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Effects of Interaction of Static Load and Frost on Damage Mechanism of Concrete Elements

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Frost damage is typical material deterioration in concrete structures subjected to external environmental conditions. However, the weather conditions do not make the sufficient factor causing the worsening of the concrete properties. Concrete structures with frost damage in service are subjected to loadings. The investigation was carried out with the primary objective to assess the influence of interaction of mechanical load and freeze-thaw cycles on damage process of concrete. The salt scaling process was observed for beam specimens subjected to cyclic freezing and thawing in third-point loading condition. The damage development due to internal cracking was monitored using fracture mechanics parameters.

Keywords: *concrete, cyclic freezing and thawing, scaling, bending, fracture mechanics, interaction.*

1. Introduction

Under severe freezing climate conditions, frost action is probably the most important cause of deterioration of exposed concrete structures. Even in structures with air-entrained concrete, frost damage can occur under certain circumstances. Usually, the weather conditions do not make the sufficient factor causing the worsening of the concrete properties. Damage evolution as well as the concrete resistance to freezing and thawing have been of great concern of researchers for many years (Pigeon *et al.* 1996, Jana 2004, Pentala 2006, Valenza and Scherer 2007).

Two types of damage to concrete may occur as a result of cyclic freezing and thawing:

- surface scaling,
- internal cracking.

Surface scaling is generally found where the surface of concrete is subjected to weak solutions of salt, typically used for de-icing purposes. Internal freeze-thaw damage results from expansive stresses generated by water on freezing when the pore structure of the concrete is saturated above a critical value, and leads to internal microcracking. Internal damage, which is likely to occur in concrete subjected to long-term wet/saturated conditions (Fagerlund 2002), is manifested macroscopically by irreversible tensile deformation and randomly oriented microcracking (Pigeon *et al*. 1996). Hence, the freezing and thawing action can be looked upon as a very complex fatigue crack propagation process (Hasan *et al*. 2008).

The most of previous works on the freeze-thaw durability of concrete have been focused on the mechanical property degradation (e. g. modulus and strength), weight change, length change, microstructural change or ultrasonic signature change after different numbers of freeze-thaw cycles, sometimes in the presence of salt solution (Cao and Chung 2002). Performance deterioration caused by a monodamaging process, such as freeze-thaw, is not consistent with real conditions to which concrete structures are actually exposed. It has been found that the deterioration of concrete could be accelerated when subjected to multidamaging processes, e. g. simultaneously exposed to external load, freeze-thaw cycles and chloride or sulphate attack. It is necessary to understand how the resulting stresses influence the concrete resistance to freezing and thawing. However, there are very few test results considering the effects of interaction of mechanical loading and cyclic freezing and thawing, and in large part, they concern the effect of internal damage on concrete properties (Zhou *et al.* 1994, Sun *et al*. 1999, Yu *et al.* 2008).

The analysis of research results, described in literature, has showed there is the lack of information concerning the influence of the tensile stress on the typical process of surface scaling due to freezing liquid contact with selected surface of element tested, which is the frequent situation in service life of concrete and reinforced concrete structures (Şahmaran and Li 2007). Since salt scaling is superficial, it does not affect mechanical integrity of a concrete body. However, this damage renders material susceptible to ingress of moisture and aggressive species that threaten durability (Valenza II and Scherer 2007).

The concrete is a heterogeneous material of high compressive strength, but its resistance to cracking is low. The destruction of concrete under the influence of external loads is affected, among other things, by material discontinuities, disruptions, and local differences in mechanical properties of material. The local accumulations of stress caused by external pressures occur in the vicinity of concrete defects (Gettu et al. 1990, Jenq and Shah 1991). They can cause violent propagation of damage, and finally lead to the destruction of the entire element. The most dangerous concentrators of stress are the tips of cracks where the greatest stress values are achieved (Schlangen and Garboczi 1997).

In the progress of freezing and thawing, recurrent frost expanding and penetration compressive stress act on concrete, each cycle produce freeze-thaw inner stress in concrete interior, the stress causes inner flaws of concrete expand, accumulate and form new damage. Freeze-thaw cycles and loads are both repetitive actions that cause accumulated physical damages in concrete. As the essential development and important supplement of fracture mechanics, damage mechanics is the part of material structure distortion and wreck theory, it emphasize the influence of material damage to mechanical properties, also the evolutive process and rules of materials or structure damage. Fracture mechanics can help analyze the response of microstructure to external load (Shah et al. 1995, Bažant 2002, Wang et al. 2010). So, it is reasonable and feasible to study the freeze-thaw damage rules of concrete by using fracture mechanics parameters. The critical stress intensity factor and the critical crack tip opening displacement, along with the Young's modulus, are sufficient to characterize the fracture resistance of concrete. The methods of fracture mechanics were approved in structural design by the latest proposal of CEB-FIP Model Code (2010).

Two different approaches to the estimation of cyclic freezing and thawing influence on concrete properties were presented in the paper. The analysis of interaction of load and freeze-thaw cycles with chloride exposure regime on surface scaling process of concrete was performed. The fracture parameters were used to assess the internal cracking progress in concrete. The investigation was not intended to perfectly simulate loading and exposure conditions, but to begin to make the preliminary understanding about the complex deterioration mechanisms of concrete in real service life conditions.

2. Methods

Specimen preparation

The tests were carried on for non-air-entrained concrete as well as for air-entrained concrete. The cement (CEM I 42,5) content in concretes tested was constant – 350 kg/m^3, and water to cement ratio was equal to 0,40. The natural aggregate with maximum diameter of 8 mm was used. The air-entraining agent content was 0,10% related to cement mass. After demoulding the specimens were stored in water with temperature 20 ± 2 °C. The compressive strength, tested after 28 days of curing, was equal respectively 59,7 MPa for non-air-entrained concrete and 55,2 MPa for concrete with AEA.

Estimation of scaling resistance

The specimens sizes were 80×120×1100 mm. Every series was composed of 3 replicates. The concrete resistance to surface scaling due to cyclic freezing and thawing with de-icing salt saturation (3% NaCl solution) was determined using the procedure described in PKN-CEN TC 12390-9:2007. In order to realize the interaction of freeze-thaw cycles and load the beam specimens were tested in third-point loading condition. The load was realized using lever gears. The tensile stress ratio c was 0,0 (control specimens); 0,17 and 0,50 with respect to the failure stress. The arrangement of test stand was presented in Fig. 1.

The scaled material was collected from the top surface of specimen, which was subjected to tensile stress. The de-icing salt solution was kept on the top of specimen thanks to the rubber sheet glued to all surfaces of the specimen except the test surface. The edge of the rubber sheet reached 20 mm above the test surface. Top specimen surface (total area for every specimen was equal to 45000 mm^2) was saturated with demineralized water during 72 hours. Immediately before the specimens were placed in the freezing chamber, the demineralized water was replaced with 3% NaCl solution. The freezing medium was prevented from evaporating by applying a flat polyethylene sheet. The loading devices with specimens were placed in freezing chamber.

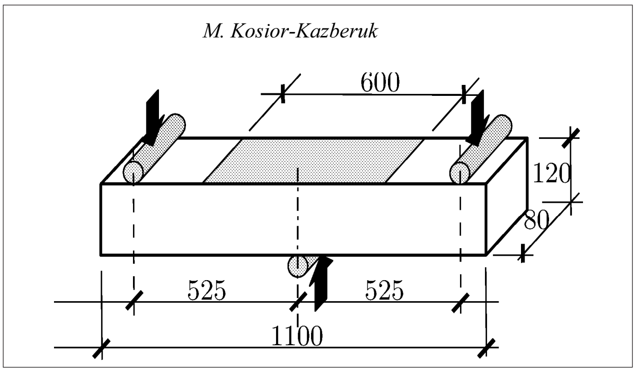

Fig. 1. *Sketch of specimen subjected to three-point bending test*

The single cycle duration was 24 hours with temperature change from 20 °C to – 18 °C. Every 7 days NaCl solution was exchanged. The material that scaled from the test surface was collected and dried to constant weight. The amount of the scaled material per unit area after n cycles m_n was evaluated for each measuring occasion and each specimen. The specimens were subjected to 56 freeze-thaw cycles, the number suggested for unmodified concrete.

Fracture parameters determination

The specimens for fracture parameters evaluation were subjected to cyclic freezing in air and thawing in water. The temperature changed from -18 °C to 18 °C. The duration of single cycle was 8 hours and the freezing period duration was 6 hours. The freezing and thawing process was finished 1 day before testing.

The critical stress intensity factor K_{Ic}^{s} and the critical crack tip opening displacement $CTOD_c$ were determined using procedure described in RILEM draft recommendation (1990), based on the fracture model elaborated by Jenq and Shah (1985). The fracture parameters were assessed in three-point bend test on beams with initial notches. The specimen sizes were 100×100×400 mm, and the initial saw-cut notch depth was equal to 30 mm and width was 3 mm. The geometry of specimen and the way of load were presented in Fig. 2a. Each series was composed of 4 replicates.

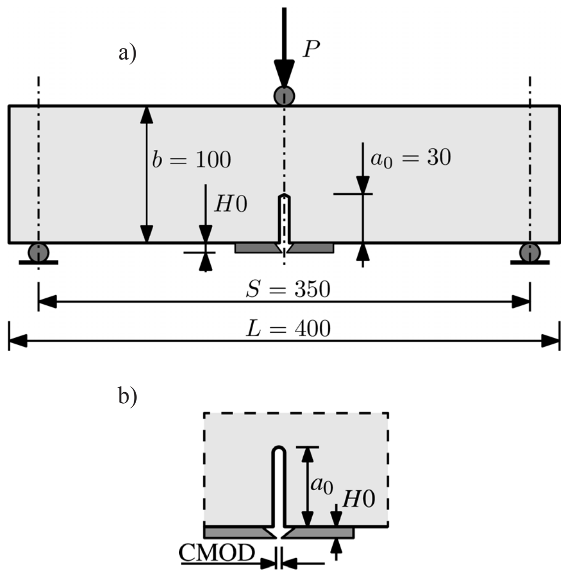

Fig. 2. *Fracture testing configuration and geometry of specimen: (a) the way of load; (b) the place of CMOD measurement*

The closed-loop testing machine with crack mouth opening displacement (*CMOD*) as the feedback signal was used to achieve a stable failure. The crack mouth opening displacement and the applied load were recorded continuously during the test. The *CMOD*, indicated in Fig. 2b, was measured by means of clip gauge. To measure the crack mouth opening displacement (*CMOD*) a pair of knife edges was attached to two sides of a notch performed on the lower surface of the beam. The rate of loading was controlled by a constant rate of increment of *CMOD* so that the peak load was reached in 5 min.

The beam was monotonically loaded up to the maximum load. The applied load was reduced after the load passed the maximum value and was at about 95% of the peak load. Then, the applied load was reduced to zero and the reloading was applied. The specimen was cyclically loaded up to failure.

After the initial cycle, each loading and unloading cycle was finished in about 1 min. The test result is a load-*CMOD* curve with several loading-unloading cycles. Based on the load-*CMOD* relation, the fracture parameters and Young's modulus can be calculated. The *P-CMOD* curve was prepared for each specimen. Typical test result (obtained for control concrete without AEA) was presented in Fig. 3.

According to RILEM recommendations (1990) the Young's modulus E is calculated from the equation

$$E = 6Sa_0V_1(\alpha_0)/[C_i d^2 b], \tag{1}$$

Where C_i is the initial compliance calculated from load-*CMOD* plot (Fig. 3), S, a_0, d, b are geometrical characteristics of specimen.

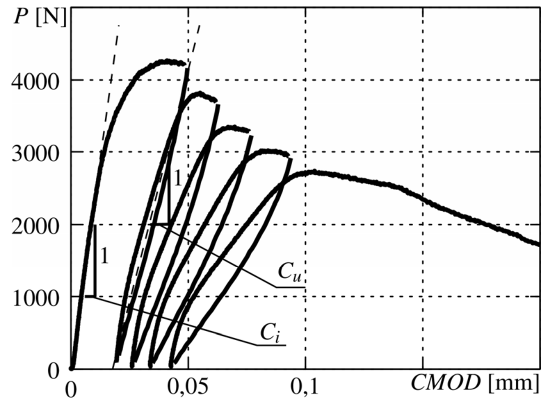

Fig. 3. *Typical experimental load-CMOD plot*

The critical effective crack length a_c ($a_c = a_0$ + stable crack growth at peak load) is determined from Equation (1) for calculated value of Young's modulus and the unloading compliance C_u measured at the maximum load (Figure 3). Using an iteration process, the critical effective crack length a_c is found when Equation (2) is satisfied:

$$E = 6Sa_cV_1(\alpha_c)/[C_u d^2 b], \tag{2}$$

The critical stress intensity factor is calculated according to relationship

$$K_{Ic}^{s} = 3(P_{\max} + 0{,}5W)\frac{S\sqrt{\pi a_c}F(\alpha_{c1})}{2d^2 b}, \tag{3}$$

where P_{max} – the measured maximum load, $W = W_0 S/L$, and W_0 – self-weight of the beam.

The critical crack tip opening displacement is calculated as:

$$CTOD_c = \frac{6(P_{\max} + 0{,}5W)Sa_cV_1(\alpha_{c1})}{Ed^2 b}\times$$
$$\times\left[(1-\beta)^2 + (1{,}081 - 1{,}149\alpha_{c1})(\beta - \beta^2)\right]^{1/2}, \tag{4}$$

in which $\beta = a_0/a_c$.

In Equations (1), (2), (3), (4) $V_1(\alpha_0)$, $V_1(\alpha_c)$, $V_1(\alpha_{c1})$, $F(\alpha_{c1})$ are geometric functions, described in details by Shah *et al*. (1995).

Simultaneously, the changes in compressive strength due to frost action were monitored, using cubic specimens 100×100×100 mm, subjected to the same freeze-thaw regime as specimens for fracture parameters testing.

3. Results and Discussion

Scaling resistance of concrete subjected to static load

The test results for both non-air-entrained and air-entrained concretes are presented in Fig. 4 and 5.

The analysis of test results showed the significant influence of considered range of stress on the increase in mass of material scaled from the specimen surface subjected to cyclic freezing and thawing. The increased susceptibility to surface scaling was observed for both concretes, with and without air-entraining admixture, although, the dosage of AEA assured very good scaling resistance for control unload concrete specimens. The influence of the tensile stress on scaling was observed after 14 cycles of the freezing and thawing. The differences in mass of material, scaled from specimens subjected to various stress levels, increased together with the number of cycles. Besides, for specimens loaded the greater scatter of measurements was noticed.

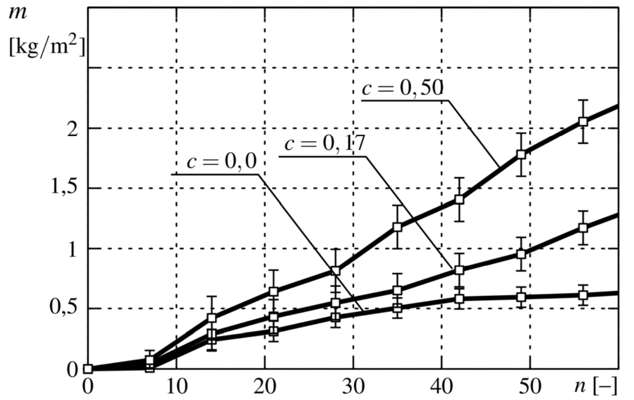

Fig. 4. *Mean mass of scaled material m vs. freeze-thaw cycles number n as well as stress level c for non-air-entrained concrete*

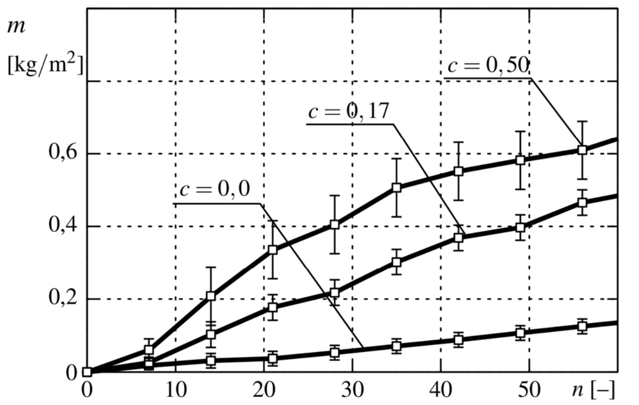

Fig. 5. *Mean mass of scaled material m vs. freeze-thaw cycles number n as well as stress level c for air-entrained concrete*

In case of the unloaded concrete specimens, after the initial rapid growth in mass of scaling, the slowdown of the process was observed and then the mass of scaling accumulated gradually. For loaded concrete specimens, the mass of the scaling increase was almost linear together with the number of cycles, for both stress levels. After 28 cycles the mass of scaled material for stress level c = 0,17 was ca. 30% greater, and for c = 0,50 twice greater in comparison to the scaling from unloaded concrete surface. After 56 cycles, the loss in material for lower stress level was twice greater and for higher stress – more than three times greater than the mass of scaling for unloaded concrete.

In case of the air-entrained concrete, the greater relative difference in mass of material scaled from concrete subjected to load was pointed out in comparison to control concrete. The tensile stress level c = 0,17 caused four times increase and stress level c = 0,50 – five times increase in the amount of scaled material. However, the air-entraining of concrete influenced the limitation of the susceptibility for scaling in comparison to the concrete without admixture. In considered range of external load of specimens in third point bending test, the rate of damage progress increased with the increase in applied stress value.

Considering the mass of scaled material after n cycles as a measure of accumulated damages, it is possible to evaluate the number of cycles after that, the scaling achieves unacceptable volume, for assessed stress level. Unacceptable level of scaling can be determined arbitrarily, regarding durability requirements, or on the basis of standards for different concrete elements. The dependence can be useful for predicting concrete ability to scaling according to the tensile stress level.

Changes in fracture parameters of concrete due to cyclic freezing and thawing

The fracture parameters were determined on the basis of *P–CMOD* curves obtained for concrete specimens. The effect of freezing and thawing on concrete properties was referee to the results obtained for reference specimens cured in water. The force *P* plotted versus *CMOD* measured for air-entrained concrete after 350 cycles and control concrete were presented in Fig. 6.

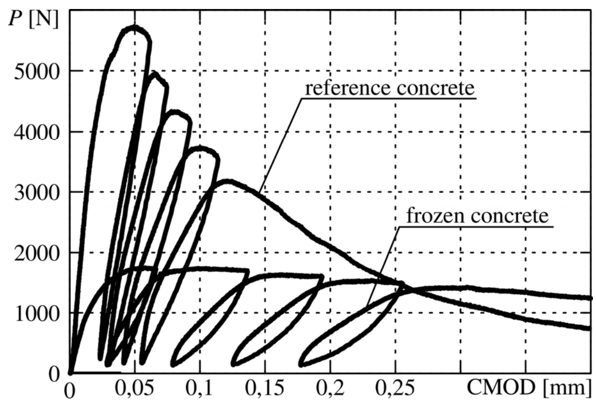

Fig. 6. *P–CMOD curves for air-entrained concrete after 350 cycles and reference concrete cured in water*

From the *P–CMOD* plot, one can see that the initial part of the curve for reference concrete is almost linear and the strain of the notch tip under tension increases with increasing load. After the linear portion of *P–CMOD* curve, deviation from linear response is observed and the tension strain reaches the maximum value, which indicates the onset of crack initiation at the tip of the notch. After the point of maximum tension, the curve exhibits increasing load until reaching the peak. Therefore, the load at which the tension reaches its maximum value is the initial cracking load. For extremely damaged concrete, the linear portion of *P–CMOD* curve is very short, the maximum load is achieved quickly, and the strain softening is observed. In the process of degradation the concrete behaviour is more ductile in

Table 1. *Properties of concrete without air-entraining agent*

Feature	90 cycles		150 cycles		200 cycles	
	frozen	reference	frozen	reference	frozen	reference
P_{max} [N]	3900	3850	4415	5100	4300	5000
a_c/d [-]	0,397	0,412	0,446	0,458	0,438	0,433
K^s_{Ic} [MN/m$^{3/2}$]	1,033	1,003	1,366	1,536	1,060	1,239
$CTOD_c$ [m×10^{-5}]	1,377	1,403	1,758	1,763	2,014	1,428
E [MPa]	21015	24143	28125	35117	17092	36214
f_{cm} [MPa]	66,0	61,8	50,1	65,8	37,5	67,8

comparison to reference concrete but the maximum load (P_{max}) is strongly limited.

The fracture parameters and $CTOD_c$ as well as the measured maximum load P_{max}, the critical effective crack length a_c related to depth of specimen d, Young's modulus E and compressive strength f_{cm} determined for concrete without AEA and for air-entrained concrete were presented in tables 1 and 2, respectively. The results for frozen as well as reference specimens were given.

The specimens of non-air-entrained concrete were subjected to 200 cycles of freezing and thawing. The fracture parameters undergo greater changes than compressive strength under frost attack. After initial slight improvement of properties, the fracture parameters were influenced by frost action. For frozen specimens the value of K^s_{Ic} decreased and the $CTOD_c$ increased, which means that the fracture process (stable crack propagation) appeared for greater crack opening displacement. After 150 cycles the reference concrete was characterized by higher critical stress intensity factor and higher value of Young's modulus than frozen concrete, but the values of $CTOD_c$ were comparable for both of them. After 200 cycles significant decrease in the mechanical as well as fracture properties of concrete subjected to freezing and thawing was found.

Table 2. *Properties of concrete with air-entraining agent*

Feature	200 cycles		350 cycles	
	frozen	reference	frozen	reference
P_{max} [N]	5230	5450	1750	5750
a_c/d [-]	0,430	0,423	0,434	0,424
K^s_{Ic} [MN/m$^{3/2}$]	0,763	0,841	0,274	0,887
$CTOD_c$ [m×10^{-5}]	1,626	1,510	1,911	1,693
E [MPa]	31940	34080	9350	32190
f_{cm} [MPa]	59,5	62,4	29,0	61,5

The specimens of air-entrained concrete were subjected to 350 cycles. The results presented in table 2 show similar changes in fracture parameters to the concrete without AEA. The concrete microstructure deterioration due to freezing caused the decrease in the maximum load, critical stress intensity factor, Young's modulus and the increase in the critical crack tip opening displacement.

Generally, the air-entrained concrete is characterized by smaller value of K^s_{Ic} than non-air-entrained concrete. The air-void system resulting from air-entraining treatment forms additional pores in concrete microstructure, which are the stress concentrators responsible for fracture.

Even though the concrete is recognized to be quasi-brittle material (Gettu et al. 1990), in the process of degradation the material showed more ductile characteristics than reference concrete. Through experimental study presented, it was found that steady crack propagation stage exist before unstable fracture. The longer critical effective crack length a_c and greater value of $CTOD_c$, needed for failure, is characteristic for damage concrete. Similar changes in concrete behavior were noticed by Hanjari *et al.* (2011) during bond properties examination and by Li *et al.* (2011) during testing the flexural fatigue influence on concrete frost resistance.

Conclusions

Two types of concrete damage due to cyclic freezing and thawing were studied. The interaction of load and freeze-thaw cycles with chloride exposure regime on surface scaling process of concrete was analyzed. The internal cracking progress in concrete was characterized using fracture parameters. The tests were carried on for non-air-entrained as well as for air-entrained concretes.

As the results of investigations, it was found that interaction of load and cyclic freezing and thawing in the presence of de-icing salt accelerates the process of surface scaling of concrete. In considered range of stress subjected to beams in three-point bending test, the rate of damages accumulation increased with the increase in stress, but the rate of damage accumulation was changing during long-term test.

The complete *P–CMOD* curves were measured from fracture tests on both frozen and reference concrete specimens. The fracture parameters of concrete were strongly influenced by cyclic freezing and thawing. It was found that the material damaged, due to cyclic freezing and thawing, is more ductile than undamaged one. The critical stress intensity factor and crack tip opening displacement can be valuable measures described the concrete degradation due to accumulation of physical damages in its microstructure.

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