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DURABILITY OF MICROFIBER-REINFORCED MORTARS

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ABSTRACT

The frost durability of steel and carbon micro-fiber reinforced mortars was assessed. Tests of freezing and thawing and surface scaling were performed on the mortars. The effect of drying on the frost durability was also studied. The results show that the use of steel and particularly carbon microfibers improve the frost and deicer salt scaling resistance of mortars. The improvement is however in part due to the "air entrainment" properties of the micro-fibers.

Introduction

Micro-reinforcement of pastes and mortars with the use of carbon, steel, and various other types of fibers represents a very interesting field of research, since it opens up the possibility of producing thin structural or cladding elements without any conventional steel reinforcement. Although many papers have been published recently on the mechanical properties of micro-reinforced systems (1, 2, 3), there are only few data available on their durability (4, 5). Such data, however, are required if micro-reinforced pastes or mortars are to be utilized in severe environments. The tests described in this paper were performed to obtain information on this important topic.

Test Program

The tests were performed on mortars reinforced with both steel and carbon fibers. The main variables investigated were the volume of fibers (0%, 1%, and 2%), the fine aggregate to total binder mass ratio (1 and 2), the silica fume to total binder mass ratio (8% and 15%), and the curing regime (normal curing, and normal curing followed by 90 days of drying at 23°C and 50% relative humidity or 38°C at 40% relative humidity). In addition to the usual strength tests, the drying shrinkage, the chloride ion permeability, the frost resistance, and the resistance to scaling due to freezing in the presence of a deicer salt solution were evaluated.

Materials, Mixture Composition, and Experimental Procedures

The same normal portland cement and the same silica fume were used for all mixtures. Their compositions are presented in Table 1. The fine aggregate was a granitic sand with a fineness modulus of 2.4 and a 24
hour absorption of 0.6%. All mixtures were prepared in a standard mortar mixer at a constant water to binder ratio of 0.35. The mixing sequence was the following: the cement, silica fume, and water containing a naphtalene based superplasticizer were first mixed to form a paste, then the fibers were slowly added while mixing continued, and finally the sand was incorporated.

Table 2 gives the composition of the mortar mixtures. Four groups of five mixtures were made: the first group was prepared with 8% silica fume (at a fine aggregate to total binder ratio of 1), the second group with 15% silica fume (at a fine aggregate to total binder ratio of 1), the third group with 8% silica fume (at a fine aggregate to total binder ratio of 2), and a fourth group with 15% silica fume (at a fine aggregate to total binder ratio of 2). In each group, one mixture was made without fibers, one with 1% of steel fibers, one with 2% of steel fibers, one with 1% of carbon fibers, and one with 2% of carbon fibers.

The steel fibers were 3 mm in length with a cross section of approximately 5 μm by 25 μm. The carbon fibers were 10 mm in length with a diameter of 18 μm. Both types of fibers have a strength of approximately 600 MPa, but the elastic modulus of the carbon, at 30 GPa, is much lower than that of the steel (200 GPa). The relative density of the carbon is 1,65 (7,85 for the steel).

The specimens required for the various tests were prepared using a vibrating table, except those made with the mixture containing 2% of carbon fibers which required rodding, since that mixture was particularly stiff. The specimens for the shrinkage measurements were cured for seven days in lime saturated water before the tests. Those for the other tests were separated into three groups. In the first group (basic tests), the specimens were simply cured for 14 days in lime saturated water, and then tested immediately, with the exception of those for the compresssive strength tests, since these tests were performed after 7 days and 28 days of curing in lime saturated water, and also with the exception of those for the deicer salt scaling tests (since these tests are normally carried out after 14 days of drying at 23°C following 14 days of curing in lime saturated water). In the second group, they were first cured in lime saturated water for the same period as in the first group, and then they were allowed to dry for 90 days at 23°C before the tests. In the third group, the procedure was similar to that for the second group, but the drying temperature was 38°C. For the strength test specimens of the second and

TABLE 1

Cement and Silica Fume Composition

Silica Fume		Cement	
	%		%
SiO_2	92.6	SiO_2	19.6
Al_2O_3	0.5	Al_2O_3	4.1
Fe_2O_3	1.8	Fe_2O_3	2.8
CaO	0.8	CaO	64.0
MgO	0.6	MgO	2.8
K_2O	1.0	SO_3	2.3
SO_3	0.3	K_2O	0.5
		Na_2O	0.5
		Blaine (cm^2/g)	3692

TABLE 2

Mix Characteristics

Mix Code	Water (kg/m^3)	Cement (kg/m^3)	Silica Fume (kg/m^3)	Sand (kg/m^3)	Sp[1] (L/m^3)	SF/B[2] (%)	S/B[3]	Fiber Content (%)	Unit Weight (kg/m^3)
N-0-08-1	320	843	73	931	3.7	8	1	0.0	2169
St-1-08-1	318	838	73	917	6.0	8	1	1.0	2230
St-2-08-1	295	775	68	847	9.0	8	1	1.9	2140
C-1-08-1	312	819	71	895	9.6	8	1	1.0	2118
C-2-08-1	299	786	68	855	19.5	8	1	1.9	2050
N-0-15-1	324	789	140	933	4.7	15	1	0.0	2191
St-1-15-1	316	767	135	902	10.0	15	1	1.0	2200
St-2-15-1	301	729	129	863	13.2	15	1	1.9	2170
C-1-15-1	325	770	136	909	12.1	15	1	1.0	2149
C-2-15-1	307	744	132	869	18.0	15	1	2.0	2080
N-0-08-2	242	635	55	1374	5.0	8	2	0.0	2310
St-1-08-2	218	574	50	1253	7.5	8	2	0.9	2172
St-2-08-2	205	539	46	1177	10.5	8	2	1.8	2113
C-1-08-2	220	579	51	1259	17.1	8	2	0.9	2134
C-2-08-2	211	555	48	1208	42.6	8	2	1.9	2074
N-0-15-2	236	573	101	1355	10.0	15	2	0.0	2265
St-1-15-2	225	545	96	1289	13.5	15	2	1.0	2160
St-2-15-2	201	488	86	1149	15.6	15	2	1.7	2066
C-1-15-2	220	535	94	1263	15.2	15	2	0.9	2136
C-2-15-2	212	516	92	1213	33.3	15	2	1.9	2080

[1]Sp: Superplasticizer; [2]SF: Silica Fume, B: Binder; [3]S: Sand Mix Code N: No fiber; St: Steel fiber; C: Carbon Code: Fiber type - Fiber percent -SF/B - S/B

third groups, only those cured for 28 days were selected. Drying for 90 days, particularly at 38°C, was used as an accelerated ageing procedure, since drying opens up the pore structure and creates microcraking (both phenomena normally having a negative influence on durability related properties).

Two 23 × 36 × 195 mm prisms were used for the shrinkage tests (ASTM C157), and two similar prisms for the rapid freezing and thawing cycle tests (ASTM C666, procedure A). Two 110 × 300 × 25 mm slabs were used for the deicer salt scaling tests (ASTM C672), and two 51 mm in length and 100mm in diameter specimens (cored in a 75 mm thick slab) for the rapid chloride permeability tests (AASTHO T227-831). These permeability tests were only performed on specimens from the non-reinforced mixtures and the steel fiber-reinforced mixtures. Three 50 mm in diameter and 100 mm in length cylinders were used for each compressive strength test. The air void system of all mortars was characterized using the modified point count method of ASTM C457.

Test Results

The basic characteristics of the air void system of all mixtures are presented in Table 3. The air void spacing factor of the micro-reinforced mortars, which varies between 170 μm and 440 μm, is generally relatively close to the usual recommended value for good frost resistance (200 μm),

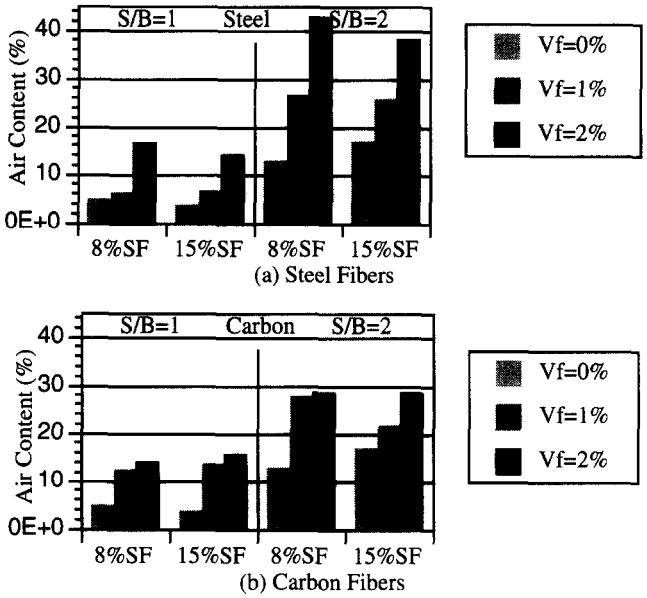

FIG.1.
Effect of various parameters on air content.

TABLE 3

Air Void System Characteristics

Mix Code	Air Content (%)	Specific Surface (mm^{-1})	Spacing Factor (μm)
N-0-08-1	5.0	13.7	629
St-1-08-1	6.2	26.5	288
St-2-08-1	16.6	18.4	258
C-1-08-1	12.3	12.9	436
C-2-08-1	13.9	20.4	254
N-0-15-1	3.8	15.7	594
St-1-15-1	6.4	19.4	376
St-2-15-1	14.0	17.0	293
C-1-15-1	13.5	14.7	367
C-2-15-1	15.5	16.2	314
N-0-08-2	12.7	10.5	544
St-1-08-2	26.4	16.1	202
St-2-08-2	42.7	9.6	176
C-1-08-2	27.6	9.9	318
C-2-08-2	28.8	11.4	255
N-0-15-2	16.9	7.5	645
St-1-15-2	25.8	11.8	282
St-2-15-2	38.0	11.3	174
C-1-15-2	21.6	13.0	318
C-2-15-2	28.8	11.0	249

TABLE 4

Compressive Strength (MPa)

Mix Code	Compressive Strength Moist Curing 7 days	Compressive Strength Moist Curing 28 days	Compressive Strength 90 Day Drying 23°C	Compressive Strength 90 Day Drying 38°C
N-0-08-1	32.8	56.3	65.8	63.4
St-1-08-1	44.9	57.5	70.3	50.8
St-2-08-1	31.0	45.7	77.6	58.0
C-1-08-1	33.4	48.3	49.1	46.3
C-2-08-1	34.6	43.6	45.2	49.3
N-0-15-1	36.4	54.2	62.6	54.3
St-1-15-1	40.7	56.7	72.2	51.1
St-2-15-1	30.7	53.6	77.9	63.8
C-1-15-1	30.2	47.6	51.1	47.1
C-2-15-1	36.6	49.0	41.9	44.2
N-0-08-2	39.8	54.9	60.7	59.1
St-1-08-2	35.2	48.2	63.3	50.6
St-2-08-2	28.9	48.8	68.0	50.7
C-1-08-2	37.9	51.1	54.7	52.5
C-2-08-2	31.4	41.3	36.5	47.6
N-0-15-2	50.6	55.8	67.6	64.0
St-1-15-2	39.3	55.5	72.1	54.5
St-2-15-2	24.9	43.3	72.9	49.3
C-1-15-2	39.2	50.7	51.7	47.8
C-2-15-2	22.9	42.2	41.2	48.7

but that of the non-reinforced mortars is approximately equal to 600 μm in all cases. This phenomenon is mostly due to the fact that the air content of the mixtures increases very significantly with the amount of fibers, as well as with the amount of fine aggregate (see Figure 1 showing the volume of air as a function of the various parameters). The lowest air content (3,8% of the paste volume) corresponds to the non-reinforced mixture prepared with 15% silica fume at a fine aggregate to binder ratio of 1. The highest air content (42,7% of the paste volume) corresponds to the mixture containing 2% of steel fibers prepared with 8% silica fumeat a fine aggregate to binder ratio of 2. As explained by Powers (6), the fine aggregate particles tend to prevent some of the air bubbles from rising to the surface during the placement operations. The test results clearly show that this phenomenon is amplified when the mixture contains microfibers.

The results of the compressive strength tests (Table 4) must be examined in relation with the values of the air content. Taking into account the strength reduction that normally results from an increase in air content, as well as the scatter of the data, it can be concluded from the results in the Table that the micro-fibers had no clear and systematic influence on the compressive strength measured after 7 or 28 days of normal curing, nor on that measured after 28 days of normal curing followed by 90 days of drying at 38°C. The strength after 28 days of normal curing followed by 90 days of drying at 23°C, however, was found to be influenced by the fibers. For reasons which are not clear, the strength of the mixtures containing steel fibers are all higher than that of the non-reinforced mixtures, and the strength of those containing carbon fibers are all lower. Some of the values at 7 days are particularly low. This could be due in part

TABLE 5

Drying Shrinkage

Mix Code	Shrinkage (μm/m)
N-0-08-1	1715
St-1-08-1	1647
St-2-08-1	1684
C-1-08-1	1765
C-2-08-1	2068
N-0-15-1	1192
St-1-15-1	1817
St-2-15-1	1908
C-1-15-1	1974
C-2-15-1	2123
N-0-08-2	1649
St-1-08-2	1070
St-2-08-2	1254
C-1-08-2	1428
C-2-08-2	2094
N-0-15-2	1430
St-1-15-2	1317
St-2-15-2	1482
C-1-15-2	1406
C-2-15-2	1996

to the retarding effect of the superplasticizer, since these low values generally correspond to the mixtures containing the largest dosages of the admixture.

The data that are obtained from drying shrinkage tests are often somewhat difficult to analyze, because it is not the free shrinkage that is measured, but rather the overall effect of the humidity gradient that is established in a mortar or a concrete specimen after a certain number of days of drying. Since the use of microfibers tends to increase the strength in tension, and thus reduce the surface cracking due to humidity gradients, it should also tend to increase the drying shrinkage measured on typical prisms. This phenomenon, however, was only noticed for the mixtures containing 2% of carbon fibers (see Table 5), and the results of the drying shrinkage tests generally indicate no significant influence of the microfibers (steel or carbon) on the shrinkage measured after 150 days of drying.

Table 6 gives the results of the rapid chloride permeability tests. All values in this Table, even those for the non-reinforced mortars subjected to 90 days of drying at 23°C and 38°C, are quite low. This indicates that the accelerated aging procedure that was used (i.e. 90 day drying) had little effect on this property of the mortars. When a mixture contains silica fume, not only is the chloride ion permeability generally low (in part due to the decrease in the alkali content of the pore water solution which increases the resistivity), but the pore structure is little influenced by drying, since the capillary pores are very small and well distributed in the matrix (7). Furthermore, it was shown recently that diffusion related properties are little influenced by microcracking (8). The microfibers, therefore, were not found to have any influence on the value of the rapid chloride permeability, either before or after drying.

Scaling due to freezing in the presence of a deicer salt solution is a very complex phenomenon, and the results of laboratory tests are often quite variable, probably in good part since it is only the surface layers that are subjected to the test, and because the microstructure

TABLE 6

Chloride Permability

Mix Code	Charge Passed (C) 14 Day Curing	Charge Passed (C) 90 Day Drying 23°C	Charge Passed (C) 90 Day Drying 38°C
N-0-08-1	1570	742	1914
St-1-08-1	1430	678	2143
St-2-08-1	1271	632	1446
N-0-15-1	768	432	711
St-1-15-1	740	330	868
St-2-15-1	688	331	633
N-0-08-2	1223	498	1555
St-1-08-2	1091	397	1114
St-2-08-2	1066	527	2519
N-0-15-2	664	391	1011
St-1-15-2	673	272	778
St-2-15-2	577	200	390

and porosity of these layers is quite variable (9). Bleeding, particularly, can influence very significantly the properties of the surface layers. Although, as expected, the results of the scaling tests performed on the micro-reinforced and on the non-reinforced mortars are relatively scattered (see Table 7), they indicate very clearly that, as a general rule, drying did not have a large influence. As just mentioned, the pore structure of pastes containing silica fume is little influenced by drying, because the capillary pores are very small and well distributed in the matrix. The results also indicate that the non-reinforced mortars generally suffered quite severe scaling (the mass of residues being larger in most cases than the 1 kg/m^2 limit), whereas the micro-reinforced mortars generally suffered little scaling. The mass of residues for the micro-reinforced mortars is larger than the 1 kg/m^2 limit in only three cases, all corresponding to steel fiber-reinforced mixtures prepared at a fine aggregate to binder content of 1 and subjected to 90 day drying at 23°C before the tests. This positive influence of the micro-fibers on the scaling resistance is certainly in good part related to the lower air void spacing factor in the micro-reinforced mixtures (and also perhaps to the lower bleeding in the mixtures containing microfibers, particularly carbon). It is thus impossible with these results to assess precisely the influence of microfibers on the salt scaling resistance.

The rapid freezing and thawing cycle test results (Table 8) confirm the good frost durability of the micro-reinforced mortars. In the series of tests performed on the specimens not subjected to drying, the length change at the end of the tests is extremely large for all four non-reinforced mortars, but generally small for the micro-reinforced mortars, particularly those containing 2% fibers (steel or carbon) and 1% carbon fibers. This positive, but variable, influence of the fibers indicates that the increase in frost durability due to the fibers can not be related only to the lower air void spacing factor, and that the microfibers, by preventing crack propagation, can help to reduce the deterioration due to frost action. The data in Table 8 further shows that, contrary to what was observed during the salt scaling tests, drying reduced significantly in many cases the freezing and thawing resistance of the micro-reinforced mortars, particularly those prepared at a fine aggregate to binder ratio of 1. This apparent paradox is difficult to explain, but could be partly due to the increased degree of saturation in the body of the

TABLE 7

Surface Scaling Test Results

Mix Code	Spacing Factor (μm)	Scaled off Mass 14 Day Curing (kg/m^2)	Scaled off Mass 90 Day Drying 23°C (kg/m^2)	Scaled off Mass 90 Day Drying 38°C (kg/m^2)
N-0-08-1	629	2.02	5.01	1.49
St-1-08-1	288	0.35	2.06	0.14
St-2-08-1	258	0.13	0.44	0.07
C-1-08-1	436	0.27	0.28	0.11
C-2-08-1	254	0.18	0.21	0.04
N-0-15-1	594	1.74	3.16	0.93
St-1-15-1	376	0.63	2.68	0.58
St-2-15-1	293	0.24	1.05	0.03
C-1-15-1	367	0.23	0.13	0.17
C-2-15-1	314	0.20	0.17	0.09
N-0-08-2	544	0.70	0.49	0.18
St-1-08-2	202	0.16	0.55	0.03
St-2-08-2	176	0.09	0.05	0.02
C-1-08-2	318	0.10	0.26	0.11
C-2-08-2	255	0.07	0.67	0.03
N-0-15-2	645	1.32	1.02	1.90
St-1-15-2	282	0.17	0.29	0.05
St-2-15-2	174	0.08	0.33	0.03
C-1-15-2	318	0.21	0.29	0.11
C-2-15-2	249	0.16	0.18	0.13

specimens during the freezing and thawing tests in water, since drying (and thus microcracking) can facilitate the ingress of moisture. This negative, but variable, influence of drying also confirms that the microfibers can help in certain cases to improve the frost resistance, probably because microfibers can reduce the microcracking due to drying. The data in Table 8 indicate that carbon fibers are generally better in this respect than steel fibers, and that 2% of steel fibers is better than 1%. It is surprising, however, that specimens prepared at a water to binder ratio of 0,35 can be significantly damaged by freezing and thawing cycles when the air void spacing factor is only slightly higher than 200 μm. It thus appears that drying can reduce the value of the critical air void spacing factor (i.e. the value needed for good frost protection). It should be noted in this respect that, in the series of specimens dried before the tests, the smallest length change was obtained with the two mixtures having the lowest air void spacing factor.

Conclusion

The use of steel and particularly carbon microfibers can help to improve the frost and deicer salt scaling resistance of mortars, although part of this improvement is due to the "air entrainment" properties of these fibers. Because of this phenomenon, more tests will be needed to assess precisely the increase in durability due to the fibers. The data presented in the paper also indicates that microfibers (and again particularly carbon fibers) can reduce the damage due to drying, since some of the mortars subjected to 90 days of drying at 23°C were severely

TABLE 8

Freeze-Thaw Test Results (300 Cycles)

Mix Code	Spacing Factor (μm)	Length Change 14 Day Curing (μm/m)	Length Change 90 Day Drying 23°C (μm/m)	Length Change 90 Day Drying 38°C (μm/m)
N-0-08-1	629	6209*	6015*	4441*
St-1-08-1	288	292	4933	1819
St-2-08-1	258	68	4737	237
C-1-08-1	436	600	782	173
C-2-08-1	254	-25	992	119
N-0-15-1	594	5382*	3736*	7548*
St-1-15-1	376	1755	3326*	1724
St-2-15-1	293	-13	3043*	345
C-1-15-1	367	465	2500	490
C-2-15-1	314	192	1220	554
N-0-08-2	544	3909	4551	4710*
St-1-08-2	202	660	2113	617
St-2-08-2	176	50	679	-78
C-1-08-2	318	92	940	606
C-2-08-2	255	85	719	654
N-0-15-2	645	4832	4243	5344*
St-1-15-2	282	1014	1160	950
St-2-15-2	174	29	598	-33
C-1-15-2	318	171	943	519
C-2-15-2	249	160	1079	558

* Last possible measurements before the end of the test

damaged by the freezing and thawing cycles, but others were not. More tests will also be required to allow the determination of the exact influence of the fibers in this respect.

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