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Influencia del refuerzo de fibra de acero y basalto en la resistencia a las heladas y los parámetros mecánicos de fractura del hormigón de alta resistencia

Influence of basalt and steel fiber reinforcement on the frost resistance and fracture mechanic parameters of high strength concrete

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Resumen-- **La resistencia a las heladas es una de las características más importantes que describen un elemento estructural de hormigón. En condiciones de procesos de congelación/descongelación frecuentes y repetidos, la estructura se debilita significativamente. Los parámetros físicos que describen el material asumido en la etapa de diseño comienzan a desviarse significativamente de las estimaciones iniciales a medida que avanza la degradación. Con el fin de aumentar la durabilidad de los elementos estructurales expuestos a ciclos de congelación/descongelación, a principios de la década de 1980 se introdujo una nueva generación de hormigones con mejores propiedades de resistencia y durabilidad. Estos hormigones, a pesar de sus muchas ventajas, se caracterizan por una mayor fragilidad y susceptibilidad a la retracción. En este estudio se determinó el efecto de la adición de un 0,5% en volumen de fibras de acero y una mezcla de fibras de acero y basalto sobre la resistencia a las heladas de hormigones con una resistencia de 90 MPa. Se presentó el grado de resistencia de los hormigones al descascarillado superficial en condiciones de tensión durante ciclos de congelación/descongelación. El análisis se basó en las normas ASTM C 666 y PKN - CEN/TS 12390 Slab Test y RILEM. Se determinó el cambio del parámetro que describe la fragilidad y el factor de intensidad de tensión del concreto de alta resistencia debido al ciclo de hielo/deshielo después de 150, 250, 350 y 450 ciclos.**

Palabras clave— Fibra de acero; fibra de basalto; hormigón de alta resistencia; parámetros de fractura; resistencia a las heladas.

Abstract— **Frost resistance is one of the most important characteristics describing a concrete structural element. Under conditions of frequent, repeatedly occurring freeze/thaw processes, the structure is significantly weakened. The physical parameters describing the material assumed at the design stage begin to deviate significantly from the initial estimates as the degradation progresses. In order to increase the durability of structural elements exposed to cyclic freeze/thaw, a new generation of concretes with improved strength and durability properties was introduced in the early 1980s. These concretes, despite their many advantages, are characterised by increased brittleness and susceptibility to shrinkage. In this study, the effect of a 0.5% by volume addition of steel fibres and a mixture of steel and basalt fibres on the frost resistance of concretes with a strength of 90 MPa was determined. The degree of resistance of concretes to surface scaling under stress conditions during cyclic freeze/thaw was presented. The analysis was based on ASTM C 666 and PKN - CEN/TS 12390 Slab Test and RILEM standards. The change of the parameter describing brittleness and the stress intensity factor of high-strength concrete due to cyclic freeze/thaw after 150,250,350 and 450 cycles were determined.**

Index Terms— Steel fiber; basalt fiber; high strength concrete; fracture parameters; frost resistance.

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I. INTRODUCTION

IN modern construction, which aims to achieve record-breaking heights and extremely durable structures, high-strength concrete is used increasingly often. Concrete with a compressive strength of over 50 MPa is characterized by a tight structure, minimal water absorption and high watertightness, as well as high abrasion resistance. However, despite its many advantages, it is a quasi-brittle material (Swamy, 1987). To increase the ductility of high-strength concretes, it is becoming increasingly common to add fiber reinforcement (steel, polymer, basalt, carbon) with a high modulus of elasticity to the concrete mixture. Once the first crack appears in the concrete, the fibres begin to have a significant impact by bridging the propagation of discontinuities. As the load increases, the fibres transfer additional stresses to the matrix. If this transfer did not occur, then the concrete would fail. The creation of cooperation between the fibres and the matrix results in a high level of ductility (Hassan-nattaj et al., 2017. The addition of steel fibres to HSC turns it into a quasi-plastic material, preventing sudden brittle fracture under loading conditions (Bywalski et al., 2010).

The major problem that concrete designers have to deal with when trying to achieve durability of a structure located in a cold climate is the effect of cyclic freeze/thaw. As a result of the difference in thawing and freezing temperatures of the individual concrete components, additional tensile stresses are generated that are destructive to the concrete structure (Karakurt et al., 2009). To achieve a sufficiently high strength of HSC, aeration, which improves the frost resistance of concrete, is increasingly being dispensed with. As the temperature drops, the water in the concrete pores freezes and increases its volume by about 9%. However, this does not always happen at 0 °C. The freezing point of water in the concrete pores is related to the structure, distribution and geometry of the pores. The smaller and denser the pores, the lower the freezing point of water in the pores. The accumulation of additional tensile stresses due to cyclic freeze/thaw of concrete occurs due to the build-up of hydraulic pressure in the concrete pores (Hale et al., 2009). The concrete properties assumed at the design stage are significantly reduced as a result of cyclic freezing/thawing. Initial internal defects propagate with the progression of additional tensile stresses. The concrete deteriorates slowly, reducing the durability and aesthetic qualities of the concrete, and may even lead to the failure of the structure in question (Kustermann et al., 2004. High-strength concrete is used primarily for infrastructure structures (bridges, road surfaces, abutments) and hydrotechnical structures, in which the surface of the concrete element also plays a significant role. Both internal frost resistance and resistance to surface scaling should be ensured in such constructions.

Numerous publications as Kustermann, (2004), Song et al., (2004) and Luo et al., (2001) present the effect of steel fibres on the mechanical properties of HSC, but little attention has been paid so far to the effect of steel and basalt fibres on the frost resistance of high-strength concretes described by changing the fracture mechanics parameters and the resistance of HSC to surface scaling.

This paper presents the effect of the addition of steel fibres at 0.5% by volume and a mixture of steel and basalt fibres at 0.25% by volume on the frost resistance of concrete with a compressive strength of 90 MPa. The results are described in terms of changes in fracture mechanics parameters (stress intensity factor, critical opening width of primary crack tip) after 150, 250,350 and 450 freeze/thaw cycles, and surface flaking mass after 28, 56, 72 and 100 freeze/thaw cycles. The tests were based on RILEM recommendations and the standard for internal frost resistance of concrete: ASTM C 666 and resistance to surface scaling: PKN - CEN/TS 12390 Slab Test.o.

II. TEST MATERIALS AND METHODS

A. *Characteristics of prepared concrete*

To analyse the effect of fibres on the frost resistance and fracture mechanics parameters of HSC, 50 mm long steel fibres and basalt fibres (Fig. 1) were used and their parameters are shown in Table 1.

TABLE I

FIBRES USED PROPERTIES

Property	Steel fibres	Basalt fibres
Fibre shape	Hooked end	Straight
Length (mm)	50	50
Diameter (mm)	1.0	0.02
Tensile strength (MPa)	900	1680
Elastic modulus (GPa)	200	89
Density (kg/m^3)	7850	2660

The internal frost resistance of HSC was analysed based on the ASTM C666 procedure after 150, 250, 350 and 450 freeze/thaw cycles. The resistance of HSC to surface scaling in the presence of a de-icing agent in the form of 3% salt solution and under stress conditions was also investigated based on the Swedish Borâs procedure presented in PKN - CEN/TS 12390 Slab Test. In the study, concrete samples with a compressive strength of 90 MPa were made using Portland Cement CEM I 42.5 R. The aggregate used was post-glacial grit with a grain size of 5-11 mm and 2-5 mm, and river sand with a grain size of 0-2 mm. A constant w/c ratio of 0.31 was maintained in all samples. Three series of high strength concrete were made: concretes with 0.5% (by volume) steel fibre addition, concretes with 0.25% (by volume) steel fibre addition and 0.25% (by volume) basalt fibre addition, and HSC without fibre addition. The internal frost resistance test was carried out on 100 x 100 x 400 mm specimens, while the resistance to surface flaking was carried out on 80 x 120 x 1100 mm and 100 x 100 x 100 mm samples. A total of 36 samples were prepared for internal frost resistance and fracture mechanics parameter measurement, 9 samples for surface flaking resistance and 9 specimens for surface flaking resistance under stress conditions. 3 series of high-strength concretes were prepared: HSC0 - high-strength concrete without fibres, HSCS - high-strength concrete with 0.5% (by volume) steel fibre by volume, HSCSB - high-strength concrete with 0.25% (by volume) steel fibre and 0.25% (by volume) basalt fibre.

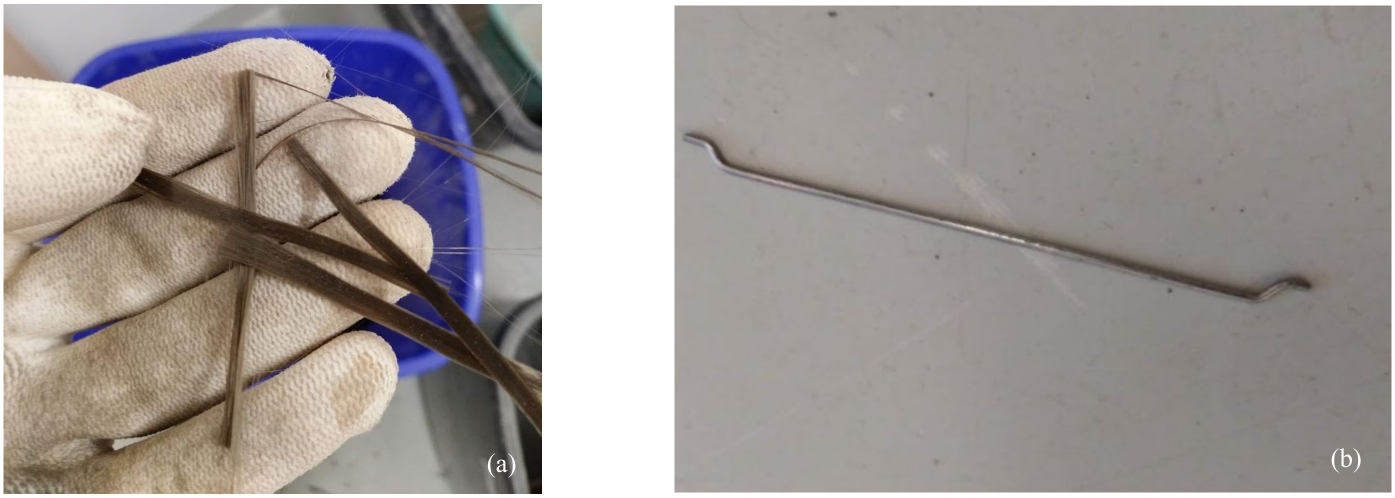
(a) (b)

Fig. 1. Basalt (a) and steel (b) fibres used.

B. Test methodology

To determine the internal frost resistance of HSC based on (ASTM, 1991), after 28 days of curing in a water bath, the samples were placed in a freezing chamber initially for 100 cycles. One full freeze/thaw cycle lasted 8 hours. The samples were frozen in air at - 18 ± 2^{o}C for 4 hours and thawed in water at +18 ± 2^{o} C for 4 hours. After 50, 100, 150, 250, 350 and 450 freeze/thaw cycles, changes in the length and weight of the specimens were measured and changes in the longitudinal modulus of elasticity were determined using a non-destructive method with a betonoscope. Frost resistance was classified on the basis of the value of durability index DF determined according to formula (1). According to [9], concrete is considered frost resistant when the DF index has a value above 60%. Additionally, cubic samples were also subjected to freezing/thawing to control changes in compressive strength of the tested concretes after n cycles.

$$DF = \frac{P \cdot N}{M} \cdot 100\ [\%];\ \ P = \frac{{n_n}^2}{{n^2}_0} \qquad (1)$$

where:

M – specified number of cycles at which the exposure is to be terminated, N- number of cycles at which P reaches the specified minimum value for discontinuing the test or the specified number of cycles at which the exposure is to be terminated, P- relative dynamic modulus of elasticity at N cycles, n_0 – transverse frequency at 0 cycles of freeze/thaw, n_n- transverse frequency after n cycles of freeze/thaw

The critical values of stress intensity factor KIC and crack mouth opening displacement CTODC were also determined to relate the durability index DF determining the frost resistance of HSC to the changes of fracture mechanics parameters. The fracture mechanics parameters were determined indirectly by the destructive method, during three-point bending test, according to the load model I (tensile at bending) and by the formulas presented in (TC 89-FMT RILEM, 1990). The value of stress intensity factor was determined based on relation (2), while the critical crack mouth opening displacement of the CTODC based on equation (3), where: B, D, L – beam width, depth and length, S- distance between support points, a – notch depth, E- modulus of elasticity, P_C- critical force.

$$K_{IC} = \sigma_c \sqrt{\pi a_c}\, Y(\frac{a}{D}) \qquad (2)$$

where: D – beam depth, a – notch depth, \sigma_c- stress at the top of crack, Y(\frac{a}{D})- function of the shape influence based on the Lotta- Kesler relation.

The test stand for the determination of HSC fracture mechanics parameters in the three-point bending test is shown in Fig. 2.

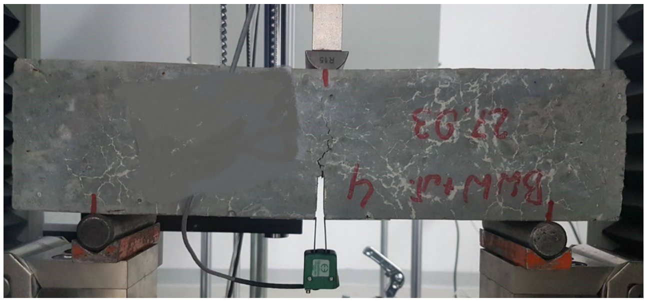

Fig. 2. Test stand for the determination of fracture mechanics.

The resistance to surface scaling was determined by subjecting the HSC specimens to cyclic freeze/thaw according to PKN - CEN/TS 12390 Slab Test. The tests were carried out under stress conditions by applying weights of 25% of the destructive force to the test specimens. Surfaces that were not subjected to the test were insulated with polystyrene pads and polyurethane foam, while the HSC surface to be analysed was enclosed with rubber foil and then covered with a 3 mm layer of 3% NaCl solution. In loaded elements, an area of 600 mm x 80 mm was analysed, while in unloaded cubic elements, the

$$CTOD_C = 6 \cdot \left(P_C + 0.5 \cdot W_0 \cdot \frac{S}{L}\right) \cdot \frac{S \cdot a_C \cdot g \cdot \left(\frac{a_C}{D}\right)}{E \cdot D^2 \cdot B} \cdot [1 - \left(\frac{a_C}{a_0}\right)^2 + [[\left(1.081 - 1.149 \cdot \frac{a_C}{D}\right)] \cdot \left[\left(\frac{a_C}{a_0}\right) - \left(\frac{a_C}{a_0}\right)^2\right]]^{1/2} \qquad (3)$$

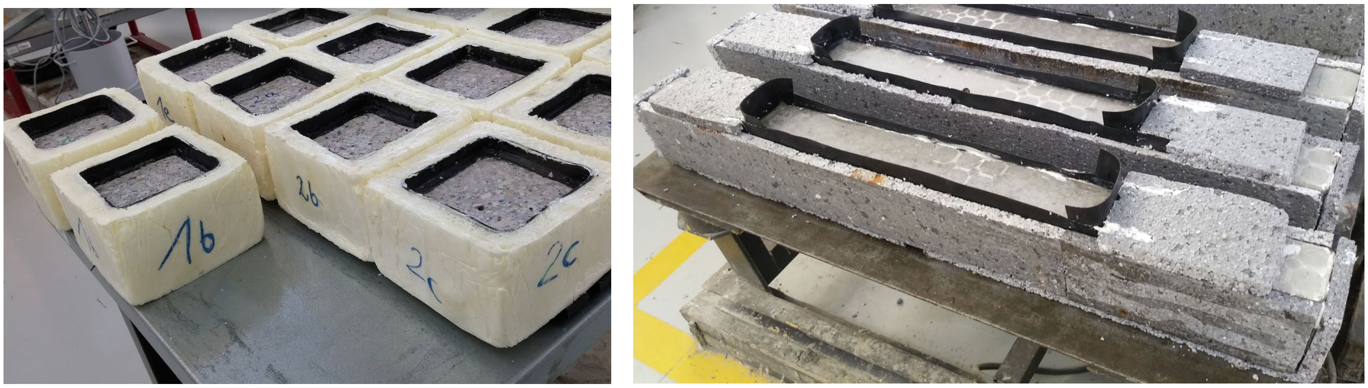

Fig. 3. Sample elements for the test of resistance to surface scaling.

entire upper surface was tested. The prepared test specimens for resistance to surface scaling are shown in Figure 3. One hundred and twenty-two freeze/thaw cycles were carried out. After each of the 7 cycles, surface scaling was removed from the test specimen surfaces and the total weight of scaling relative to the subjected freezing/thawing surface was determined. One cycle lasted 24 hours (+/- 1h). A static diagram of the specimens for the surface scaling resistance test under stress conditions is shown in Figure 4.

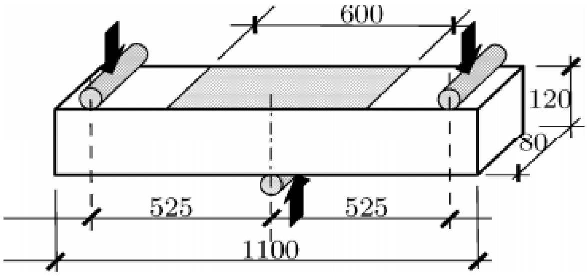

Fig. 4. Load application points of test specimens for resistance to surface scaling [12] (Kosior-Kazberuk, 2012)

The surface scaling masses were determined as follows (4):

Where: m_{s,n} – total mass of dried scaled material after n freeze-thaw cycles, A – test area calculated from the measurement of the length before sealing, rounded to the nearest 100 mm^2.

The test procedure used was based on the Swedish Boräs method (SS, 1990), developed for verifying the durability of bridge structures. The assessment of frost resistance of concretes by the Boräs method is presented in Table 2.

TABLE II
ASSESSMENT OF THE FROST RESISTANCE OF CONCRETE USING BORÄS METHOD (SS, 1990)

Frost resistance	Requirements
Very good	m56 < 0,10 kg/m2
Good	m56 < 0,20 kg/m2 bądź m56 < 0,50 kg/m2, gdy m56/m28 < 2, bądź m112 < 1,00 kg/m2
Fair	m56 < 1,00 kg/m2, gdy m56/m28 < 2, bądź m112 < 1,00 kg/m2
Unsatisfactory	Requirements for frost resistance considered inadequate are not fulfilled

III. RESULTS AND DISCUSSION

Table 3 compares the changes in the durability factor determining the frost resistance of HSC and the changes in fracture mechanics parameters (critical stress intensity index and critical crack tip opening displacement) after 150, 250, 350, 450 freeze/thaw cycles. The following results show a relatively rapid deterioration of fracture mechanics parameters and DF durability index for all series of high-strength concretes. The loss of frost resistance described by a decrease in DF below 60% was recorded after 450 freeze/thaw cycles for HSC without fibres and with steel fibres. This indicates a minor effect of 0.5% steel fibres on the frost resistance of high-strength concretes. After 450 freeze/thaw cycles, the durability index of HSC0 series concretes (without fibres) decreased by 97%, while after 350 freeze/thaw cycles, the value oscillated within the initial value. The DF value of the HSCS series decreased by 96% after 450 freeze/thaw cycles, with a decrease of 9% after 350 freeze/thaw cycles. In the case of HSCSB series concretes (mixed steel and basalt fibres), the loss of frost resistance was already noted after 150 freeze/thaw cycles with a decrease in DF value of more than 75%. The negative effect of basalt fibres on the frost resistance of high-strength concretes becomes visible in this case. Corresponding to the decrease in durability factor of HSC0 and HSCS series concretes, after 450 freeze/thaw cycles there is a sudden decrease in the critical stress intensity index KIC by 68% for HSC0 and by 60% for HSCS. After 150 freeze/thaw cycles, the high strength concrete of the HSCSB series had a stress intensity index 85% lower compared to the value before cyclic freeze/thaw. The addition of steel or basalt fibres to the HSC bridging the developing cracks caused by cyclic freeze/thaw should improve the HSC durability over the service life, however, the critical tip crack opening displacement of the high strength concretes with steel fibres and steel and basalt fibres increased by 70% and 140% respectively due to cyclic freeze/thaw. The fibre content was insufficient to take up the accumulated tensile stresses due to cyclic freeze/thaw.

TABLE III
FRACTURE MECHANICS PARAMETERS AFTER N CYCLES OF FREEZE/THAW

No.	Concrete type	Number of freeze/thaw cycles *n*	*DF*	$K_{IC,n}/K_{IC,0}$	$CTOD_{c,n}/CTOD_{c,0}$
1	**HSC0**	0	1,00	1,00	1,00
2	**HSC0**	150	0,98	0,98	0,94
3	**HSC0**	250	1,00	1,01	0,96
4	**HSC0**	350	1,00	1,04	0,99
5	**HSC0**	450	0,03	0,32	1,70
7	**HSCS**	0	1,00	1,00	1,00
8	**HSCS**	150	0,92	0,71	0,72
9	**HSCS**	250	0,86	1,11	1,17
10	**HSCS**	350	0,91	0,84	0,86
11	**HSCS**	450	0,04	0,40	1,92
13	**HSCSB**	0	1,00	1,00	1,00
14	**HSCSB**	150	0,24	0,15	2,40

Table 4 shows the total mass of surface scaling of high-strength concretes after 28, 56 and 112 freeze/thaw cycles. The concrete specimens tested were loaded at 25% of the ultimate strength and the surface analysed was covered with a 3% salt solution. Table 5 shows the total mass of HSC surface scaling not subjected to loading during cyclic freeze/thaw. For concretes with dispersed reinforcement (HSCS, HSCSB), the load applied during cyclic freeze/thaw had no significant effect on the total mass of surface scaling obtained. In the case of concretes of the HSC0 series (without fibres), the additional load during freeze/thaw cycling resulted in a slight increase of 23% in surface scaling.

All the tested concretes are frost resistant to a good degree according to the Boräs classification [11]. The addition of fibres to the tested high-strength concretes did not significantly reduce the total mass of surface scaling. The addition of mixed steel and basalt fibres (HSCSB) resulted in a reduction in the total mass of surface scaling in case of specimens loaded, up to 56 freeze/thaw cycles compared to the reference concrete (HSC0), but after 112 cycles there was a significant increase in the mass of surface scaling which exceeded the values determined for concrete without fibres.

TABLE IV
TOTAL MASS OF SURFACE SCALING OF PRISM SAMPLES UNDER STRAIN AFTER N CYCLES OF FREEZE/THAW

	Total mass of surface scaling after n cycles [kg/m^2]		
Number of cycles *n*	**HSC0**	**HSCS**	**HSCSB**
28	0,096 (0,029*)	0,077 (0,010*)	0,058 (0,005*)
56	0,164 (0,035*)	0,154 (0,020*)	0,132 (0,003*)
112	0,303 (0,036*)	0,261 (0,041*)	0,320 (0,025*)
m_{56}/m_{28}	1,71	2,01	2,26
***deviation**			

TABLE V
TOTAL MASS OF SURFACE SCALING AFTER N CYCLES OF FREEZE/THAW WITHOUT STRAIN

	Total mass of surface scaling after n cycles [kg/m2]		
Number of cycles *n*	**HSC0**	**HSCS**	**HSCSB**
28	0,068 (0,031*)	0,082 (0,033*)	0,071 (0,010*)
56	0,129 (0,054*)	0,150 (0,069*)	0,153 (0,010*)
112	0,245 (0,108*)	0,293 (0,142*)	0,311 (0,015*)
m_{56}/m_{28}	1,90	1,83	2,14
***deviation**			

IV. CONCLUSIONS

The study presents the effect of the addition of 0.5% by volume of steel and basalt fibres on the internal frost resistance of concretes with a compressive strength of 90 MPa described by fracture mechanics parameters (stress intensity factor and critical tip crack opening displacement). The analysis showed a small effect of 0.5% steel fibres on the changes in the values of the fracture mechanics parameters due to cyclic freeze/thaw. Both the HSC0 reference concretes and the concretes with the addition of HSCS steel fibres showed a significant deterioration in mechanical parameters, which was associated with a loss of frost resistance after 450 freeze/thaw cycles. The addition of basalt fibres to the high strength concrete caused failure of the test pieces after only 150 freeze/thaw cycles. This may have been due to inadequate adhesion of the fibres to the cement matrix, resulting in the formation of numerous discontinuities and leaks. Analysis of the resistance to surface scaling of high-strength concretes showed that there was no significant effect of the addition of steel fibres and steel and basalt fibres on the total mass of surface scaling after 112 freeze/thaw cycles. the presence of fibres in the concrete led to a reduction in the total mass of surface scaling to 39% for specimens loaded to 56 freeze/thaw cycles. After a period of 112 freeze/thaw cycles, the reference concrete had the lowest total mass of surface scaling in both stressed and unstressed conditions. Steel and basalt fibres had a beneficial effect on the concrete until greater surface damage occurred and the fibres began to separate from the cement matrix.

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