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DEICER SALT SCALING RESISTANCE OF STEEL-FIBER-REINFORCED CONCRETE

Richard Cantin and Michel Pigeon
Department of Civil Engineering, Laval University
Ste-Foy (Qué), Canada, G1K 7P4

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ABSTRACT

This project is part of a global research program aimed at studying the durability of steel-fiber-reinforced concrete exposed to severe winter conditions. It was carried out to determine if the use of steel fibers can have a significant influence on the deicer salt scaling resistance of concrete. Sixteen steel-fiber-reinforced concrete mixtures were investigated. The test variables were the water/binder ratio, the use of silica fume, the type of fiber and the quality of the air-void network. The results of the tests show that the fibers have no apparent influence on the deicer salt scaling resistance of concrete. Furthermore, it has been observed that a very small difference in the minimal freezing temperature could have a great influence on the deicer salt scaling resistance.

Introduction

Despite the recent progress in concrete technology, the basic mechanisms of deicer salt scaling are still not perfectly understood. It is clear, however, that this phenomenon only affects a surface layer of a few millimeters and that the microstructure of this layer can be quite different from that of the bulk of the concrete (1). Of course, since scaling is due to freezing (in the presence of deicer salts), it is influenced both by the air-void characteristics and by the porosity of the surface layers.

There are very little data available on the deicer salt scaling resistance of steel-fiber-reinforced concrete (2,3). Fibers can be expected to influence scaling indirectly, mostly through their negative effect on workability. The presence of fibers generally requires the use of higher dosages of the admixtures, and it can also make the finishing operations more difficult. These, in turn, can affect the microstructure of the surface layers, which control the deicer salt scaling resistance. Furthermore, because of their coarser porosity, the presence of fiber-matrix interfaces may also promote deicer salt scaling.

The experiments described in this paper were performed to obtain more information on the influence of fibers on the resistance to scaling. The basic parameters of this study were the quality of the air-void network, the water/binder ratio, the presence of silica fume and the type of fibers.

TABLE 1.
Mixture Proportions.

Mixture	Water/binder ratio	Water (kg/m3)	Cement		Sand (kg/m3)	Coarse aggregate (kg/m3)	Fibers (kg/m3)	Admixture dosages (ml/kg of cement)		
			(Type 10) (kg/m3)	(Blended) (kg/m3)				W.R.	A.E.A.	S.P.
45N	0.45	168	373	--	800	975	0	2	0.25	0.00
45C	0.45	168	373	--	800	975	40	0	0.25	2.98
45T	0.45	168	373	--	800	975	40	0	0.25	2.84
45FN	0.45	168	--	373	800	975	0	2	0.25	1.00
45FC	0.45	168	--	373	800	975	40	0	0.25	4.96
45FT	0.45	168	--	373	800	975	40	0	0.25	5.67
35N	0.35	150	429	--	800	975	0	0	1.00	7.00
35N(2)	0.35	150	429	--	800	975	0	0	0.50	7.00
35C	0.35	150	429	--	800	975	40	0	1.00	8.00
35T	0.35	150	429	--	800	975	40	0	0.85	8.00
35FN	0.35	150	--	429	800	975	0	0	0.50	9.00
35FC	0.35	150	--	429	800	975	40	0	0.75	9.00
35FT	0.35	150	--	429	800	975	40	0	1.00	10.00
35FN/NA	0.35	150	--	429	800	975	0	0	0.00	9.00
35FC/NA	0.35	150	--	429	800	975	40	0	0.00	11.00
35FT/NA	0.35	150	--	429	800	975	40	0	0.10	10.00

Experimental

Mixtures and Materials. All mixture compositions are given in Table 1. Two cements were used: a normal Canadian Type 10, and a blended cement containing 8.5% silica fume. The Blaine fineness of the former is 422 m^2/kg and that of the latter, 595 m^2/kg. The chemical compositions and properties of these two cements are similar: their C_3A contents are 6.9% and 7.1% respectively, and their alkali content is 0.66% (Na_2O equivalent). The mixtures made with silica fume are identified in Table 1 by the letter F. The same natural sand was used for all mixtures. The fineness modulus of this sand varies between 2.3 and 2.6. The coarse aggregate that was used is a crushed limestone with nominal dimensions of 14/5 mm. The admixtures were of the following types: a fatty acid-based air-entraining agent, a hydroxycarboxylic acid-based water-reducer, and a naphtalene-based superplasticizer.

Two types of steel fibers with different geometries were selected (Table 2). One is deformed along its entire length and the other is deformed only at the ends. After preliminary trials, the dosage was established at 40 kg/m^3 (about 0.5% by volume). Such a dosage is considered sufficiently high to take advantage of the improvements relative to the use of fibers while being realistic enough to be used on the job site. Reference mixtures containing no fibers were also prepared. In Table 1, the mixtures containing the crimped fibers, the end-deformed fibers, and no fibers are identified by the letters C, T and N respectively.

The mixtures were designed to have an adequate air-void network and workability by varying the dosages of the admixtures. As can be seen in Table 1, six mixtures were made at a water/binder ratio of 0.45 (typical of normal strength concrete) and ten at 0.35 (a ratio expected to yield a very good scaling resistance). Three of these last ten mixtures were made with little or no air-entraining admixture in order to evaluate the effect of the quality of the air-void network. These mixtures are identified by the letters NA in Table 1.

Casting, Curing and Testing. Mixing was carried out in a 0.1 m^3 drum-type mixer. The fibers were premixed with the dry materials before adding the water and the admixtures. The sand was always placed first in the mixer, followed by the coarse aggregates, the binder, the fibers, the water, and, finally, the admixtures. To assess workability, the Vebe test was carried out for all mixtures containing fibers. This test is more adapted to fiber-reinforced concrete because it measures the workability under vibration rather than the fluidity of the mixture. The fluidity of fiber-reinforced concrete is significantly reduced which makes the slump test less applicable. However, since the Vebe test is not widely used, slump was also determined.

The following specimens were cast from each mixture: two slabs to evaluate the salt scaling resistance according to the ASTM C-672 method, one prism to measure the characteristics of the air-void network using the ASTM C-457 modified point-count method, and two 150 × 30 mm cylinders to assess the compressive strength. All specimens were cast in

TABLE 2
Fiber Characteristics (from ref. (4))

Fiber	Geometry	Cross-section shape	Length (mm)	Diameter (mm)	Weight (g)	Number per kg
	Crimped	Circular	60	1.0	0.37	2703
	End-deformed	Circular	54	1.0	0.34	2941

two layers, the vibration time varying between 10 and 20 seconds, depending upon the mixture and the type of specimen. Special care was taken to avoid over finishing the slabs. Immediately after casting, all specimens were covered with a wet canvas and a polyethylene sheet. After demolding at 24 hours of age, the slabs were immersed in lime saturated water for 13 days and the cylinders were stored in a moist room for 27 days. The cylinders were tested immediately after curing, but the slabs were placed in a drying room for 14 days before the scaling tests, which were performed using a 3% NaCl solution.

Compressive strengths are shown in Table 3. All values can be considered normal for these types of concrete, except those for the 0.35 mixtures without silica fume which are a little low for such a water/cement ratio. The results of the Vebe test and the values of slump are given in Table 4, together with the air-void network characteristics. As expected, the spacing factor of all air-entrained mixtures is close to the target value of 200 μm. Furthermore, due to air losses that may occur after casting, the air content of hardened concrete is, in most cases, lower than that of fresh concrete. However, the air content of mixture 35N is higher for fresh concrete than for hardened concrete. Such a result may be explained by some imprecisions in the methods used for the determination of the air content (the pressiometric method and the ASTM C457 method), by different methods of compaction between concrete tested in the air-meter and cast-in-place concrete and by the heterogeneity of concrete (5).

Due to a technical error, the minimum temperature during the first 50 freezing and thawing cycles was somewhat higher than that specified in the standard (i.e. approximately −14 °C instead of −18 °C). The main objective of the experiments being to compare the scaling resistance of fiber-reinforced and of non-fiber-reinforced concrete, it was decided simply to subject all specimens, after a drying period of a few days, to an additional 50 cycles using the minimum temperature prescribed by the standard.

TABLE 3
Compressive Strengths

Mixture	Compressive strength (MPa)
45N	38.69
45C	41.23
45T	40.85
45FN	58.20
45FC	55.08
45FT	53.71
35N	41.83
35N(2)	43.94
35C	41.79
35T	43.97
35FN	60.06
35FC	54.72
35FT	57.29
35FN/NA	71.43
35FC/NA	67.62
35FT/NA	62.60

TABLE 4.
Workability and Air-Void Network Characteristics.

Mixture	Slump (mm)	Vebe test results				Air content of concrete		Spacing factor (μm)	Specific surface (mm-1)
		H1* (mm)	H2** (mm)	H2-H1 (mm)	Time (sec)	Fresh (%)	Hardened (%)		
45N	110	6.5	17.5	11	3.35	8.4	7.3	106	33.8
45C	70	6.5	17.5	11	2.78	6.6	4.2	120	41.5
45T	85	9.5	17.5	8.0	2.38	6.2	5.6	150	29.8
45FN	60	4.5	17.5	3.0	3.57	7.0	4.6	148	32.1
45FC	45	4.5	17.5	3.0	3.97	5.3	3.3	211	26.7
45FT	60	5.0	18.0	3.0	3.83	6.0	4.0	167	31.6
35N	110	11.5	17.5	6.0	2.26	9.0	9.8	90	29.2
35N(2)	125	12.0	17.5	5.0	2.00	7.6	6.8	152	27.3
35C	85	7.5	17.5	10.0	2.99	8.5	6.6	102	39.6
35T	100	9.0	17.5	8.5	2.95	n/a	6.0	131	33.8
35FN	70	6.5	17.5	11.0	4.49	4.6	3.4	247	22.4
35FC	70	6.5	17.5	11.0	3.97	5.7	5.0	232	20.5
35FT	70	9.0	17.5	8.5	3.05	5.3	4.9	191	25.4
35FN/NA	70	6.0	17.5	11.5	3.31	3.4	1.6	607	13.3
35FC/NA	130	9.5	17.5	8.0	2.81	2.7	1.6	563	13.6
35FT/NA	80	6.0	17.5	6.5	3.41	3.5	2.8	486	12.1

* Distance between the reference point and the top of concrete after the slump cone has been removed

** Distance between the reference point and the concrete surface (after vibration)

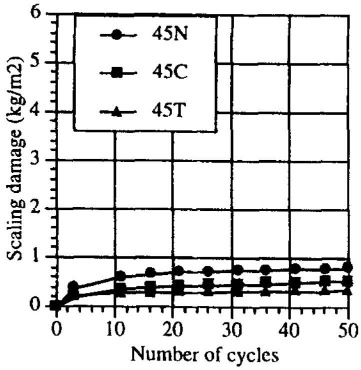

FIG. 1.
W/B = 0.45, Type 10, air-entrained.

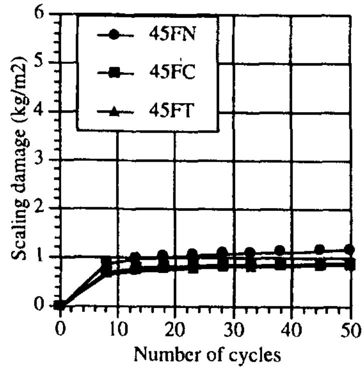

FIG. 2.
W/B = 0.45, blended, air-entrained.

Results and Discussion

The results of the deicer salt scaling tests are shown in Figures 1 to 5 (minimum temperature of −14 °C) and 6 to 10 (minimum temperature of −18 °C). As it is very often observed in laboratory tests, the shape of the curves in Figures 1 to 5 indicate in most cases the rapid deterioration of a thin layer at the surface during the first cycles.

Influence of Fibers. It is clear from the data in Figures 1 to 10 that neither the presence of fibers nor the type of fiber had any significant influence on the scaling resistance. For each of the 5 series of mixtures, i.e. for all types of cement matrix, the curves for the two fiber-reinforced concretes are very similar to that for the reference non-reinforced mixture. This is true even if the presence of fibers generally required higher dosages of the admixtures. It was observed that there was often more scaling deterioration close to the fibers on the surface, probably due to the porosity of the fiber-matrix interfaces, but the amount of scaling residues was obviously not significantly influenced by this phenomenon.

The mixtures prepared were designed to contain fibers, i.e. had a slightly higher sand content than most common mixtures. It is thus possible that the mixtures made without

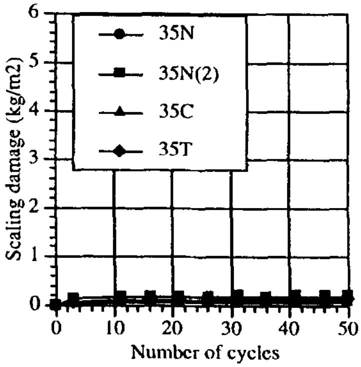

FIG. 3.
W/B = 0.35, Type 10, air-entrained.

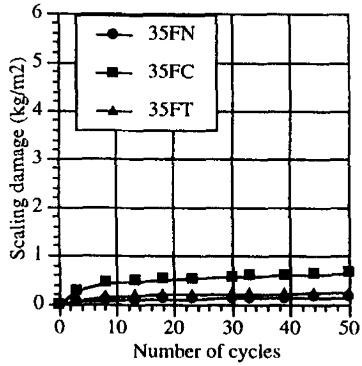

FIG. 4.
W/B = 0.35, blended, air-entrained.

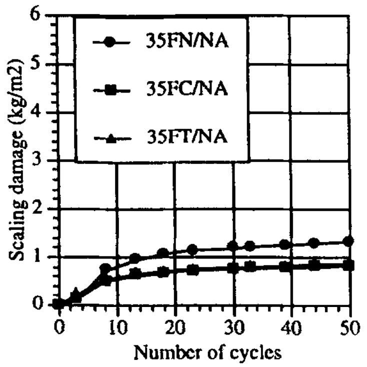

FIG. 5.
W/B = 0.35, blended, non air-entrained.

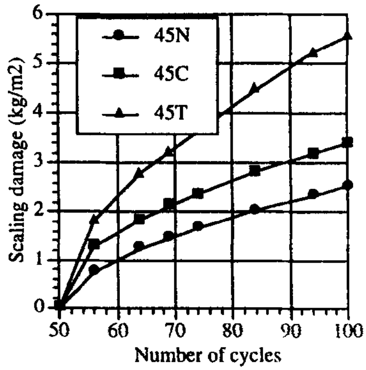

FIG. 6.
W/B = 0.45, Type 10, air-entrained.

fibers would have performed somewhat better had they been optimized to minimize the paste content. However, it can be noticed in Figures 1 to 10 that the best and the worst overall performances were both achieved with fiber-reinforced concretes.

Influence of Testing History. The results of the scaling tests for the various reference mixtures in Figures 1 to 4 appear to be typical of properly air-entrained laboratory concretes: the amount of residues after 50 cycles for the 0.45 mixtures are equal to or lower than 1.0 kg/m^2, and, as expected, the scaling resistance is better for the 0.35 mixtures. Furthermore, the results for the non-air-entrained 0.35 silica fume mixture (Figure 5) seem to confirm that such concretes can have a fairly good resistance to scaling. The results in Figures 6 to 9 for the air-entrained reference concretes, however, are not typical, since the rate of deterioration, both in the first cycles and after, is generally quite high for such tests performed using the basic freezing and thawing cycle of ASTM C672. It thus seems that either these reference concretes were abnormally susceptible to scaling (which would be surprising considering their composition, their fresh concrete properties and their compressive strength), or the testing conditions (a short drying period after 50 "soft" cycles followed by 50 "normal"

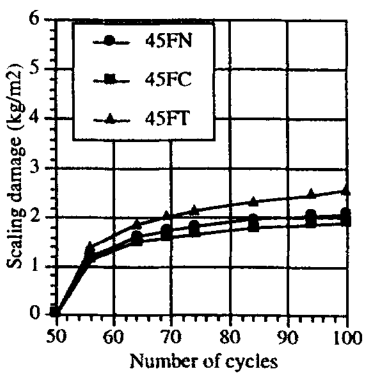

FIG. 7.
W/B = 0.45, blended, air-entrained.

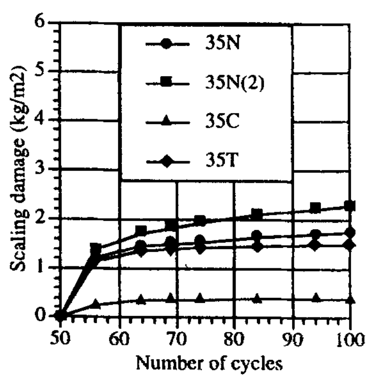

FIG. 8.
W/B = 0.35, Type 10, air-entrained.

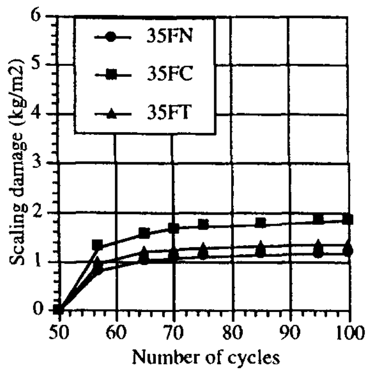

FIG. 9.
W/B = 0.35, blended, air-entrained.

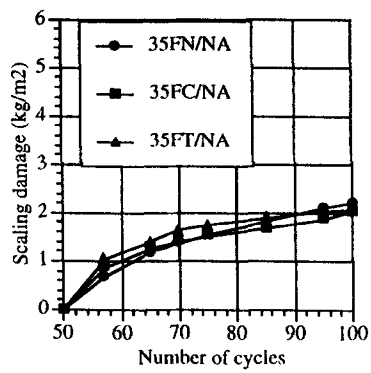

FIG. 10.
W/B = 0.35, blended, non air-trained.

cycles) were particularly harsh (for reasons still to be found). The result in Figure 10 for the non-air-entrained 0.35 silica fume mixture confirms the lower scaling resistance observed during the second series of 50 cycles, and thus shows that the lower scaling resistance for the other reference mixtures is probably not due to air entrainment problems in the surface layers.

Figures 1 to 10 show that the rate of scaling deterioration during the second series of cycles (with a lower minimum temperature) is much larger than that during the first series of cycles, but particularly for the mixtures made without silica fume. At lower temperatures, ice can be formed in smaller pores, which thus increases the total amount of ice formed during each cycle. It is then possible that the pore size distribution in the concretes made without silica fume was such that a significant amount of ice was formed between −14 °C and −18 °C. However, several low temperature calorimetry tests carried out on various dried and resaturated concretes have shown that most of the ice has already been formed at −15 °C (6, 7, 8).

Influence of the Quality of the Air-Void Network. The results for the 0.35 silica fume mixtures with high spacing factor values (Figures 5 and 10) can be compared to the results for the similar air-entrained mixtures (Figures 4 and 9). Even if the deterioration due to scaling is always smaller for the properly air-entrained mixtures, the difference is small. This tends to confirm previously published data indicating that air-entrainment is not required for scaling resistance when the water/binder ratio is sufficiently low (9).

Presence of Silica Fume. From Figures 1 to 4 and 6 to 9, it can be observed that the use of silica fume had more influence on the 0.45 than on the 0.35 mixtures. Surprisingly, however, the deterioration due to scaling is higher in the silica fume mixtures than in the mixtures without silica fume during the first 50 cycles, but lower during the second series of 50 cycles (with a lower minimum temperature). The use of silica fume (which causes a refinement of the porosity and thus reduces the amount of freezable water and the permeability) has been observed to have both positive and negative effects on the resistance to scaling (9), but these observations do not allow any valid explanation of the test results presented here. In this study, it seems that the use of silica fume had a slightly negative influence during the first "soft" cycles, but helped, either to prevent the problems due to the drying period before the second series of cycles, or to reduce the damage during the second series of "normal" cycles with a minimum temperature of −18°C.

Conclusions

The first conclusion that can be drawn from this study is that the use of macro steel fibers does not affect the deicer salt scaling resistance of concrete. Scaling can occur over the fibers that are near the surface, but this has no significant overall influence on the total amount of scaling damage. During normal scaling tests, the surface of concrete is always covered with (salt) water, and hence corrosion is prevented. The results could have thus have been different if the fibers had been allowed to corrode. A special procedure including wetting and drying cycles could therefore be developed to determine the deicer salt scaling resistance of steel-fiber-reinforced concrete.

Since fibers were not found to affect the scaling resistance, the same trends as for ordinary concretes were observed for fiber-reinforced concretes. Lower water/binder ratios and adequate air-void networks were found to improve the deicer salt scaling resistance.

The test conditions are of prime importance for the determination of the deicer salt scaling resistance. Concretes that seem durable when tested at −14 °C may be much less when tested at −18 °C, although other conditions such as drying could also have influenced the observed results.

The influence of silica fume was found to vary with the test conditions: it was slightly negative during the first series of cycles (with a minimum temperature of −14 °C), but quite positive when the concretes were subjected to a second series of more severe cycles.

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