

Study of the damage evolution of the concrete under freeze-thaw cycles using traditional and non-traditional techniques

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Abstract

Some experiments have been performed to investigate the cyclic freeze-thaw deterioration of concrete, using traditional and non-traditional techniques. Two concrete mixes, with different pore structure, were tested in order to compare the behavior of a freeze-thaw resistant concrete from one that is not. One of the concretes was air entrained, high content of cement and low w/c ratio, and the other one was a lower cement content and higher w/c ratio, without air-entraining agent. Concrete specimens were studied under cyclic freeze-thaw conditions according to UNE-CENT/TS 12390-9 test, using 3% NaCl solution as freezing medium (CDF test: Capillary Suction, De-icing agent and Freeze-thaw Test). The temperature and relative humidity were measured during the cycles inside the specimens using embedded sensors placed at different heights from the surface in contact with the de-icing agent solution. Strain gauges were used to measure the strain variations at the surface of the specimens. Also, measurements of ultrasonic pulse velocity through the concrete specimens were taken before, during, and after the freeze-thaw cycles.

According to the CDF test, the failure of the non-air-entraining agent concrete was observed before 28 freeze-thaw cycles; contrariwise, the scaling of the air-entraining agent concrete was only 0.10 kg/m² after 28 cycles, versus 3.23 kg/m² in the deteriorated concrete, after 28 cycles. Similar behavior was observed on the strain measurements. The residual strain in the deteriorated concrete after 28 cycles was 1150 μm versus 65 μm, in the air-entraining agent concrete. By means of monitoring the changes of ultrasonic pulse velocity during the freeze-thaw cycles, the deterioration of the tested specimens were assessed.

Originality

Concrete durability in climates where freezing and thawing occurs is a complex phenomenon. The deterioration of concrete under the action of freeze-thaw cycles is reflected in surface scaling and internal cracking. Almost all of the frost resistance research and test methods concentrate on the degradation of the concrete surface, but recently there was an increased concern about the internal damage of the material.

In this research project, the freeze-thaw durability of concrete is evaluated by means traditional and non-traditional techniques. Nondestructive test (NDT) methods were adopted to monitoring the behavior of concrete specimens exposed to freeze-thaw cycling, according to UNE-CENT/TS 12390-9 test.

During the freeze-thaw cycles, the variations of temperature and relative humidity inside the specimens were measured continuously by mean embedded sensors. Along the test, ultrasonic equipment was used to monitoring the ultrasonic pulse velocity to define the variations of the microstructure of the concrete due to freezing. Strain gauges were employed to determine the strains caused by the temperature variations in each cycle.

Chief contributions

This experimental research has shown outstanding results about the durability of concrete, under freezing and thawing cycles. Relationships of superficial deterioration and internal damage of concrete specimens were drawn by means the results of durability test (CDF – Scaling) and other monitored parameters like strain, ultrasonic pulse velocity, relative humidity and temperature.

These results provide great reference for further research on the development of a calculation modeling of deterioration process in concrete structures under a freeze-thaw environment.

The main task of this project was concerned with the use of different sensors in concrete specimens that should develop a monitoring system for assessed freeze-thaw damage. More accurate information about the behavior of concrete against physical or chemical aggressive factors or unfavorable environments, that involve its durability, is needed, to reduction of the inspection and maintenance costs and to improve the residual service-life prediction of the concrete structure.

Keywords: Concrete, Freezing and Thawing, NDT Methods, Scaling, CDF test.

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1. Introduction

Concrete durability caused by freeze-thaw cycles (FTC), is a major task for infrastructure in countries experiencing changing seasons and different weather conditions, because it is one of most aggressive mechanisms for the deterioration of concrete, causing serious damage to the material which will be severe in the presence of de-icing salts. The freeze-thaw effect is a complex phenomenon that has been studied for many years, but is not fully explained yet. The work of several researches (Powers and Helmuth, 1953; Fagerlund, 1977; Setzer, 2001; Valenza and Scherer, 2007), allowed to establish the main theories of frost action mechanisms, which are related to the movements and change of liquid and solid pore solution states in the concrete during FTC, generating expansion and shrinking of the material (Pigeon, 1995).

The conventional freeze-thaw deterioration in cement materials is caused by internal frost action and it is generally characterized by a reduction of stiffness and strength, micro-cracking and surface scaling. The use of deicing salts to remove snow from the surface of concrete structures intensifies the progressive damage of concrete through the removal of small chips or flakes of material. Surface scaling may be easily observed in field conditions while the cracking may start at the interior and initially not be visible at the outside. Almost all of the frost resistance research and test methods concentrate on the degradation of the concrete surface, but recently there was an increased concern about the internal damage of the material. Some tests are available to determine the frost resistance of concrete or to evaluate damage caused by internal cracking. The basis of these test methods is a partial or total immersion of specimens subjected to a high number of rapid FTC. To detect deterioration, at certain intervals, the dynamic elasticity modulus and the durability factor of the samples are measured. Otherwise, to evaluate damage or resistance to scaling, the specimens exposed to water or salt solution are subjected to a few slower cycles. At certain intervals, the scaled off material is collected, dried and weighted.

In this paper, the freeze-thaw durability of two different types of concrete is evaluated by means of traditional and non-traditional techniques. Some non-destructive tests methods (NDT) were employed for monitoring the performance of concretes during an accelerated test of freeze-thaw resistance (scaling) according to UNE-CENT/TS 12390-9 standard. To detect the material deterioration, the porous structure and air content of the two concretes were modified, resulting in one concrete damaged by the FTC and another concrete, with air entrained bubbles, able to resist the FTC attack.

During the scaling test, the variations of temperature and relative humidity inside the specimens were measured continuously by mean embedded sensors. Strain gauges were employed to determine the strains in concrete specimens as an extension of length measurements which are a traditional measure of freeze-thaw deterioration. Moreover, transducers glued to the concrete surface were used to continuously monitoring the ultrasonic pulse velocity (UPV) during all the FTC, and then the Relative Dynamic Modulus of Elasticity was determined to evaluate internal damage of the concretes.

2. Experimental programme

2.1 Materials

The cement was CEM I 42.5 R. Silica river sand was used like fine aggregate and silica crushed coarse aggregate having a maximum size of 25.4 mm was also used. The fineness modulus of the fine and coarse aggregates was 2.87 and 7.31, respectively. A polycarboxylate based water reducing admixture was used in both concretes. In this study to compare the behavior of concretes with different freeze-thaw resistance, two concrete mixes with differences in cement content, w/c ratio, air content, but with almost the same slump and similar compressive strength, were made with and without air-entrained agent. The composition of the mixes and the main concrete properties are given on Table 1.

Table 1: Composition and concrete properties

| Mix Proportions | Air Entrained Agent Concrete (AEAC) | Non Air Entrained Agent Concrete (NAEAC) |
|---|-------------------------------------|--|
| Fine Aggregate (kg/m ³) | 640.9 | 710.2 |
| Coarse Aggregate (kg/m ³) | 1159.1 | 1129.8 |
| Cement (kg/m ³) | 450 | 360 |
| Water (kg/m ³) | 180 | 162 |
| w/c ratio | 0.40 | 0.45 |
| Superplasticizer (kg/m ³) | 1.80 | 1.08 |
| Air-Entraining Agent (kg/m ³) | 0.45 | - |
| Properties of Concrete | | |
| Slump (cm) | 8.0 | 7.5 |
| Air Content (%) | 7.5 | 2.6 |
| Compressive Strength - 28 d (MPa) | 32.4 | 28.5 |

2.2 Description of the testing procedure

From each mixture, five specimens were tested for scaling resistance. The concrete specimens with a surface area of 150 x 150 mm² and thickness of 70 mm were demoulded after 24 hr, cured and exposed to the freeze-thaw test, according to the technical specification UNE-CEN/TS 12390-9 EX - Alternative Method (UNE-CEN/TS 12390-9 EX, 2008).

Before starting the cycles, the specimens needed a special preparation that consisted in four steps: stored for 6 days at 20 ± 2 °C in water, dry storage in a climatic chamber (20 °C / 65% RH) during 21 days for surface drying; before at the age of 28 days, the specimens were sealed on the lateral surfaces with epoxy resin. After the dry storage, the specimens were placed for 7 days in the test containers with the test surface on the bottom for pre-saturation of test liquid by capillary suction. At the age of 35 days, the specimens were ready to be exposed to the cycles. A 12 h freeze-thaw cycle in which temperature varied between +20 and -20 °C was applied starting at +20 °C (Figure 1a).

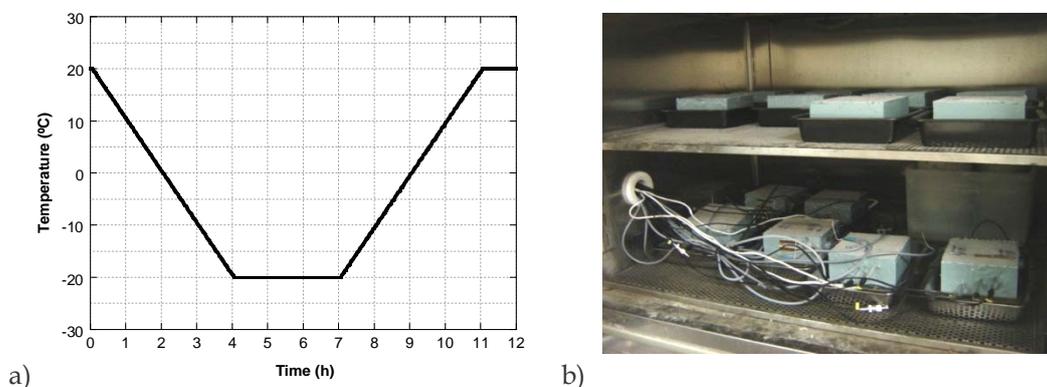


Figure 1: Freeze-Thaw Test. a) Temperature for one FTC, b) Concrete specimens inside the climatic chamber

The test was performed with standard de-icing agent solution, 97% by weight of distilled water and 3% by weight of NaCl. The surface deterioration was measured by weighting after 4, 6, 14 and 28 FTC. Before each measurement, loosely adhering particles were removed from the surfaces of the specimens by treatment by ultrasonic bath. Then the scaling particles were collected and dried for 24 h at 100 °C. After cooling, the weights of the scaled particles were measured.

2.3 Non-destructive test measurements

For temperature and humidity measurements inside the concrete prisms, during the concrete cast, digital humidity sensors were embedded in each specimen. The measurements were taken continuously during all the FTC in each prism specimen using three sensors placed 40 mm inside the concrete at different heights from the surface in contact with the test liquid (Figure 2a).

The superficial strain of the prism concrete samples, during the freeze-thaw cycles was measured using two commercial strain gages by specimen, which were glued with an adhesive in the middle and upper part of the lateral surface of the specimens as shown in Figure 2b ($H_1= 30$ mm y $H_2= 55$ mm).

A double zero crossing algorithm (Hernández et al., 2006) was used to know the travelling time of the ultrasonic signal and then the ultrasonic pulse velocity (UPV) was established. For each concrete specimen two longitudinal wave transducers (500 kHz) were glued directly to the surface of the concrete prisms. The position of the transducers is shown in Figure 2c. The internal damage has been studied by the Relative Dynamic Modulus of Elasticity of concrete (R_{UPVT}), calculated using the Ultrasonic Pulse Transmission Time (UPTT) measurements, according to the RILEM TC 176-IDC standard (RILEM TC 176-IDC, 2004).

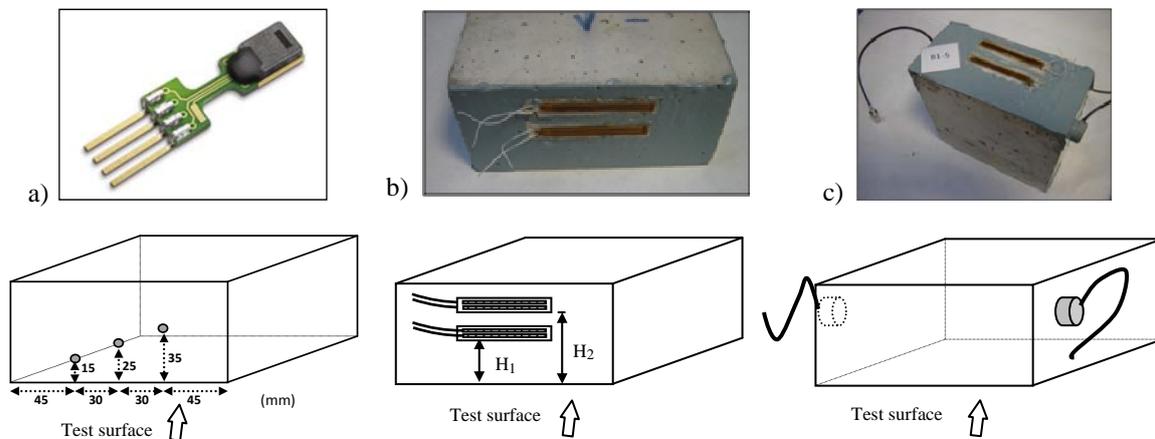


Figure 2: Sensors used for NTD measurements in concrete prisms subjected to Freeze-thaw cycles:
a) Temperature & humidity, b) Strain gauges, c) Ultrasonic transducers

3. Experimental results and analysis

3.1 Loss of weigh – Scaling

The results of scaling are shown in Fig. 3a. According to the freeze-thaw resistance test, the failure of the non air-entraining admixture concrete (NAEAC) occurred before 28 freeze-thaw cycles, the cumulative amount of scaling of 1.5 kg/m² was near to the 17th FTC. In contrast to that, the scaling of the air-entraining admixture concrete (AEAC) was only 0.10 kg/m² after 28 cycles, in comparison with 3.23 kg/m² in the deteriorated concrete, at the same time. The concrete test surfaces in contact with the de-icing agent solution of some specimens of both concretes before the test, after 14 and 28 FTC, are shown in Figure 3b-d. Salt scaling is often observed with the exposure of coarse aggregate.

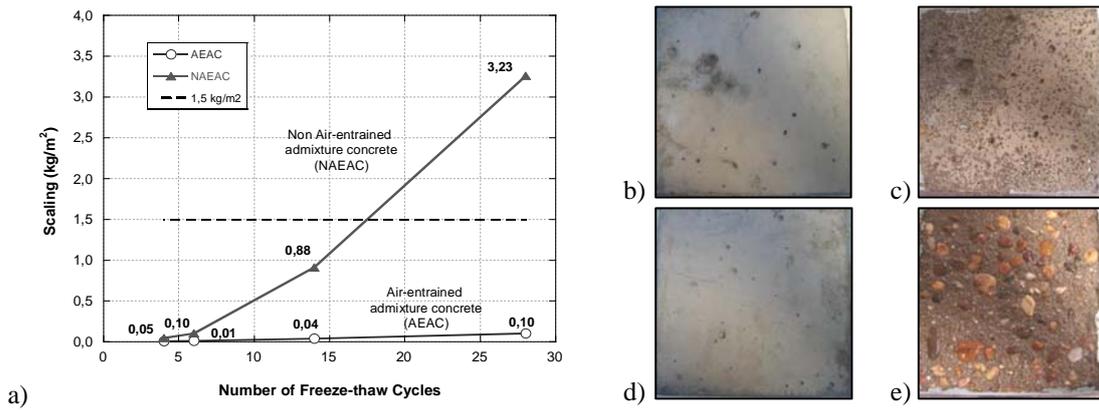


Figure 3: Freeze-thaw test. a) Cumulative scaling, Photographs of test surface of concrete slabs during the FTC: b) AEAC before the test, c) AEAC after 28 FTC, d) NAEAC before the test, e) NAEAC after 28 FTC.

3.2 Temperature and Humidity

The temperature in the climate chamber and inside the specimens for the first two and the last two FTC are shown in Figure 4a. The temperature in both concretes was almost the same. Moreover, the temperature variations at different locations inside the specimen were negligible. Thermal inertia was observed between the surface and inside the concrete specimens. The maximum and minimum humidity inside the specimens of both concretes during the FTC are shown in Figure 4b. In NAEAC the range of humidity variation was higher than in AEAC, even the total saturation of the NAEAC specimen was achieved after the 21st FTC.

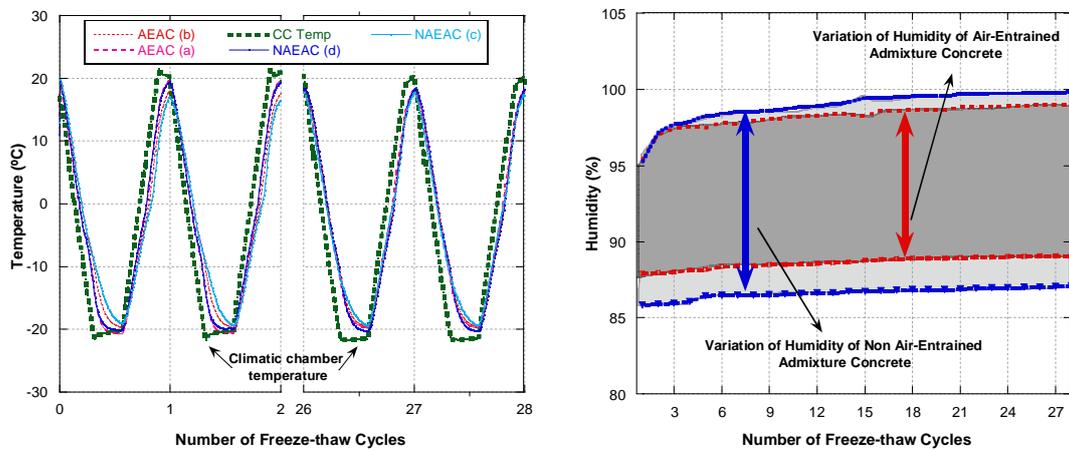


Figure 4: a) Temperature inside the specimens b) Maximum and minimum humidity inside the specimens.

3.3 Strain measurements

The strains measurements are shown in Figure 5a. The residual strain in the middle part of the NAEAC after 28 FTC was 1150 $\mu\text{m}/\text{m}$, in comparison with only 65 $\mu\text{m}/\text{m}$ in the AEAC. In NAEAC, the residual strain measured in the middle part of the prism was quite higher than the 800 $\mu\text{m}/\text{m}$ of the upper part, which this is an indicator of stress gradient due to the differences in moisture, as the bottom of the specimen is in contact with the test liquid. The strain-temperature behavior of NAEAC specimen for the first four FTC is shown in Figure 5b. In a closer look into each freeze-thaw cycle, it can be seen that strain is compressive under decreasing temperature, while concrete expands when the temperature is increased. When the temperature is minimal (-20 °C), a large contraction of concrete is observed up to a maximum value which in turn remains constant until heating starts. Once the

temperature rises above $-15\text{ }^{\circ}\text{C}$, the strain increases and concrete expands until the end of the cycle. The positive strain continues until the temperature is under $5\text{ }^{\circ}\text{C}$ in the next cycle, and it will contract again with the cooling. In the NAEAC specimen, the strain increases progressively with the number of cycles generating residual strains. This behavior is according to the theories that explain the phenomenon and with the results that have been reported that residual strains have been shown to increase progressively with the progress of deterioration (Bishnoi and Uomoto, 2008; Jacobsen et al., 2008; Penttala, 1998; Penttala and Al-Neshawy, 2002).

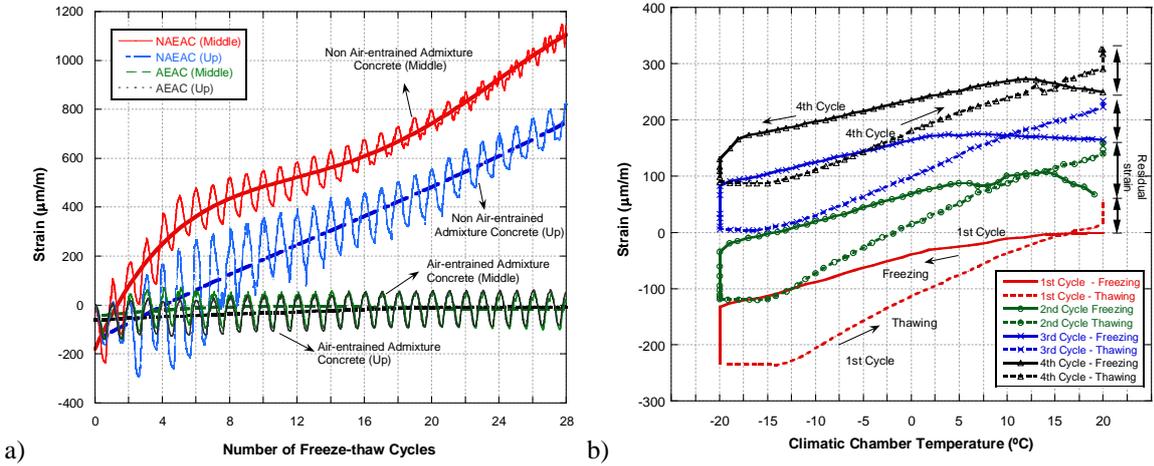


Figure 5: Strains measurements a) Strains of concrete samples during 28 Freeze-thaw cycles, b) Strains values of NAEAC against temperature during first four Freeze-thaw cycles

3.4 Ultrasonic pulse velocity

The ultrasonic pulse velocity (UPV) measured in both concrete specimens in each cycle at the end of the freezing, while the temperature is lowest ($-20\text{ }^{\circ}\text{C}$) is shown in Figure 6a. The UPV is increased as the exposure to FTC. These could be as result of ice formed inside the specimens due freeze of water porous, like is know that the UPV is higher in ice than in water or air (Kaufmann, 2004). Also, in the same figure is observed that UPV of NAEAC is higher than UPV measured in AEAC. This is because the inclusion of air-entraining agent generates air bubbles, causing a decrease of the UPV, as result of the lower density of the medium of propagation. The UPV measured in both concrete specimens in each cycle at the end of the thawing, while the temperature is highest ($+20\text{ }^{\circ}\text{C}$), is decreased as the exposure to FTC. This may be related to the increased porosity of the material, because with increasing porosity, decreases UPV (Lafhaj et al., 2006). The decrease in UPV can also be related to the formation of micro-cracks inside the concrete. The R_{UPVT} is shown in Figure 6b. The R_{UPVT} value decrease over the FTC in both concretes, which is evidence of internal deterioration of concrete. The loss in R_{UPVT} is higher in NAEAC compared with AEAC specimens.

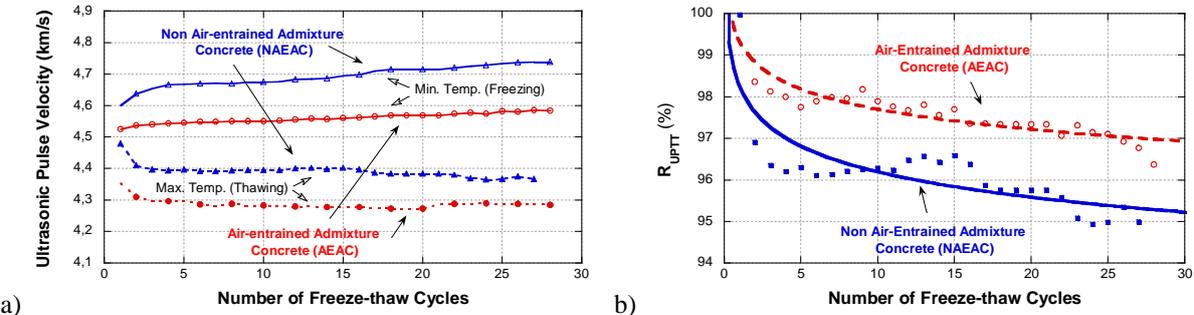


Figure 6: a) UPV during FTC. At the end of freezing (Min. Temp) and at the end of thawing (Max. Temp) b) Relative Dynamic Modulus of Elasticity (R_{UPVT}).

4. Conclusions

The damage caused by the freeze-thaw cycles in the AEAC prisms was negligible compared with the deterioration of the NAEAC specimens. The resistance of concrete to freezing and thawing is significantly improved by the use of intentionally entrained air, which is confirmed by the results of scaling test and the continuously measurement of strain and Ultrasonic Pulse Velocity.

Strain as a measurement of length changes is an indicator of freeze-thaw concrete deterioration. The residual strain increased when a high degree of saturation is reached and the expansion of ice dominates during cooling and its contraction due to melting ice during heating. The use of commercial strain gages was verified and results showed that it is a reliable, easily and simply method that could supplement or even replace the conventional scaling measures, which corresponding to an awkward procedure.

According to Figure 4b, there is a greater amount of water inside the NAEAC specimen in comparison to AEAC specimen. This conclusion should be carefully considered since the w/c ratio in both concretes is different (0.40 for AEAC and 0.45 for NAEAC).

The measured differences of UPV of concretes specimens before and after 28 freeze-thaw cycles were very small. That means that 28 freeze-thaw cycles according to the UNE-CENT/TS 12390-9 test, do not lead to considerable internal damage of tested concretes as have been reported in studies that use a high number of rapid FTC like the ASTM CC 666/C standard.

5. References

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