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Influence of freeze-thaw cycles on capillary absorption and chloride penetration into concrete

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ABSTRACT

Combined mechanical and environmental actions reduce service life of reinforced concrete structures more than each of the participating actions alone. In this contribution, the influence of freeze-thaw cycles on capillary water absorption and chloride penetration into ordinary concrete with two different water-cement ratios and air-entrained concrete was investigated. Water profiles in concrete were quantified by neutron radiography. Capillary water absorption and chloride penetration are both slowed down considerably by air entrainment. Chloride ions dissolved in water are filtered out of the penetrating salt solution and remain concentrated near the surface. Capillary water absorption and chloride penetration into ordinary concrete are accelerated considerably by frost damage. After exposure to freeze-thaw cycles a damage gradient from the surface to the center of the samples was observed. Transport mechanisms were studied in some detail and the data obtained can serve as a basis for more realistic prediction of service life of reinforced concrete structures under the influence of combined freeze-thaw cycles and chloride penetration.

1. Introduction

Reinforced concrete structures are usually exposed to complex mechanical states of stress in combination with environmental loads such as thermal and hygral gradients. The behavior of concrete under the influence of static and dynamic loads has been studied in great detail in the past and can be taken into consideration in structural design. National and international codes for structural design have been developed and refined over the years. In practice, however, most reinforced concrete structures are exposed at the same time to mechanical loads and in addition to environmental loads such as drying and rewetting, time-dependent thermal gradients, freeze-thaw cycles, chemical attack, or vibrations. Complex transport processes in the pore structure of concrete lead to time-dependent carbonation of hydration products and chloride penetration.

There are a number of standardized test methods to determine the rate of carbonation of a given type of concrete, to determine the time-dependent chloride penetration into concrete, and to observe the strength decrease under imposed freeze-thaw cycles [1–6]. Up to now structural design and service-life design are carried out in parallel and independent from one another. In the meantime, however, it became obvious that there is a strong interaction between an applied mechanical load and the simultaneously acting environmental loads. That means they cannot be considered separately.

The combination of mechanical load and chloride penetration has been studied in great detail and a RILEM recommendation has been published recently [7].

In this contribution, the influence of a given number of freeze-thaw cycles on capillary absorption and on chloride penetration into normal concrete and air-entrained concrete has been studied experimentally. Additional damage near the surface due to hygral gradients during frost cycles has been observed by neutron radiography. Results will be presented and discussed in details.

2. Preparation of test specimens and applied test methods

2.1. Preparation of test specimens

For the tests described in this paper three different types of concrete were produced. Concrete A and C correspond to the traditional classification as applied in our laboratory. Concrete type A has a water-cement ratio of 0.4 and may be considered to be frost resistant. Concrete type C with a water-cement ratio of 0.6 in contrast must be considered to be not frost resistant. In addition, the third type of concrete has again

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Table 1
Composition of the three types of concrete used in these test series.

Type	W/C	Cement kg/m^3	Sand kg/m^3	Gravel kg/m^3	Water kg/m^3	Air-entr. %	Air content %	28 day comp. strength MPa
A	0.4	380	653	1267	152	–	1.4	57.2
C	0.6	300	699	1191	180	–	2.1	37.7
CA	0.6	300	699	1191	180	0.003	5.2	33.5

a water-cement ratio of 0.6 but in this case an air entraining agent was added to make the concrete frost resistant. For all three types of concrete Portland cement Type 42.5 was used. The coarse aggregates consisted of local crushed aggregates with a maximum diameter of 20 mm and a density of 2620 kg/m^3 and local river sand with a maximum grain size of 5 mm and a density of 2610 kg/m^3 from Qingdao area. The exact composition of all three types of concrete is given in Table 1.

From all three fresh mixes prisms with a cross section of 100 × 100 mm and a length of 400 mm were produced. In addition, cubes with a side length of 100 mm were produced from the same mixes. The fresh concrete was compacted in steel molds and allowed to harden in the laboratory under plastic sheets. After 24 h, the steel molds were removed and the prisms and cubes were placed in a curing room with a controlled temperature of $T = 20 \pm 2$ °C and a relative humidity RH > 95%. When the specimens had reached an age of 24 days they were placed in water at a temperature of 20 °C until they have reached an age of 28 days.

2.2. Exposure to freeze-thaw cycles

When the concrete specimens had reached an age of 28 days, they were exposed to a pre-defined number of freeze-thaw cycles in an appropriate chamber. These tests were run according to the Chinese standard GB/T 50082–2009 [8]. In this case one cycle of freezing and thawing lasts about 2 1/2 hours. The temperature of the cooling box varies between + 20 ± 2 °C and − 20 ± 2 °C. The temperature in the center of the concrete specimens varies under the given conditions between + 8 ± 2 °C and − 15 ± 2 °C. The measured temperature change as function of time t under the given conditions are shown in Fig. 1. The dynamic elastic modulus E_d has been determined via the measured pulse velocity after 10, 25, 50, 75 and 100 freeze-thaw cycles. The influence of freeze-thaw cycles on porosity and pore size distribution was determined by mercury intrusion porosimetry (MIP).

In the following, specimens will be characterized by the type of concrete (A, C, and CA) and the number N of freeze-thaw cycles to which they were exposed, as for instance specimens prepared with concrete Type CA after exposure to 100 freeze-thaw cycles will be called "CA ($N = 100$)".

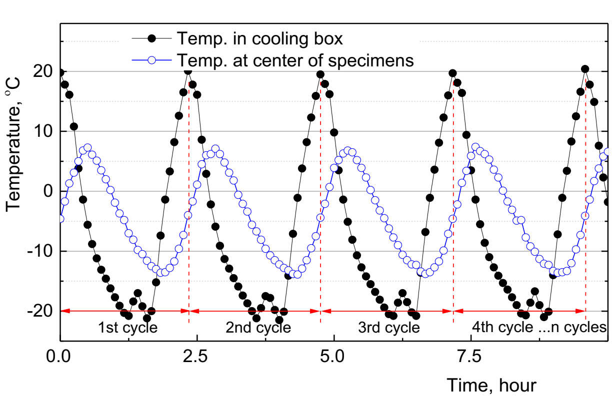

Fig. 1. Temperature T in the cooling box and at the center of the concrete specimens as function of time t.

2.3. Capillary absorption and chloride penetration

Concrete cubes, which were exposed to 0, 10, 50, and 100 freeze-thaw cycles, were cut into two halves. All half cubes were then first dried in a ventilated oven at 50 °C until constant weight was reached. Then the four side surfaces (50 × 100 mm) were covered with aluminum foil. The cast surface (100 × 100 mm) of the dry concrete specimens was then brought into contact with water. The water surface was kept constant at approximately 3 mm above the surface of the concrete specimens by a special support. The mass of the water absorbed by capillary action was determined after 0.5, 1, 2, 4, 8, 12 and 24 h by weighing.

In addition, concrete specimens after a certain number of freeze-thaw cycles were put in contact with an aqueous 3% NaCl solution for testing chloride penetration. After 3, 10 and 100 days, thin layers of 1 mm thickness were milled consecutively from the surface, which was in contact with the salt solution. The chloride content of the powder, obtained in this way, was finally determined by titration.

2.4. Neutron radiography

After exposure to a given number of freeze-thaw cycles, concrete prisms were taken out of the frost chamber. Cubes with an edge length of 100 mm were cut from the concrete prisms. In addition, two opposite layers with a thickness of 25 mm were cut from the obtained cubes. Finally, the obtained block with the dimensions of 100 × 100 × 50 mm was cut into five slices with a thickness of approximately < 20 mm. This cutting sequence to obtain specimens with dimensions of approximately 100 × 50 × 20 mm is schematically shown in Fig. 2. The two slices near the two opposite surfaces were numbered with 1, followed by slices 2 and 3. The thin slices obtained in this way were then dried in a ventilated oven at 50 °C until constant weight was attained. Then four surfaces were covered with aluminum foil leaving two opposite surfaces with the following dimensions free: 20 × 100 mm. One of the two surfaces was then put in contact with water and with 3% NaCl solution respectively.

The penetration of water was visualized by neutron radiography. These tests were run at Paul Scherrer Institute (PSI) in Switzerland [9,10]. In the neutron beam samples were imaged serially by a cooled slow-scan CCD camera system. After the first image had been taken in the dry state the aluminum container was filled with water with a level of about 3 mm above the bottom surface of the specimen. Then neutron images were taken again after 4 h. From the attenuation of the neutron beam, which passes through the concrete slice the local moisture content can be obtained. For the quantitative evaluation of the neutron images, neutron signal transfer analysis was used, in which a scattering correction based on Point Scattered Function (PScF) was applied. More details on the technique of NR and the quantitative analysis can be found in references [11–14].

3. Results and discussion

3.1. Compressive strength and elastic modulus

Compressive strength was determined by means of a servo-controlled testing machine. The results obtained for all three types of