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RESEARCH ARTICLE

De-Icing Salt Scaling Damage Kinetics of Fibre Reinforced Concretes Made with High Bond Crimped Steel Fibres

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Abstract

Durability of steel fibre reinforced concrete (SFRC) specimens is tested and evaluated. Concrete is mixed with moderately sulphate resistant CEM I 42.5 cement and does not contain air-entraining agent. The aim of the research is to study how the dosage of high bond crimped steel fibre influences the durability damage kinetics of SFRC; freeze-thaw resistance, de-icing salt scaling resistance and resistance to water penetration are studied, completed with basic mechanical performance tests (compressive strength, modulus of elasticity, flexural tensile strength, splitting tensile strength, flexural toughness, fracture toughness, apparent porosity and vacuum water absorption). Results reveal the importance of the increased volume of the interface transition zone (ITZ) around the steel fibres in the first freeze-thaw cycles and the importance of the internal restrain activated by the steel fibres during later freeze-thaw cycles.

Keywords

Steel fibre reinforced concrete · crimped fibre · durability · salt scaling · freeze-thaw

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1 Introduction

Steel fibre reinforced concrete (SFRC) is a widely used construction material in civil engineering for several decades as the fabrication of this composite is relatively simple. Key issue is the improved toughness and shear capacity of SFRC [1–6] that makes possible to increase ductility of structural members and avoid brittle failure by additional energy absorbing capacity provided by the randomly distributed fibres in the concrete matrix [7–10]. Recent advances address the use of glass, polymer, carbon, basalt and natural fibres as well as high strength concrete (HSC) to deliver further advantageous applications [11–13].

Considerable amount of data are available in the technical literature on the improved properties of steel fibre reinforced concretes. A short overview is given in the followings without aiming to a comprehensive literature review regarding the most important properties of SFRC. Compressive strength and modulus of elasticity is generally expected to be increased by the addition of fibres only in the range of high fibre content, and the ultra high performance needs the advances of concrete technology and the use of supplementary cementitious materials as well [14]. If the steel fibre content does not exceed 2 V%, the distribution of the fibres is even and the concrete is well compacted then no notable increase in strength and modulus of elasticity is expected. Increased toughness of steel fibre reinforced concretes is studied in details in the technical literature [15–17].

Toughness of SFRC is described by the parameters defined for and measured during the post-cracking phase of mechanical tests. Apart from water-cement ratio and fibre content, the basic parameters of fracture mechanics (e.g. fracture energy) and special toughness parameters defined by load–deflection and load–crack mouth opening displacement (CMOD) curves are used. Fracture parameters and toughness indices closely correlate with fibre content [18].

Ductility is also one important parameter of structural behavior (especially in seismic design) that is reported to be considerably increased by the use of SFRC members [19]. Energy dissipation achieved by steel fibres due to crack arrest and multiple cracking of the concrete matrix, as well as the pull-out of steel fibres in plastic hinges at the cross sections of maximum inner forces considerably add to the pseudo-ductile/ductile behavior of structural members.

Another issue is the fatigue strength of concrete that is also considerably increased by the addition of steel fibres. Most important parameters in this sense are the fibre content, the bond properties of the fibres and the aspect ratio of the fibres [20]. Efficiency of steel fibres in bond behavior depends mainly on fibre geometry and orientation [21, 22]. Steel fibres effectively reduce the shrinkage deformation of concrete as well. It was reported that application of 1 V% fibres decreases the shrinkage deformations by almost 10% and produces almost twice reduction of the crack width [23]. It has recently been remarked that SFRC provides greater self-healing capacity with a reduction in water permeability [24].

Design aspects, partial safety factors, constitutive laws and cross sectional design for conventional SFRC and for high strength SFRC are detailed in the literature. Besides ultimate limit state resistance, steel fibre reinforcement can significantly improve structural behavior at serviceability limit state [11, 25, 26]. Level of knowledge on design of SFRC has been increased, and design rules have been optimized resulting more economical solutions that may allow more effective use of HSC together with steel fibres. With the application of steel fibre reinforced self compacting concrete (SFRSCC) and fibre reinforced polymer (FRP) reinforcements and laminates, innovative special sandwich panel applications have recently become available both for building construction and pedestrian bridge construction [27–29]. Fibre reinforced concretes and fibre reinforced polymers provide one of the most important research trends nowadays in concrete construction. Still limited and contradictory data are, however, available on durability, particularly on de-icing salt scaling resistance of steel fibre reinforced concretes. It is not clearly demonstrated how and which extent the steel fibres can decelerate the de-icing salt scaling deterioration, as the failure is started at the very surface that is usually richer in cement paste and poorer in fibres. However, clear experimental evidence demonstrates that steel fibres do have advantageous influences on the scaling resistance under certain conditions [30, 31].

Typical deterioration of the concrete infrastructure in cold climates is the de-icing salt scaling that usually results serious surface damage during freeze-thaw cycles in the presence of saltwater pools on horizontal surfaces of structural elements. The damage is progressive and results the removal of small parts (flakes) of the surface of concrete.

Resistance to freeze-thaw cycles and de-icing agents are tested usually on surfaces of plain concrete specimens, and the pressure due to forming of iron-oxides is, therefore, excluded and scaling deterioration is explained with the cracking tendency of the brine ice formed in the saltwater pool resulting in glue spalling of the concrete surfaces [32, 33]. Short steel fibres in concrete may, however, add to the salt scaling resistance by the increased fracture toughness since the glue spalling crack propagation during scaling is a result of the ratio of fracture toughness of the ice film and that of the cementitious substrate [34]. Technical literature evidently shows that steel fibres alone cannot produce complete scaling resistance without the simultaneous application of air entraining agents [30, 31, 34]. It is also demonstrated that different supplementary cementing materials (fly ash, blast furnace slag, silica fume, metakaolin, calcined clay and natural pozzolans) can give even adverse influences on both the scaling phenomenon and the chloride binding capacity [35–38]. Therefore, the effects of fibres and mineral additives need separate analyses.

Understanding of the de-icing salt scaling behavior and scaling resistance of steel fibre reinforced concretes should be started at the composite material level of Ordinary Portland Cement (OPC) concretes. The possible influences of cast surfaces, supplementary cementing materials and air-entraining agents – use of the latter is, however, obligatory in case of freeze-thaw exposure of structures – is to be excluded from an exploratory study.

The present experiments, therefore, targeted to study the neat behavioral aspects of scaling damage on SFRC by conventional de-icing salt scaling test methods completed with a testing method developed by the authors, resulting more severe damage than the conventional methods.

2 Selection of materials for testing

For the durability studies of SFRC specimens Ordinary Portland Cement (OPC) of low C_3A content was selected (CEM I 42.5) and concrete mixes intentionally did not contain air entraining admixture. Main aim was to exclude the advantageous influence of entrained air and to study the direct influence of the steel fibres on the scaling performance. Crimped steel fibres (30/0.5; manufacturer D&D, Hungary) were applied based on their favorable properties demonstrated in earlier experiments. Dosage of fibres was fit to amounts accepted in construction practice (25, 50, 75 kg/m^3). Two different concrete mixes were studied: one with 300 kg/m^3 cement, $w/c = 0.54$ water-cement ratio and $V_{paste} = 259$ l/m^3 cement paste volume; the second mix is with 400 kg/m^3 cement, $w/c = 0.42$ water-cement ratio and $V_{paste} = 297$ l/m^3 cement paste volume. Quartz sand and gravel was used with maximum size of aggregate, MSA = 16 mm. Consistency of the fresh concrete was designed to be 500 ± 20 mm flow and was set by HRWR admixture in each case. Air content was targeted to be 10 l/m^3. Standard cube specimens were prepared and a laboratory vibrating table was used for compaction. Cubes were kept under water for 7 days. After 7 days the specimens were stored at laboratory condition (i.e. 20 ± 3°C temperature and 65 ± 5% relative humidity).

Main aims of the present studies are to reveal the influence, if any, of the steel fibres on the de-icing salt scaling resistance and to find the most appropriate material property that can characterize the damage accumulation. Authors aim to perform a comprehensive analysis that utilizes many different testing methods that may add to the better understanding of the de-icing salt scaling behavior of steel fibre reinforced concretes.

3 Results and evaluation

3.1 Mechanical and fracture properties

All important mechanical and fracture properties were assessed before the durability tests. General trends of group average values are indicated in Fig. 1 to 4 for the body density, the compressive strength, the flexural tensile strength and the splitting tensile strength. It can be realized that the influence of the steel fibres – as it was expected – is almost negligible on the compressive strength and on the flexural tensile strength, for the applied dosage of the steel fibres. Body density follows the increase in the steel fibre content. Splitting tensile strength is considerably increased by the steel fibres: 35% is the increase for 75 kg/m^3 steel fibre in the case of Mix 1 ($w/c = 0.54$) and 26% is the increase for 75 kg/m^3 steel fibre in the case of Mix 2 ($w/c = 0.42$).

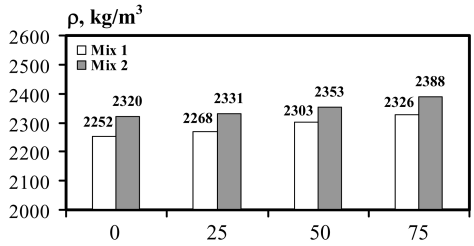


Fig. 1. Initial body density at the age of 28 days (before performing the durability tests)

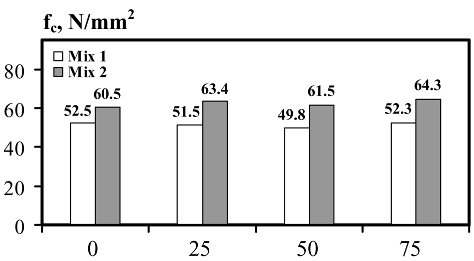


Fig. 2. Initial compressive strength at the age of 28 days (before performing the durability tests)

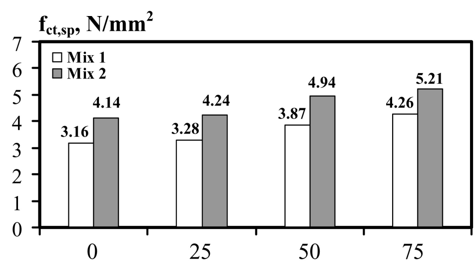


Fig. 3. Initial splitting tensile strength at the age of 28 days (before performing the durability tests)

Representative results of beam flexural tests are shown in Fig. 5 in the form of bending stress vs. mid-span deflection

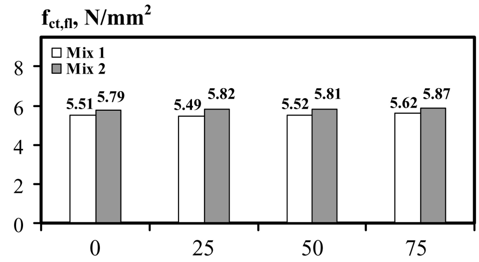
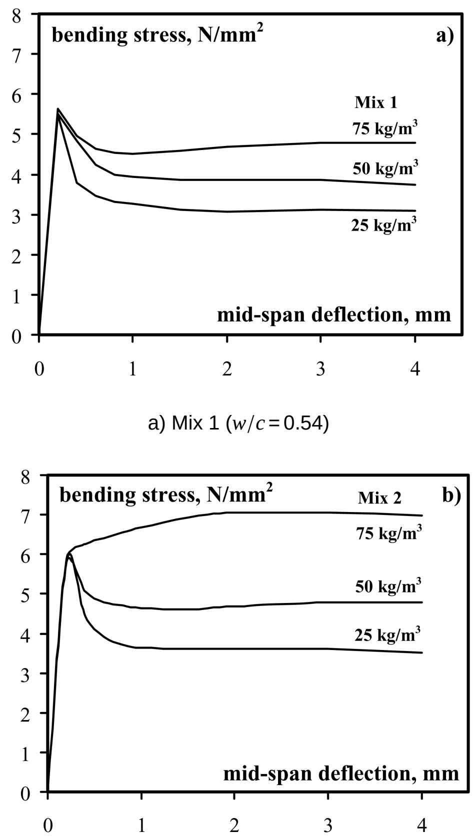


Fig. 4. Initial flexural tensile strength at the age of 28 days (before performing the durability tests)

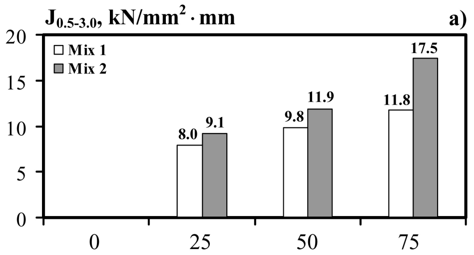
responses (75×150 mm cross section beams were tested in four-point bending over 600 mm clear span). It can be realized that considerable post cracking toughness can be activated in the case of Mix 2 ($w/c = 0.42$) at 75 kg/m^3 steel fibre content. However, majority of the results follow the typical shape of the load-deflection relationships found for steel fibre reinforced concretes of low fibre content. Post cracking flexural toughness ($J_{0.5-3.0}$) has been calculated as the area under the bending stress vs. mid-span deflection curve between the limits of $\delta_0 = 0.5$ mm and $\delta_1 = 3.0$ mm. Numerical values of post cracking flexural toughness ($J_{0.5-3.0}$) are indicated in Fig. 6a. Superior behavior of Mix 2 ($w/c = 0.42$) with 75 kg/m^3 steel fibre content is clearly visible.



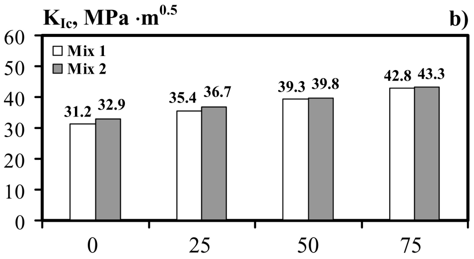
a) Mix 1 ($w/c = 0.54$)

b) Mix 2 ($w/c = 0.42$)

Fig. 5. Bending stress vs. mid-span deflection responses of beams tested in four-point bending



a) Post cracking flexural toughness ($J_{0.5-3.0}$ area under the bending stress vs. mid-span deflection curves)



b) Fracture toughness (K_{Ic} critical stress intensity factor)

Fig. 6. Toughness parameters of the mixes

Beam flexural tests were also carried out on notched members with CMOD instrumentation. Calculated values of the fracture toughness (K_{Ic} critical stress intensity factor) are indicated in Fig. 6b. The K_{Ic} critical stress intensity factor was calculated as $K_{Ic} = 6\text{Fl}/4\text{bh}^2(\text{cY})^{1/2}$; where F – concentrated load, l – span, b – depth of cross section, h – height of cross section, c – notch length, Y – geometry parameter; which latter was approximated with the following polynomial: $Y = 1.93 - 3.07\text{c/h} + 14.53\,(c/h)^2 - 25.11(c/h)^3 + 25.80(c/h)^4$ based on literature data. It can be realized that the fracture toughness is strongly influenced by the amount of steel fibres, and the effect of the strength of concrete is less pronounced.

3.2 Salt scaling tests

The suggestions of the CEN document CEN/TS 12390-9:2006 [39] for *slab test* were followed in the salt scaling tests. An alternative dimension of 150×150×50 mm was selected since the slab test specimens were sawn from larger beams. To avoid carbonation, the exposed surfaces were prepared right before the slab tests. Freeze-thaw cycles were applied at five levels and the scaling loss was measured after 7, 14, 28, 42 and 56 cycles. The exposure solution of 3% NaCl was refreshed after each level. All the specimens were tested up to 56 cycles. High scaling loss (g/m^2) was realized (Fig. 7). Severe scaling of more than 1000 g/m^2 was observed for the majority of the test slabs after 28 cycles.

The total scaling loss was determined first in the representation of the scaling loss that consisted the complete loss of mass (concrete + steel fibres) from which the mass of steel fibres (removed with a magnet) was subtracted and the final scaling loss (g/m^2) was resulted by adding the extra loss of mass for concrete (of which volume corresponded to the mass that is equal

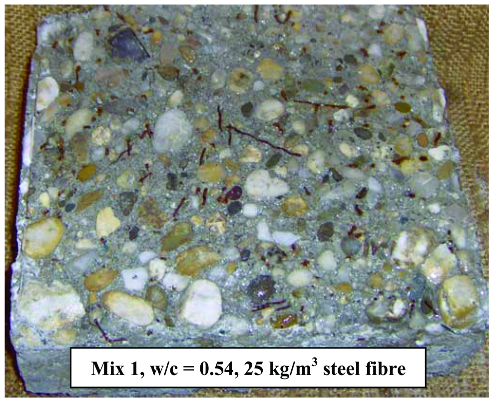
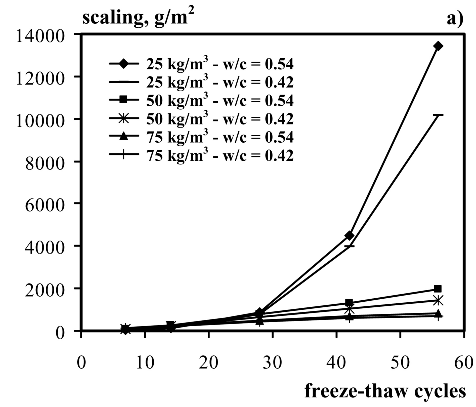


Fig. 7. Salt scaling damage of slab specimen tested according to CEN/TS 12390-9:2006 [39]

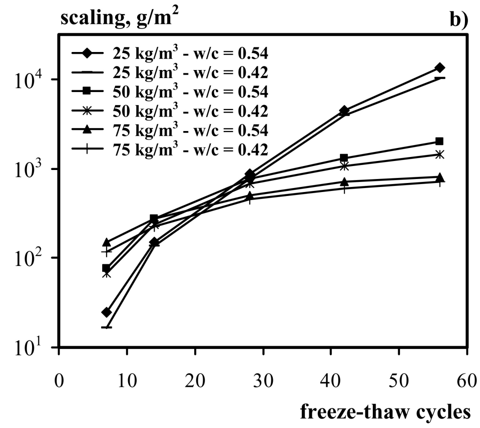
to the mass of steel fibres removed). Results for the scaling loss are indicated in Fig. 8. The diagrams show the group average responses (each data point gives the average of two or three individual measurements) with two different scales of the vertical axes: both a linear scale and a logarithm scale of the loss of mass are indicated. Clear occurrence of the rapidly increasing scaling damage *after 28 cycles* is realized along the linear scale of the vertical axis for those mixes which are the most sensitive to scaling (25 kg/m^3 fibre content). Influence of the concrete strength is almost negligible (that can be understood by the fracture toughness values given in Fig. 6b being less sensitive to strength and more sensitive to fibre content). It can be seen that 25 kg/m^3 steel fibre content could not utilize almost any scaling resistance.

The logarithm scale representation helps to confirm that the most important driver of the scaling resistance is the fibre content: data points corresponding to each dosage (25, 50 and 75 kg/m^3) show surprisingly similar trends, independently from the concrete strength. A possible combined action of the increasing interface area – consequently porosity due to the fibre addition – and the parallel increasing internal restrain action by the fibres can be visualized. During the first 7 freeze-thaw cycles the lowest scaling was realized on the 25 kg/m^3 fibre content specimens and the highest scaling was realized on the 75 kg/m^3 fibre content specimens. With increasing the number of the freeze-thaw cycles, the scaling of the 25 kg/m^3 fibre content specimens is accelerated at extreme rate, while the scaling of the 75 kg/m^3 fibre content specimens is increased linearly or even at a decreasing rate.

To see if percolated porosity accounts for these tendencies, the atmospheric water absorption and the vacuum water absorption of the specimens were measured and evaluated. Calculated values are given in Fig. 9 (apparent porosity is in V% and vacuum water absorption is in m%). It can be seen that the percolated porosity follows the change of the steel fibre content only in the case of the higher strength concrete (Mix 2; $w/c = 0.42$). The percolated porosity of specimens from Mix 1 ($w/c = 0.54$) is rather high and the influence of the additional interface area



a) Linear scale of vertical axis (scaling loss)

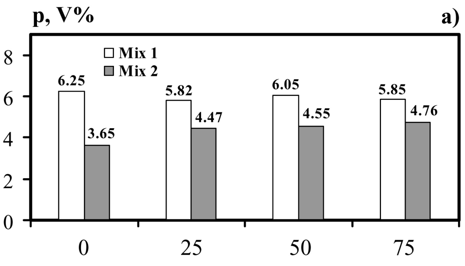


b) Logarithm scale of vertical axis (scaling loss)

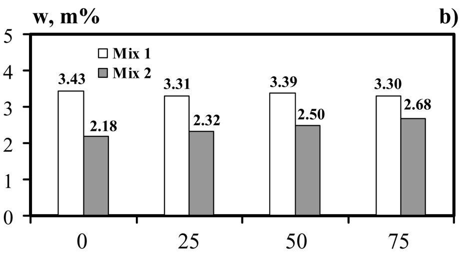
Fig. 8. Cumulative normalized scaling losses of slab specimens vs. number of freeze-thaw cycles

appearing by the addition of the steel fibres is not utilized as extra water permeable capillaries. It can be postulated that the behavior observed in Fig. 8 is due to the increased volume of the *interface transition zone* (ITZ) around the steel fibres that is basically not a water permeable layer; however, its porosity is higher than that of the cement gel [40, 41]. Technical literature explains that the most sensitive part of the hardened cement paste from the point of view of salt scaling is the ITZ because its fracture toughness is at least one order of magnitude smaller than that of the concrete as a resultant [34]. Damage within the ITZ is performed very fast during salt scaling as it is clearly visible in Fig. 8. If there is no adequate internal restrain (i.e. steel fibres) available in the concrete matrix then the scaling deterioration is accumulating very fast and the disintegration of the concrete specimen occurs (see Fig. 7). If there is, however, more than 50 kg/m^3 steel fibres available in the concrete then the high stiffness of the fibres is utilized and the scaling can be hindered.

Although, the experimental results presented here have evidently demonstrated the advantages of the application of steel fibres, it should be generally concluded that fibres alone could not provide appropriate scaling resistance to the studied medium strength concrete mixes.



a) Apparent porosity from atmospheric water absorption test



b) Vacuum water absorption

Fig. 9. Percolated porosity parameters of the mixes

3.3 Combined capillary suction/salt scaling/salt crystallization tests

In a realistic salt scaling situation, concrete can be damaged due to the crystallization pressure of NaCl (in case of saturation and drying) additionally to the scaling damage caused by the glue spalling mechanism. The damage can be present even without any frost action. Capillary activity (capillary suction) can also have an influence in particular cases. The effect of salt solution is more emphasized if combined with wetting and drying rather than stored continuously in a salt solution pool. To model a more severe damage, two test protocols have been developed for the present research, expecting more damage that is realized by the standard slab tests.

Protocol A: Prismatic samples (75×75×150 mm) are immersed up to half depth into NaCl solution of 3 m% concentration, and rotated by 90 degrees after each 8th cycle during the test of 32 freeze-thaw cycles. The protocol results *more severe* damage than classic methods that are using completely immersed specimens or slab specimens with a pool at their top. By the protocol, all sides of the samples are exposed to the combined action of freeze-thaw cycles and possible crystallization of NaCl since the surfaces can become saturated and can dry out and NaCl solution can be transported by capillary suction. Results (Fig. 10) supported the supposition that the developed test method results severe damage.

Protocol B: the same as above, but *without rotating* the prismatic samples. The *protocol B* seems to be less severe than *protocol A*.

Both *protocols A* and *B* resulted an accelerated deterioration compared to the slab test of CEN/TS 12390-9:2006 [39].

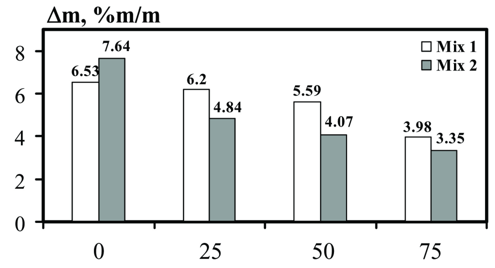


Fig. 10. Loss of mass after 32 freeze-thaw cycles by *protocol A*

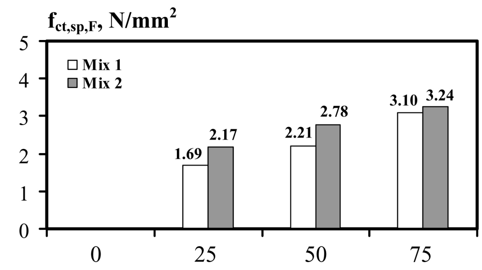


Fig. 12. Splitting tensile strength of specimens after 32 freeze-thaw cycles by *protocol A* (condition F)

3.4 Residual properties

Moduli of elasticity of the prismatic specimens were recorded both before and after applying the most severe *protocol A*. Results are indicated in Fig. 11. Favorable influence of the steel fibres is clearly demonstrated. All slab specimens after scaling tests according to CEN/TS 12390-9:2006 [39] and prismatic specimens after applying the *protocol A* were split for visual inspection and pH measurements, and the splitting loads were recorded to calculate the residual splitting tensile strengths. Average values corresponding to the prism specimens are indicated in Fig. 12. Nevertheless severe surface deterioration of the specimens was realized, considerable residual splitting tensile strength remained (generally higher than 2 N/mm^2). It indicates that steel fibres located farer from the surface are still effective. Results confirm how efficient can be the steel fibre addition on the splitting tensile strength in even weaker concrete matrices.

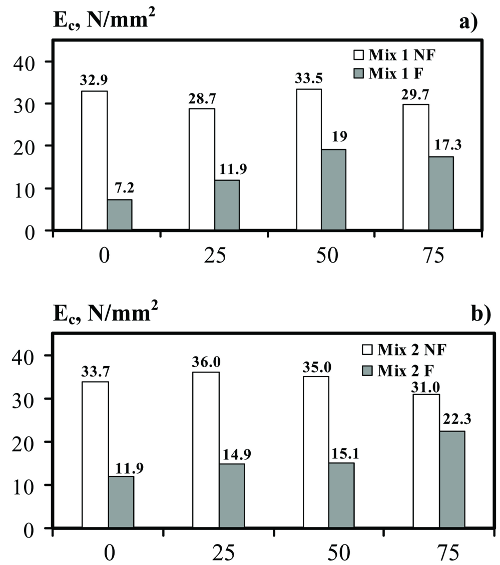


Fig. 11. Moduli of elasticity before (condition NF) and after (condition F) 32 freeze-thaw cycles by *protocol A*

Resistance against water penetration was tested both on specimens after freeze-thaw cycles and on specimens free of freeze-thaw influence but stored under laboratory conditions for more than 4 years. Tests were carried out according to EN 12390-8:2009 [42] applying 5 bar water pressure for 72 hours. Results of the tests for the specimens free of freeze-thaw influence are indicated in Fig. 13. Results are satisfactory; one may refer to DIN 1045-2 and DIN 1048-5 for the acceptable maximum water penetration depth suggested to be $h_{max} = 50$ mm [43, 44]. Results of the tests for the specimens after freeze-thaw cycles were found in the same satisfactory range (not represented in the diagram). Some larger scatter of the measured water penetration depths were realized (between 6 mm to 28 mm). It was demonstrated that even high fibre content may result favorable resistance against water pressure without any sign of compaction defect.

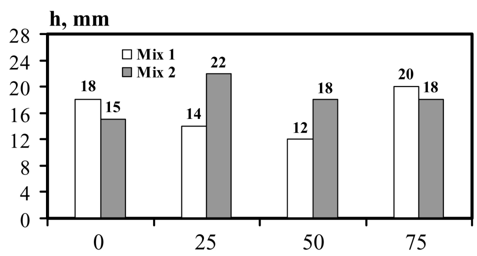


Fig. 13. Water penetration depths of 4 years old NF condition specimens recorded in watertightness tests according to EN 12390-8:2009 [42]

4 Discussion

Scaling and salt crystallization damage studies of SFRC as a composite material need to exclude the evidential influences of cast surfaces, air-entraining agents and supplementary cementing materials. This view can be, on the one hand, disputed from a practical point of view, but can be, on the other hand, tolerable from a basic research point of view that targets the fundamental understanding of the effect of the fibres. Technical literature emphasizes the importance of the paste rich cast surfaces of structural elements under realistic de-icing salt scaling conditions and, however, reflects on the possible influence of the macroscopic steel fibres on the scaling damage as well [30]. It is also discussed that the first freeze-thaw cycles may incorporate rapid deterioration of a thin layer at the surface [30]. Technical literature demonstrates that the addition of steel fibres may produce even reduction of the scaling resistance of air-entrained concrete by the disadvantageous increase of the spacing factor and making the air-voids in concrete become coarser [31].

Misleading results of such influences that may hide the neat effect of the fibres are successfully eliminated in the present experiments. Further, the importance of the increased volume of the interface transition zone (ITZ) around the steel fibres is highlighted for the first freeze-thaw cycles and the importance of the internal restrain activated by the steel fibres during later freeze-thaw cycles. Damage within the ITZ is performed very fast during salt scaling as it was demonstrated experimentally (see Fig. 8). If there is no adequate internal restrain available in the concrete matrix, then the scaling deterioration is accumulating rapidly, and the disintegration of the concrete specimen occurs. If there is, however, more than 50 kg/m^3 steel fibres available in the concrete, then the high stiffness of the steel fibres can be utilized and the scaling can be hindered. Superior performance of the crimped steel fibres used in the present studies has been demonstrated. Residual modulus of elasticity or residual splitting tensile strength measurements can be one appropriate measure in this sense.

5 Conclusions

De-icing salt scaling studies were performed on SFRC specimens made by Ordinary Portland Cement (OPC) of low C_3A content of concrete mixes that intentionally did not contain air entraining admixture. Neat behavioral aspects of damage kinetics of SFRC were studied by salt scaling tests according to CEN/TS 12390-9:2006 slab test, and by a combined capillary suction/salt scaling/salt crystallization tests developed by the authors. Test configuration made possible to reveal the importance of the increased volume of the interface transition zone (ITZ) around the steel fibres in the first freeze-thaw cycles and the importance of the internal restrain activated by the steel fibres during later freeze-thaw cycles. Damage within the ITZ was realized to be rapid during salt scaling. If there is no adequate internal restrain (i.e. steel fibres) available in the concrete matrix then the scaling deterioration is accumulating very fast and the disintegration of the concrete occurs. If there is, however, more than 50 kg/m^3 steel fibres available in the concrete then the high stiffness of the fibres is utilized and the scaling can be hindered. It can be demonstrated that the application of steel fibres fibres alone could not provide scaling resistance to the studied medium strength concrete mixes, but the increased fibre content considerably adds to the scaling resistance.

Acknowledgements

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References

1 **Madhavi T, Rao K**, *Fibre Reinforced Concrete*, VDM Publishing, 2011.

2 **Soutsos M, Le T, Lampropoulos A**, *Flexural performance of fibre reinforced concrete made with steel and synthetic fibres*, Construction and Building Materials, **66**, (2012), 704–710, DOI 10.1016/j.conbuildmat.2012.06.042.

3 **Meda A, Minelli F, Plizzari G, Riva P**, *Shear behaviour of steel fibre reinforced concrete beams*, Materials and Structures, **38**, (2005), 343–351, DOI 10.1007/BF02479300.

4 **Slater E, Moni M, Alam M**, *Predicting the shear strength of steel fibre reinforced concrete beams*, Construction and Building Materials, **26**, (2012), 423–436, DOI 10.1016/j.conbuildmat.2011.06.042.

5 **Cuenca E, Serna P**, *Shear behavior of prestressed precast beams made of self-compacting fibre reinforced concrete*, Construction and Building Materials, **45**, (2013), 145–156, DOI 10.1016/j.conbuildmat.2013.03.096.

6 **Neto B, Barros J, Melo G**, *A model for the prediction of the punching resistance of steel fibre reinforced concrete slabs centrically loaded*, Construction and Building Materials, **46**, (2013), 211–223, DOI 10.1016/j.conbuildmat.2013.04.034.

7 **Bayramov F, Tasdemir C, Tasdemir M**, *Optimisation of steel fibre reinforced concretes by means of statistical response surface method*, Cement and Concrete Composites, **26**, (2004), 665–675, DOI 10.1016/S0958-9465(03)00161-6.

8 **Luccioni B, Ruano G, Isla F, Zerbino R, Giaccio G**, *A simple approach to model SFRC*, Construction and Building Materials, **37**, (2012), 111–124, DOI 10.1016/j.conbuildmat.2012.07.027.

9 **Akcay B, Tasdemir M**, *Mechanical behaviour and fibre dispersion of hybrid steel fibre reinforced self-compacting concrete*, Construction and Building Materials, **28**, (2012), 287–293, DOI 10.1016/j.conbuildmat.2011.08.044.

10 **Abrishambaf A, Barros J, Cunha V**, *Relation between fibre distribution and post-cracking behaviour in steel fibre reinforced self-compacting concrete panels*, Cement and Concrete Research, **51**, (2013), 57–66, DOI 10.1016/j.cemconres.2013.04.009.

11 **di Prisco M, Plizzari G, Vandewalle L**, *Fibre reinforced concrete: new design perspectives*, Materials and Structures, **42**(9), (2009), 343–351, DOI 10.1617/s11527-009-9529-4.

12 **Merta I, Tschegg E**, *Fracture energy of natural fibre reinforced concrete*, Construction and Building Materials, **40**, (2013), 991–997, DOI 10.1016/j.conbuildmat.2012.11.060.

13 **López-Buendía A, Romero-Sánchez M, Climent V, Guillem C**, *Surface treated polypropylene (PP) fibres for reinforced concrete*, Cement and Concrete Research, **54**, (2013), 29–35, DOI 10.1016/j.cemconres.2013.08.004.

14 **Hassan A, Jones S, Mahmud G**, *Experimental test methods to determine the uniaxial tensile and compressive behaviour of ultra high performance fibre reinforced concrete (UHPFRC)*, Construction and Building Materials, **37**, (2012), 874–882, DOI 10.1016/j.conbuildmat.2012.04.030.

15 **Banthia N, Sappakittipakorn M**, *Toughness enhancement in steel fibre reinforced concrete through fibre hybridization*, Cement and Concrete Research, **37**(9), (2007), 1366–1372, DOI 10.1016/j.cemconres.2007.05.005.

16 **Buratti N, Mazzotti C, Savoia M**, *Post-cracking behaviour of steel and macro-synthetic fibre-reinforced concretes*, Construction and Building Materials, **25**(5), (2011), 2713–2722, DOI 10.1016/j.conbuildmat.2010.12.022.

17 **Wang J, Banthia N, Zhang M**, *Effect of shrinkage reducing admixture on flexural behaviors of fibre reinforced cementitious composites*, Cement and Concrete Composites, **34**, (2012), 443–450, DOI 10.1016/j.cemconcomp.2011.12.004.

18 **Pajak M, Ponikiewski T**, *Flexural behavior of self-compacting concrete reinforced with different types of steel fibres*, Construction and Building Materials, **47**, (2013), 397–408, DOI 10.1016/j.conbuildmat.2013.05.072.

19 **Tokgoz S, Dundar C**, *Tests of eccentrically loaded L-shaped section steel fibre high strength reinforced concrete and composite columns*, Engineering Structures, **38**, (2012), 134–141, DOI 10.1016/j.engstruct.2012.01.009.

20 **Nanni A**, *Fatigue behaviour of steel fibre reinforced concrete*, Cement and Concrete Composites, **13**(4), (1991), 239–245, DOI 10.1016/0958-9465(91)90029-H.

21 **Soetens T, Van Gysel A, Matthys S, Taerwe L**, *A semi-analytical model to predict the pull-out behaviour of inclined hooked-end steel fi-*

bres, Construction and Building Materials, **43**, (2013), 253–265, DOI 10.1016/j.conbuildmat.2013.01.034.

22 **Lublóy É, Halvax K**, *Study of steel fibre bond strength*, Építőanyag-JSBCM, **64**, (2012), 41–45, DOI 10.14382/epitoanyag-jsbcm.2012.7.

23 **Gribniak V, Kaklauskas G, Bacinskas D, Sung W-P, Sokolov A, Ulbinas D**, *Investigation of shrinkage of concrete mixtures used for bridge construction in Lithuania*, The Baltic Journal of Road and Bridge Engineering, **6**, (2011), 77–83, DOI 10.3846/bjrbe.2011.10.

24 **Desmettre C, Charron J**, *Water permeability of reinforced concrete with and without fibre subjected to static and constant tensile loading*, Cement and Concrete Research, **42**(7), (2012), 945–952, DOI 10.1016/j.cemconres.2012.03.014.

25 **Vasanelli E, Micelli F, Aiello M, Plizzari G**, *Crack width prediction of FRC beams in short and long term bending condition*, Materials and Structures, (2013), DOI 10.1617/s11527-013-0043-3. Published online: 26 March 2013.

26 **Tiberti G, Minelli F, Plizzari G, Vecchio F**, *Influence of concrete strength on crack development in SFRC members*, Cement and Concrete Composites, **45**, (2014), 176–185, DOI 10.1016/j.cemconcomp.2013.10.004.

27 **Mendes P, Barros J, Sena-Cruz J, Taheri M**, *Development of a pedestrian bridge with GFRP profiles and fibre reinforced self-compacting concrete deck*, Composite Structures, **93**(11), (2011), 2969–2982, DOI 10.1016/j.compstruct.2011.05.005.

28 **Lameiras R, Barros J, Valente I, Azenha M**, *Development of sandwich panels combining fibre reinforced concrete layers and fibre reinforced polymer connectors. Part I: Conception and pull-out tests*, Composite Structures, **105**, (2013), 446–459, DOI 10.1016/j.compstruct.2013.06.022.

29 **Lameiras R, Barros J, Azenha M, Valente I**, *Development of sandwich panels combining fibre reinforced concrete layers and fibre reinforced polymer connectors. Part II: Evaluation of mechanical behaviour*, Composite Structures, **105**, (2013), 460–470, DOI 10.1016/j.compstruct.2013.06.015.

30 **Cantin R, Pigeon M**, *Deicer salt scaling resistance of steel-fibre-reinforced concrete*, Cement and Concrete Research, **26**(11), (1996), 1639–1648, DOI 10.1016/S0008-8846(96)00162-7.

31 **Quanbing Y, Beirong Z**, *Effect of steel fibre on the deicer-scaling resistance of concrete*, Cement and Concrete Research, **35**(12), (2005), 2360–2363, DOI 10.1016/j.cemconres.2005.04.003.

32 **Valenza J, Scherer G**, *A review of salt scaling: I. Phenomenology*, Cement and Concrete Research, **37**(7), (2007), 1007–1021, DOI 10.1016/j.cemconres.2007.03.005.

33 **Valenza J, Scherer G**, *A review of salt scaling: II. Mechanisms*, Cement and Concrete Research, **37**(7), (2007), 1022–1037, DOI 10.1016/j.cemconres.2007.03.003.

34 **Valenza J, Scherer G**, *Mechanism of salt scaling*, Journal of the American Ceramic Society, **89**(4), (2006), 1161–1179, DOI 10.1111/j.1551-2916.2006.00913.x.

35 **Van den Heede P, Furniere J, De Belie N**, *Influence of air entraining agents on deicing salt scaling resistance and transport properties of high-volume fly ash concrete*, Cement and Concrete Composites, **37**, (2013), 293–303, DOI 10.1016/j.cemconcomp.2013.01.005.

36 **Ahani R, Nokken M**, *Salt scaling resistance – The effect of curing and pre-saturation*, Construction and Building Materials, **26**(1), (2012), 558–564, DOI 10.1016/j.conbuildmat.2011.06.058.

37 **Shi X, Xie N, Fortune K, Gong J**, *Durability of steel reinforced concrete in chloride environments: An overview*, Construction and Building Materials, **30**, (2012), 125–138, DOI 10.1016/j.conbuildmat.2011.12.038.

38 **ASTM**, *Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration. ASTM C1202-12*, ASTM International, 2012, DOI 10.1520/C1202-12. March 2012.

39 **CEN**, *CEN/TS 12390-9:2006. Testing hardened concrete - Part 9: Freeze-thaw resistance – Scaling*, CEN/TC 51 - Cement and building limes, 2006-08-31.

40 **Mehta P, Monteiro P**, *Concrete: Microstructure, Properties, and Materials*, McGraw-Hill, 2006.

41 **Wasserman R, Bentur A**, *Interfacial interactions in lightweight aggregate concretes and their influence on the concrete strength*, Cement and Concrete Composites, **18**(1), (1996), 67–76, DOI 10.1016/0958-9465(96)00002-9.

42 **CEN**, *EN 12390-8:2009. Testing hardened concrete - Part 8: Depth of penetration of water under pressure*, CEN/TC 104 - Concrete and related products, 2009-08-31.

43 **DIN**, *DIN 1045-2:2008-08. Tragwerke aus Beton, Stahlbeton und Spannbeton - Teil 2: Beton - Festlegung, Eigenschaften, Herstellung und Konformität - Anwendungsregeln zu DIN EN 206-1*, Deutsches Institut für Normung, 2008-08.

44 **DIN**, *DIN 1048-5:1991-06. Prüfverfahren für Beton; Festbeton, gesondert hergestellte Probekörper*, Deutsches Institut für Normung, 1991-06.