Zeszyty Naukowe Politechniki Częstochowskiej
Budownictwo
ISSN 0526-5916

Zeszyty Naukowe Politechniki Częstochowskiej nr 26 (2020), 12-17
DOI: 10.17512/znb.2020.1.02

Stress intensity factor in the assessment of frost degradation of high-strength fibre-reinforced concretes

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ABSTRACT:
The paper presents an assessment of the degradation of cyclic freeze/thaw on high-strength concretes, based on changes in the stress intensity factor K_{IC}. The degree of HSC destruction due to cyclic freeze/thaw was determined by the longitudinal modulus of elasticity E, weight loss, and wall strength reduction, determined after 150, 250, 300, and 350 cycles and the total mass of surface scaling after 28 and 70 cycles. The degree of degradation was compared with the modification of stress intensity factor values. Three types of high-strength concretes (compressive strength about 90 MPa) were tested: concrete without fibres, concrete with steel fibres in the amount of 0.5% by volume (39 kg/m^3) and concrete with a mixture of steel fibres (19.5 kg/m^3) and basalt (6.8 kg/m3). The testing methodology is based on RILEM recommendations [1] and ASTM C666 [2] and PKN – CEN/TS 12390 Slab Test [3].

KEYWORDS:
high-strength concrete; fibres; concrete degradation; stress intensity factor; surface scaling

1. Introduction

Modern building design focuses on ensuring the durability of the structure while ensuring the economic use of materials. By using high-strength concretes, it is possible to limit the geometry of vertical structural elements and the degree of reinforcement [4]. Factors of the external environment may lead to slow degradation of concrete elements, which in the long term, |results in the deterioration of their load capacity. One of the common causes that initiates the destruction of concrete elements is cyclic freeze/thaw. This leads to an accumulation of significant stresses, which in effect causes cracks to form. Moreover, high-strength concrete is brittle and contains a large number of structural defects, the presence of which is difficult to predict at the stage of construction design [5].

The addition of steel fibres to high-strength concrete leads to modification of the material from quasi-brittle to quasi-plastic. Steel and basalt fibres transfer the loads acting on a given heterogeneous concrete element, due to a much higher value of steel modulus of elasticity in comparison to Young's modulus of concrete. The stresses at the crack ends are reduced and the propagation of micro-scratches is limited [6]. The degradation process is stopped. Currently, methods are being searched for that will enable a good indication of the state of destruction in high-strength concretes as a result of cyclic freeze/thaw. The basic dimensions of structural elements are based on the assumption that the materials constitute an ideal continuum, do not contain defects, discontinuities, or changes of the structure resulting from the influence of external conditions [7]. The results of conducted analyses are characterized by considerable randomness. Internal defects occurring in the material, together with the progress of the service life, may affect the significant deterioration of strength parameters. Initial discontinuities and

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losses of material are the beginning of fracture development, and together with the accompanying destructive impact of the environment may lead to a catastrophic failure of the structure. Cyclic freeze/thaw harms the modulus of elasticity of concrete and tensile strength [7]. Research on the possibility of using the parameters of fracture mechanics for the assessment of frost degradation in regular concretes is presented in the paper [8]. The combined analysis of fracture mechanics parameters characterizing high-strength concretes and the degree of degradation resulting from cyclic freeze/thaw leads to a more complete description of events occurring in the structure of this type of concrete. Many studies were carried out on the influence of fibres on the improvement of mechanical parameters and the durability of normal concretes. However, there are few studies on the benefits of adding fibres to high-strength concretes. Studies on the influence of hybrid fibres on high-strength concrete are presented in [9]. Numerous advantages of mixing steel fibres of different dimensions indicate the potential to achieve an optimal composition of the HSC mix [10]. A comparative analysis of mechanical parameters of high-strength fibre-reinforced concrete compared to HSC without fibre addition was also carried out in the study [11]. According to [6], the addition of 2% of high-strength steel and polyolefin fibres to the concrete significantly improves its resistance to fracture.

The studies presented in this paper led to the assessment of the relationship between the frost resistance of high-strength concrete and the stress factor K_{IC} after 150, 200, 250, 300, and 350 freeze/thaw cycles. High-strength concrete without fibres and concrete with 0.5% steel fibres and a mixture of steel and basalt fibres, each 0.25% by volume, were analysed. Both the internal frost resistance of HSC and the resistance to surface scaling in the presence of a 3% solution of salt, in the concentration state, were tested. The analyses were based on RILEM recommendations [1], ASTM C666 [2] and PKN-CEN/TS 12390 [3]. To determine the stress intensity factor, the post-dependence of force as a function of deformation under three-point bending conditions was performed.

2. Experimental program

2.1. Materials and preparation of specimens

High strength concrete with an average compressive strength of 90 MPa was tested. The concrete mix consisted of portland cement CEM I 42.5 R in the amount of 440.5 kg/m^3, keeping a constant water-bonded point (0.31) in all series of test pieces. Polypropylene gravel aggregate with a grain size up to 11 mm was used. The consistency of the mixture at the S3 level was provided using a super-plasticizer based on polycarboxylates with a density of 1.085 g/cm^3, appropriately dosed depending on the addition of dispersed fibres to the concrete. The super-plasticizer content ranged from 1.65% in concrete without fibres to 1.85% in the case of HSC with fibres. To obtain increased concrete strength and tight structure, silica dust, representing 7% of binder volume, was implemented. Three series of samples were made: B1 - HSC concrete without fibres, B2 - HSC with 50 mm long steel fibre-diffused reinforcement, and B3 - high-strength concrete with 50 mm steel fibre and 50 mm basalt fibre mixture. The addition of steel fibres in the B2 mix was 0.5% (39 kg/m^3), while the addition of steel fibres in the B3 mixture was 0.25% (19.5 kg/m^3) and basalt fibres 0.25% (6.75 kg/m^3).

To determine the stress intensity factor and changes in the modulus of elasticity of the HSC, 12 test pieces of 10 x 10 x 40 cm were prepared, all of them notched with a circular saw. The initial notch, 30 mm deep and 3 mm wide, was made in the middle of the beam span. The frost resistance of HSC, as changes in compressive strength and weight loss after freeze/thaw cycles, was tested on 10 cm cubic samples. Resistance to surface scaling under stress conditions was determined using 110 cm long prisms and a cross-section of 12 x 8 cm. After 24 hours from the preparation, the test elements were stripped off and until the beginning of the individual tests they were kept in a water bath at 18 (+/–2)° C. In the analysis of the resistance to surface scaling of HSC, the specimens were loaded with weights of mass amounting to 25% of the destructive force determined in the flexural tensile strength test.

2.2. Test methodology

The stress intensity factor is a measure of a material's resistance to brittle fracture. In a flat stress condition, it characterizes the stress state around the tip of the original crack and, as a material constants, it characterizes the material's susceptibility to fracture development and scratching due to exploitation [12]. The fracture mechanics parameter K_{IC} was determined on the basis of the RILEM TC 89-FMT recommendation [1], under three-point bending tests. The force was applied in such a way that the maximum load is reached within five minutes from the start of the test. The load was carried out by adjusting the displacement of the piston, at an average speed of 0.012 mm/s. The frost resistance of HSC was determined on the basis of the measurements of compression strength decrease and mass loss of cubic samples and control of changes in the *DF* prism durability factor, based on the ASTM C 666 method [2]. The test pieces were frozen in air at –18 ±2°C for 4 hours and thawed in water at +18 ±2°C for 4 hours. Concrete series B1 and B2 were subjected to 350 freeze/thaw cycles. In the case of the B3 series of concretes, the cyclic freeze/thaw was carried out until the moment of loss of frost resistance of these concretes, determined by the non-destructive method after 150 cycles. After this time, numerous cracks and surface scratches were also observed. The control of resistance to surface scaling, based on the Slab Test method PKN-CEN/TS 12390 [3], was carried out for B1, B2, and B3 series after 28 freeze/thaw cycles and after 70 cycles for B1 and B3 series.

3. Results and discussion

Figure 1 shows a comparison of changes in the durability factor *DF*, characterizing the frost resistance of concretes, and the stress intensity factor K_{IC}, representing the fracture mechanics parameters of the analysed B1, B2 and B3 series subjected to cyclic freeze/thaw. Based on the diagrams below, a correlation between the changes of *DF* and K_{IC} values is noticeable. In concretes of the B1 series after 150 freeze/thaw cycles, with the number of cycles increasing, the value of stress intensity factor raised, reaching about a 6% increase after 350 cycles, with a simultaneous increase of durability factor value by 1%. The increase in the durability factor resulted from the increase in concrete strength over time while maintaining its resistance to cyclic freeze/thaw. High-strength concretes with the addition of steel fibres (B2) were characterized by a simultaneous decrease of stress intensity index value by 28% and *DF* factor value by 3% after 150 freeze/thaw cycles and then an increase of K_{IC} value by 18% and *DF* index value by 1% after 350 freeze/thaw cycles. In the case of the B3 series (high-strength concretes with steel and basalt fibres), after 150 freeze/thaw cycles there was a loss of both durability – a decrease of *DF* factor by over 78% and mechanical properties – and a reduction of K_{IC} by over 80%.

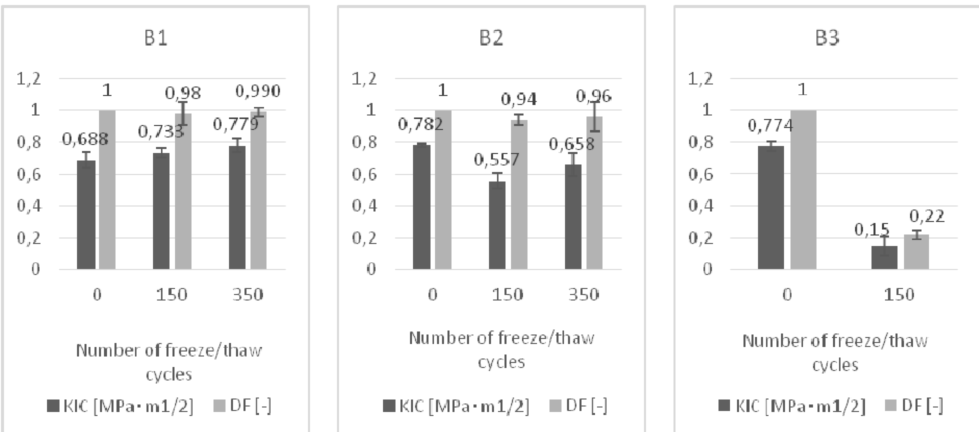

Fig. 1. Changes in K_{IC} and *DF* stress factor as a result of cyclic freeze/thaw

Instead of stopping the propagation of internal fractures in the concrete, basalt fibres have contributed to the formation of numerous poor areas in the concrete due to the lack of bonding between basalt fibre and the concrete.

Changes in the modulus of elasticity of the tested high-strength concretes due to cyclic freeze/thaw after 50, 100, 150, 200, 250, 300 and 350 cycles are shown in Figure 2. In the case of concretes without fiber addition (B1) and HSC with steel fibres (B2), after 350 freeze/thaw cycles, no significant changes in the modulus of elasticity were observed, which varied around value 1. High-strength concrete with a mixture of steel and basalt fibres after 150 freeze/thaw cycles undergoes frost degradation, with a significant decrease in the modulus of elasticity to 90%. Cracks occurred on the surface of the test elements. The reason for the lack of resistance to cyclic freeze/thaw of high strength concretes with a mixture of steel and basalt fibres may be the loss of continuity of the layer that the basalt fibres were coated with.

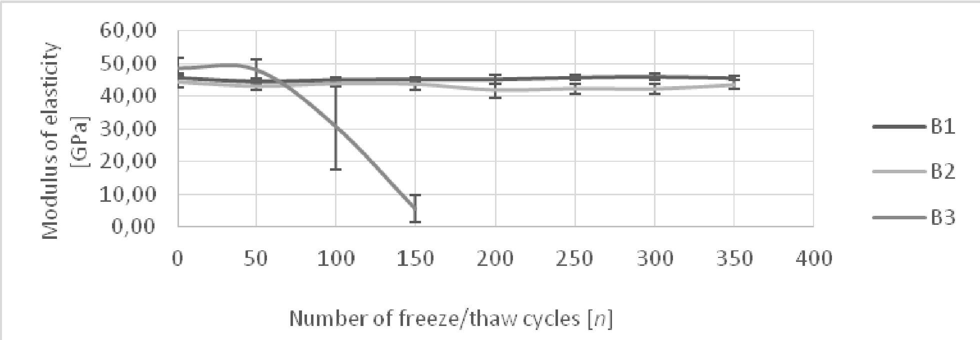

Fig. 2. Changes in modulus of elasticity with the number of freeze/thaw cycles

The decrease in the modulus of elasticity is also related directly to the reduction in the compressive strength of the B3 series, which is more than 15%, as shown in Figure 3. The analysis of the cyclic freeze/thaw cycles for the B1 series showed a compression strength reduction of more than 8% and a weight loss of 1.5%, as shown in Figure 4. In the case of HSC with steel fibres, the strength after 350 freeze/thaw cycles was reduced by more than 13%, and the weight of the samples was reduced by less than 1.5%. High strength concrete series B1 and B2 did not show frost degradation after 350 freeze/thaw cycles.

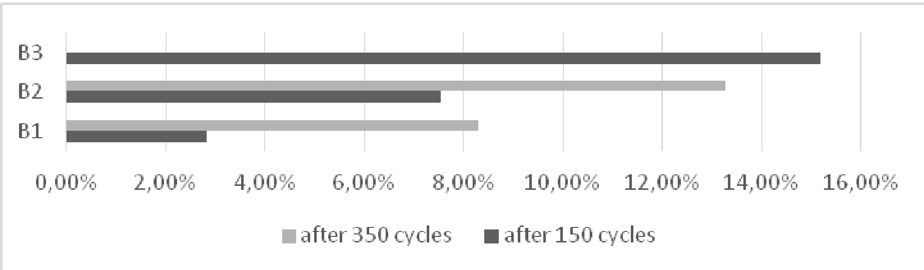

Fig. 3. Reduction of compression strength due to frost degradation of HSC

The analysis of the resistance to surface scaling of HSC is shown in Fig. 5. After 28 freeze/thaw cycles, based on the Slab Test [3], the highest mass of surface scaling was recorded for high-strength concretes without fiber addition (B1). The rest of the HSC series showed similar values of total masses of surface scaling at 0.02 kg/m^2. None of the HSC series showed zero resistance to surface scaling in the presence of a 3% salt solution under stress conditions after 28 freeze/thaw cycles. In the case of HSC without the addition of fibres (B1), after 70 freeze/

thaw cycles there was an increase in the total mass of surface scaling by more than 50% compared to the values achieved after 28 days, but still, after this period the concrete surface did not undergo significant degradation. High-strength concrete shows a long-term resistance to surface scaling in the presence of a de-icing agent, while the addition of fibres that bridge internal fractures contributes to enhancing the frost resistance of HSC, providing a tight structure and surface that retains its durability and aesthetic appearance.

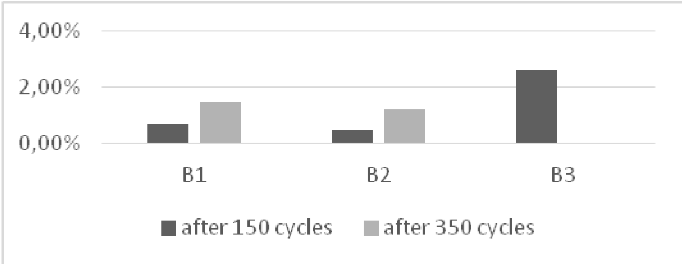

Fig. 4. Weight loss due to frost degradation of HSC

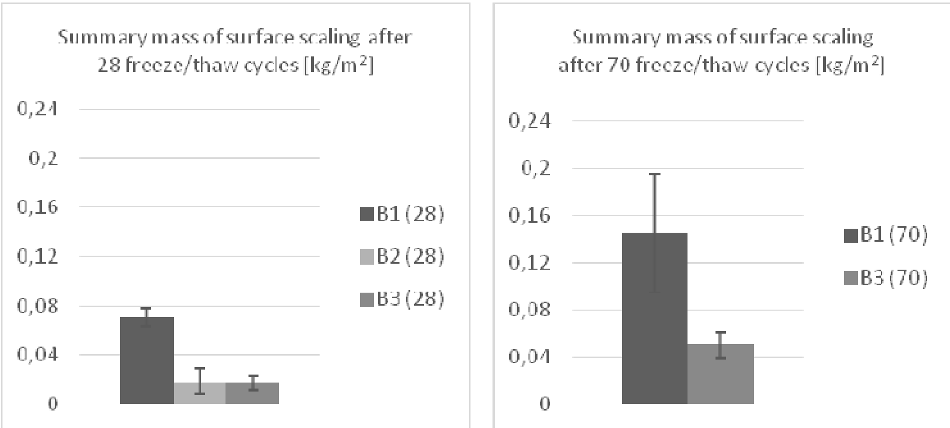

Fig. 5. Total mass of surface scaling after *n* freeze/thaw cycles

4. Conclusions

Changes in the mechanical properties and durability of HSC resulting from cyclic freeze/thaw can be presented using the fracture mechanics parameter K_{IC}, which is a material property constant. The stress intensity factor after 150/350 freeze/thaw cycles changes respectively to the modification of the durability factor *DF* in high-strength concrete with the addition of mixed fibres (B3). Cyclic freeze/thaw led to degradation of concretes with mixed steel and basalt (B3) fibres after 150 cycles. The reason for the destruction of the B3 series concretes was the poor adhesion of basalt fibres to concrete and non-cooperation with steel fibres in the cement matrix. In the case of HSC without fibres (B1), an improvement in fracture mechanics parameters, described by the K_{IC} factor, becomes noticeable after being subjected to cyclic freeze/thaw, with a negligible decrease in the modulus of elasticity by about 4% and a slightly decreased mass (1.5%) and compressive strength (8.3%). In the case of HSC with steel fibres (B2), there was an increase in the stress ratio value after 250 cycles, and after 350 cycles a clear decrease in this parameter by more than 16%, with a simultaneous decrease in the modulus of elasticity by 4%. Steel fibres improve the cyclic freeze/thaw resistance of HSC, but with more cycles, more than 0.5% of the steel fibres in the concrete matrix would be required to stop crack propagation.

Fibres evenly distributed in the mix contribute to crack bridging that occurs during subsequent freeze/thaw cycles. When a developing scratch encounters a steel fiber, a rapid increase in stress occurs. The lowest total mass of surface scaling was recorded for the B3 series concretes (HSC with a mixture of steel and basalt fibres). The addition of fibres significantly increases the resistance to surface scaling of HSC. Replacement of steel fibre parts with basalt fibres contributed to the reduction of the total mass of surface scaling while reducing the corrosion effects of reinforcement on the analysed surface.

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Współczynnik intensywności naprężeń w ocenie degradacji mrozowej fibrobetonów wysokowytrzymałych

STRESZCZENIE:
W pracy przedstawiono ocenę degradacji betonów wysokowytrzymałych poddanych cyklicznemu zamrażaniu/rozmrażaniu, w oparciu o zmiany współczynnika intensywności naprężeń K_{IC}. Stopień zniszczenia na skutek cyklicznego zamrażania/rozmrażania BWW określono za pomocą modułu sprężystości podłużnej *E*, ubytku masy, redukcji wytrzymałości na ściskanie, wyznaczanych po 150, 250, 300 oraz 350 cyklach oraz sumarycznej masy złuszczeń powierzchniowych po 28 i 70 cyklach. Stopień degradacji porównano z modyfikacją wartości współczynnika intensywności naprężeń. Badaniom poddano trzy rodzaje betonów wysokiej wytrzymałości (wytrzymałość na ściskanie około 90 MPa): beton bez dodatku włókien, beton z włóknami stalowymi w ilości 0,5% objętości (39 kg/m^3) oraz beton z mieszanką włókien stalowych (19,5 kg/m^3) oraz bazaltowych (6,8 kg/m^3). Metodologię badań oparto na zaleceniach RILEM [1] oraz normach ASTM C666 [2] i PKN – CEN/TS 12390 *Slab Test* [3].

SŁOWA KLUCZOWE:
beton wysokowytrzymały; włókna; degradacja betonu; współczynnik intensywności naprężeń; złuszczenie powierzchniowe