 mm) with 2.71 fineness module, crushed limestone aggregates (5–20 mm) with 6.96 finesse module, and ViscoCrete superplasticizers 3425 to improve workability. The air-entraining agent used was Aer 5 with a proportion of 0.022% of cement weight. The proportion of HA-30 concrete is outlined in Table 2.

The specimens were manufactured according to the standard UNE 12390-2 [23]. Subsequently, the specimens were cured in a climate chamber (DYCOMETAL CCK-40/1000) at a temperature of 30 °C and a relative humidity of 37% for 28 days. These selected curing conditions responded to the summer conditions in Madrid (Spain) [24]. In total, there were two groups of seven specimens: HA-30/00-0-6 corresponding to HA-30 concrete specimens without air-entraining agents and HA-30/05-0-6 corresponding to HA-30 concrete specimens with air-entraining agents.

3.2. Freeze–thaw cycles

The specimens were subjected to accelerated F–T cycles according to the standard ASTM C 666 [6], but were adjusted to the curing conditions specified earlier. The trial consisted of 300 accelerated cycles of 4 hr each, between 10 and -17 °C, as shown in Fig. 1. Two experiments were performed to study the two concrete groups of specimens. The duration of a complete experiment was approximately 50 days. The HA-30/00-0 and HA-30/05-0 specimens acting as reference were not subjected to the process of degradation; these samples were stored in a curing condition of 20 °C and 50% relative humidity.

4. Non-destructive testing by ultrasound

The damage caused by accelerated F–T cycles was evaluated using ultrasonic measurements by the contact method and automated immersion inspections, both operated in a through-transmission mode. These ultrasonic measurements were made before

Table 2
Concrete mix proportion HA-30.

Material	Cement (kg)	*w/c* ratio	Sand (kg)	Aggregates (kg)	Water (l)	Superplasticizers (% of cement weight)
amount/m^3	381.1	0.5	879.99	936.4	190.55	0.60

Table 1
Failure criteria for the assessment of the frost resistance of concrete.

Rilem TC 176 criteria	Not deteriorated	Possibly deteriorated	Deteriorated	Severely deteriorated
Relative velocity (RV)	> 100%	90–100%	80–90%	< 80%
ASTM C 666 criteria	**Frost resistant**	**With Passable frost resistance**	**With Unproven frost resistance**	**Non-resistant to frost**
Durability factor D (RDME when N=300)	≥ 80%	≥ 60%	< 60%	≤ 40%