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Effect of fiber on the concrete resistance to surface scaling due to cyclic freezing and thawing

Piotr Berkowski[a]*, Marta Kosior-Kazberuk[b]

[a]*Faculty of Civil Engineering, Wroclaw University of Technology, Wyb. St. Wyspianskiego 27, PL-50-370 Wroclaw, Poland*
[b]*Faculty of Civil and Environmental Engineering, Bialystok University of Technology, Wiejska St. 45A, PL- 15-351 Bialystok, Poland, tel. +48 85 746 95 60, fax +48 85 746 95 59, e-mail: m.kosior@pb.edu.pl*

Abstract

Frost damage is considered to be a typical material deterioration in the concrete structures subjected to external environmental conditions. The effect of different types of steel and polypropylene fibers on the surface scaling resistance of concrete subjected to cyclic freezing and thawing in the presence of deicer salt was analyzed. The test parameters included fiber type and dosage and the type of concrete surface subjected to freezing and thawing. Both the cut and cast surfaces of specimens were tested. The dispersed steel reinforcement was found to improve the scaling resistance significantly. However, the effectiveness of fibers was related to their shape and dimensions. The beneficial effect of polypropylene fibers on salt scaling resistance was apparent only in case of the extruded fibers with treated surface.

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Keywords: Concrete; Steel fibers; Polypropylene fibers; Freeze/thaw cycles; Deicer salt; Scaling

1. Introduction

The suitability of cement composites with fiber reinforcement for structural applications is usually assessed considering their mechanical properties [1,2,3], while the frost resistance of such materials is the issue relatively little recognized. The results of previous studies on the frost resistance of the fiber concretes are various and often

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* Corresponding author. Tel.: +48-71-320-30-12; fax: +48-71-320-36-45.
E-mail address: piotr.berkowski@pw.edu.pl

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divergent, due to the variations in the composition of concretes tested, diversity of fibers used and different test methods. The most extensive study on the influence of steel fibers on the concrete resistance to frost was conducted by Cantin and Pigeon [4] and Pigeon et al. [5,6]. They found that the steel fibers with a length of 54 and 60 mm do not have a significant influence on the concrete resistance to surface scaling. In contrast, the incorporation of short fibers with a length of 3 mm, resulted in reducing the concrete degradation. According to Pigeon et al. [5] the improvement of durability of microfiber reinforced mortars was in part due to the "air entrainment" properties of the microfibers. Sun et al. [7] and Mu et al. [8] reported a beneficial influence of steel fibers (length of 20 mm) on resistance to the internal destruction of concrete due to frost, evaluated on the basis of changes in the value of dynamic modulus of elasticity. Similar effects were obtained by Niu et al. [9], who studied the effect of steel fibers with a length of 30 mm. On the other hand Quanbing and Beirong [10] noticed that the incorporation of steel fibers with a length of 35 mm makes it difficult to air-entrain concrete in a proper way, thus it causes the decrease in frost resistance, despite the increase in the tensile strength of material. The beneficial effect of short polypropylene fibers on surface scaling due to cyclic freezing and thawing was pointed out by Richardson [11], who used the fibers with a length of 6,5 mm and by Sahmaran and Li [12], who used 8 mm fibers. However, according to Persson [13] the incorporation of polypropylene fibers to self-compacting concrete caused the decrease in its internal frost resistance.

The analysis of the research results described in literature, has demonstrated the lack of data concerning the influence of fiber reinforcement on the process of surface scaling due to the freezing of the liquid being in contact with the selected surface of element or structure, which is the frequently occurring situation in service life of concrete and reinforced concrete structures. Salt scaling is defined as superficial damage caused by freezing a saline solution on the surface of a concrete body. The damage is progressive and consists of the removal of small chips or flakes of material. Since salt scaling is superficial, it does not affect the mechanical integrity of a concrete body. However, this damage renders material susceptible to ingress of moisture and aggressive species that threaten the durability of structure [14,15].

The surface scaling of the concrete can be the result of the propagation of existing defects or development of microcracks from the ice layer on the surface into the concrete element [14,16]. The frost damage occurs when the internal pressure generated due to changes in temperature and moisture content, induces locally the stress exceeding the tensile strength of material. A number of reports [17,18,19] points out that the material resistance to frost damage depends on its strength and deformability. In compliance with the latest theories of frost deterioration of concrete [20,21] maintained that the micromechanical properties of the phases in different locations determine the scaling resistance throughout the material surface rather than the global (average) tensile strength of the cementitious material.

Among the methods improving the cement composite resistance to brittle fracture is the incorporation of fiber reinforcement. The most important application of fibers would be to prevent or control the tensile cracking occurring in the concrete elements [2, 22]. The increase in ductility and strength is mainly achieved by the stress transfer from matrix to the reinforcement through the adhesive contact of paste surrounding the reinforcement [23].

The present study was carried out with the main objective to assess the influence of steel and polypropylene fibers of different shapes and lengths on the surface scaling process of concrete due to cyclic freezing and thawing in the presence of chloride salt solution.

2. Materials and research methods

2.1. Materials and specimens

The concretes tested contained 350 kg/m^3 Portland cement (CEM I 42,5 HSR NA). The water to cement ratio of 0.40 was kept constant in all mixes. The natural aggregate with a maximum size of 8 mm was used. The aggregate mix consisted 40% of 0÷2 mm fraction, 25% of 2÷4 mm fraction and 35% of 4÷8 mm fraction.

The steel microfibers (A) and macro fibers (B) of different shape and length were used. The polypropylene fibers were characterized by the same length but different surface finish: smooth fibers (C) and structural, extruded (D) fibers. The structural D fiber surface is crypsinated to improve the initial dispersion within the concrete. The treated surface creates a multi-directional bond between the fiber and the cement matrix. The geometry and properties of fibers are given in Table 1.

Table 1. Geometry and properties of fibers used.

Property	A Dramix Hi Perform OL 6/.16	B Dramix RC-65/35-BN	C CHRYSO Fiber S50	D CHRYSO Structural
Material	steel	steel	polypropylene	polypropylene
Fiber shape	straight	hooked end	straight	fabricated
Length (mm)	6	35	50	50
Diameter (mm)	0.16	0.55	-	2 (rectangular cross-section)
Tensile strength (MPa)	2000	1345	600	550
Elastic modulus (GPa)	210	210	5	6
Density (kg/m^3)	7850	7850	920	910

The steel fibers were incorporated in concrete at content of 30 and 60 kg/m^3, which gave volume fractions 0.38% and 0.76%, respectively. The polypropylene fibers were added at content of 4.5 and 9.0 kg/m^3, which gave volume fractions 0.50% and 1.0%, respectively. The fibers were added as a replacement of adequate portion of aggregate by volume. The effect of fibers on concrete properties was referee to the results obtained for the reference concrete without fibers.

The superplasticizer (polycarboxylate polymer-based) was used to minimize fiber clumping and to enhance fiber dispersion in concrete mix. The superplasticizer was applied with water in the amount of 0.6% of cement mass. The concretes were not air-entrained.

The dry aggregate was mixed with fibers followed by cement. The materials were dry mixed for 2 min before adding the water with super-plasticizer. Mixing continued for a further 4 min. The time of mixing was considered sufficient for the proper dispersion of the fibers in the mix without causing a “balling” effect. The 100×100×400 mm beams were formed for tests. The specimens were vibrated in moulds and then stored under polyethylene cover for 24 hours. After demoulding all specimens were cured in water at the temperature of 20±2°C till they were tested.

The flexural strength of concrete was determined using beam specimens. For the compressive strength and water absorbability tests the 100×100×100 mm cubes were cut. The cut specimens of size 100×100×50 mm were used for testing the frost scaling resistance and capillary suction of chloride salt solution. The capillary suction of salt solution was tested for both cut and cast surfaces of concrete specimens. The amount of solution absorbed was calculated per unit area of the surface tested.

The concrete susceptibility to frost scaling was assessed on both types of specimen surfaces: cast and cut. The rubber sheet was glued to all surfaces of the specimen except the test surface. The edge of the rubber sheet extended 20 mm above the test surface forming a pond. Then, all surfaces of the specimen except the ponding surface were thermally insulated. The demineralized water was added to the pond for 72 hours to pre-saturate the specimen. It was then replaced by 3% NaCl solution at the beginning of test. The freezing medium was prevented from evaporating by applying a flat polyethylene sheet as shown in Fig 1.

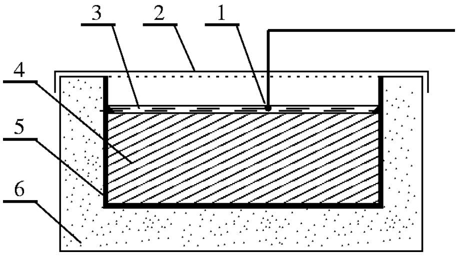

Fig 1. The test specimen used for freeze-thaw test: 1 – temperature measuring device; 2 – polyethylene sheet; 3 – freezing medium (3% NaCl); 4 – specimen; 5 – rubber sheet; 6 – thermal insulation.

2.2. Procedure of scaling resistance test

The concrete resistance to scaling due to cyclic freezing and thawing with de-icing salt saturation (3% NaCl) was determined using the procedure described in CEN/TS 12390-9:2007 (slab test) [24]. It is the most sever method of frost resistance test. The behavior of concrete under field exposure conditions is simulated, the type of deterioration is found in real structures and the test results evaluation is quantitative [17,25].

The test was conducted on the sawn surface and the cast surface against formwork to compare the efficiency of different types of fibers. In the freezing chamber with temperature and time controlled cooling and heating system, the specimens were subjected to repeated freezing and thawing. The curing conditions and freeze/thaw cycles, were performed according to the slab test procedure [24]. In each freeze and thaw cycle, the temperature in the layer of freezing medium changed from 20^oC to -18 ^oC, per 24 hours.

Every 7 days NaCl solution was exchanged. The material that had 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 calculated for each measuring occasion and each specimen. The specimens with steel fibers and reference specimens were subjected to 100 cycles of freezing and thawing. The test of concretes with polypropylene fibers was completed after 84 cycles because of the significant damage of part of specimens.

3. Analysis of test results

3.1. Concretes with steel fibers

The properties of concretes with steel microfibers A and macro fibers B, determined after 28 days of curing, are presented in Table 2.

The presence of steel fibers did not significantly affect the physical properties of the tested concretes, such as water absorption and the ability to capillary suction of salt solution. The incorporation of a distributed reinforcement resulted in a slight increase in compressive strength of concrete and a significant increase in flexural strength.

The cumulated mass of scaled material after n cycles of freezing and thawing for cut and cast surfaces were presented in Figs 2a and 2b, respectively.

The analysis of the relations between the mass of scaling and the number of freeze-thaw cycles for all concretes tested, showed that the cast surface of samples was much more susceptible to scaling than the cut surface. For control concrete, without fibers, the mean mass of scaling after 100 cycles from cut surface was 1.96 kg/m^2, and form cast surface – 3.4 kg/m^2. The different physical and chemical properties of cast surface (due to wall effect and bleeding) in comparison to cut surface had a crucial impact on the test results.

The steel fibers caused a significant improvement in the concrete resistance to surface scaling. However, the effect of fibers varied depending on their features and the surface tested. For both cut and cast surfaces, the favorable effects of reducing the mass of scaled material were obtained by incorporation to concrete the straight microfibers A.

Table 2. Selected properties of concretes with steel fibers after 28 days of curing: compressive strength f_{cm}, flexural strength f_{ctm}, water absorbability n_w, capillary suction for cast surface n_{cap1}, capillary suction for cut surface n_{cap2}.

Concrete	Fiber content	f_{cm} (MPa)	f_{ctm} (MPa)	n_w (%)	n_{cap1} (kg/m^2)	n_{cap2} (kg/m^2)
0	0	67.7 (2.5)	5.0 (0.19)	3.9 (0.10)	3.4 (0.18)	3.3 (0.13)
A0.38	0.38%	70.3 (3.3)	6.2 (0.41)	4.1 (0.09)	3.0 (0.33)	3.5 (0.16)
A0.76	0.76%	73.8 (2.8)	6.7 (0.47)	3.8 (0.07)	3.3 (0.11)	3.4 (0.08)
B0.38	0.38%	68.0 (1.7)	6.5 (0.13)	4.0 (0.16)	3.4 (0.07)	3.5 (0.09)
B0.76	0.76%	70.1 (2.3)	7.9 (0.33)	4.2 (0.13)	3.4 (0.26)	3.6 (0.18)

*Standard deviations of the test results are given in brackets

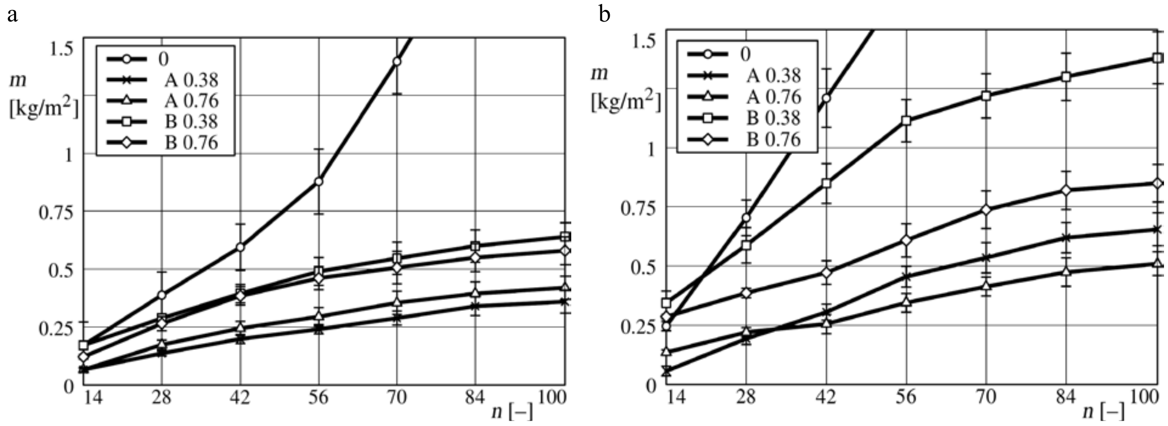

Fig. 2. Mean mass m of scaling vs. freeze-thaw cycles number n as well as the type and content of steel fibers: (a) cut surface; (b) cast surface.

The comparison of the mass of scaling from cut surface (Fig. 2a) of concrete specimens containing straight microfibers A and specimens with macro fibers B with hooked ends showed that the difference in the scaling resistance slightly depended on the fiber content in the concrete. The mass of scaling, slowly increasing with the number of freeze-thaw cycles, after 100 cycles for concrete with fibers A were: 0.36 and 0.42 kg/m^2, and for concretes with fibers B: 0.64 and 0.58 kg/m^2, respectively for smaller and higher content of fibers.

When freezing a cast surface of specimens (Fig. 2b), the efficiency of the fiber influence on the scaling resistance was more variable. The increase in the fiber A content from 0.38% to 0.76% resulted in the decrease in the mean mass of scaled material of about 20%. In the case of concretes with fibers B, the differences in the mean mass of scaling for various content of addition were significantly greater throughout the test. The cumulative mass of scaling for concrete containing 0.76% of fibers B was 0.85 kg/m^2. The scaling for concrete with 0.38% of fibers reached 1.38 kg/m^2 after 100 cycles.

3.2. Concretes with polypropylene fibers

The physical properties of concretes with both types of polypropylene fibers, determined after 28 days of curing, are presented in Table 3. The incorporation of the polypropylene fibers caused an increase in the flexural strength of concrete. Higher flexural strength was recorded for concretes with extruded fibers D with treated surface which creates better bond between reinforcement and cement matrix. The concretes with synthetic fibers revealed slightly higher capillary suction in comparison to reference concrete without fibers.

Table 3. Selected properties of concretes with polypropylene fibers after 28 days of curing: compressive strength f_{cm}, flexural strength f_{ctm}, water absorbability n_w, capillary suction for cast surface n_{cap1}, capillary suction for cut surface n_{cap2}.

Concrete	Fiber content	f_{cm} (MPa)	f_{ctm} (MPa)	n_w (%)	n_{cap1} (kg/m^2)	n_{cap2} (kg/m^2)
0	0	67.7 (2.5)	5.0 (0.19)	3.9 (0.10)	3.4 (0.18)	3.3 (0.13)
C0.50	0.50%	66.5 (2.2)	5.3 (0.20)	4.3 (0.18)	3.7 (0.15)	3.6 (0.33)
C1.0	1.0%	66.6 (0.7)	6.3 (0.32)	4.0 (0.11)	3.8 (0.08)	3.4 (0.28)
D0.50	0.50%	67.8 (1.2)	6.4 (0.17)	4.1 (0.07)	3.6 (0.08)	3.5 (0.08)
D1.0	1.0%	66.9 (4.1)	6.6 (0.25)	3.9 (0.09)	3.5 (0.13)	3.3 (0.27)

*Standard deviations of the test results are given in brackets

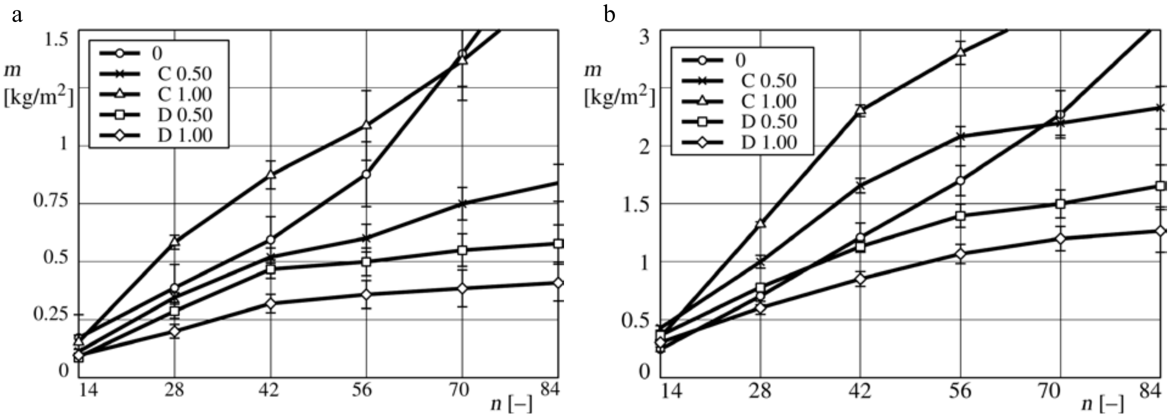

Fig. 3. Mean mass *m* of scaling vs. freeze-thaw cycles number *n* as well as the type and content of polypropylene fibers: (a) cut surface; (b) cast surface.

The cumulated mass of scaled material after *n* cycles of freezing and thawing for cut and cast surfaces of concretes with polypropylene fibers were presented in Figs 3a and 3b, respectively.

Similarly to the above-described performance of concretes with steel fibers to freezing conditions, the cast surface of specimens with polypropylene fibers were much more susceptible to scaling than the cut surface. Generally, the effectiveness of polypropylene fibers in concrete protection against the damaging influence of frost was not as significant as the influence of steel fibers. In addition, the effect of polypropylene fibers used on the reduction of scaling was much more diverse than that of steel fibers. The significant effects of both the type and fiber content were observed.

The incorporation of the extruded fibers D with modified surface led to improve the protection of concrete against frost. The increase in fiber content from 0.5% to 1.0% caused the decrease in the mean mass of scaling nearly 30% in case of cut surface (Fig. 3a) and approx. 25% for cast surface (Fig. 3b). For the cut test surface the mass of scaling after 84 freeze-thaw cycles was only slightly higher than the mass of scaling recorded at the same time for the cut surface of the concrete with steel microfibers A. Thus, the role of structural polypropylene fiber D in protecting the concrete against frost damage can be considered satisfactory.

The concretes containing plain C fibers revealed significant susceptibility to scaling due to frost in comparison to the concretes with fibers D. The cumulative mass of scaling for concretes with smooth fibers C was many times greater than for concretes with fibers D. The assessment of the fibers C influence is not clear. Although for fiber content of 0.5% the mass of scaling was less than for the reference concrete without fibers, it was significantly higher than the values obtained for concretes with steel fibers. The increase in the fiber C content to 1.0% did not result in any improvement of the resistance to surface scaling.

4. Conclusions

The concretes tested, characterized by comparable physical properties except the flexural strength, showed different resistance to cyclic freezing and thawing in the presence of chloride salt solution. The incorporation of a distributed reinforcement in concrete could help to improve the frost and deicer salt scaling resistance. Considering the types and dosage of fibers used, the effectiveness of dispersed reinforcement was related mainly to the type (material) and geometry. The steel fibers used appeared to be more effective than the polypropylene ones. Steel fibers could reduce the rate of crack propagation and retard the performance deterioration of the concrete. Moreover, for the considered content of reinforcement in concrete, the straight high performed short fibers (A) revealed more efficiency than the longer ones (B) with hooked ends. This phenomenon can be explained by higher number of microfibers per unit volume of material and at the same time in the surface layer. In the case of polypropylene macro fibers similar effect of reducing the rate of scaling was observed for structural fibers with surface modified to improve the bond between reinforcement and cement matrix. The polypropylene fibers of smooth surface were totally ineffective in protecting the concrete against deterioration due to freezing and thawing cycles.

Considering the way of concrete surface damage due to frost, the properly selected fibers can play a blocking role in the process of initiation and propagation of microcracks, accompanying scaling phenomenon. The fibers take over a part of tensile stresses generated locally in the conditions of cyclic temperature changes, thereby reducing the formation of microcracks and crack propagation, help to keep a compact microstructure, that has a direct influence on the resistance to surface scaling.

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