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CAN MICROFIBERS PREVENT FROST DAMAGE?

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ABSTRACT

To analyze the influence of microfibers on the durability of frost susceptible cementitious systems, eight paste mixtures and eight mortars were batched under vacuum. Such a procedure was found to reduce very significantly the volume of air entrapped in the micro-reinforced pastes and mortars during the mixing process. The test parameters included the water/binder ratio (0,35 and 0,45) and the fiber type and dosage. The pastes were made with 2% steel fibers, 5% steel fibers and 2 % carbon fibers. The mortars were made with 1% steel fibers, 2% steel fibers and 1% carbon fibers. The results of the freezing and thawing cycle tests and of the deicer salt scaling tests show that the micro-fibers reduce the rate of deterioration due to freezing phenomena but do not completely prevent damage

Introduction

In a recent publication on the durability of micro-reinforced mortars, it was observed that the use of steel or carbon micro-fibers could improve the frost and deicer salt scaling resistance of mortars, but that part of this improvement was due to the "air entrainment" properties of the fibers [1]. As explained by Powers [2], the fine aggregate particles act as a grid to prevent some of the air bubbles entrapped by the mixing action from rising to the surface and this is why, even if no air-entraining admixture is used, there is still a relatively large volume of air in most mortars. It was therefore concluded that micro-fibers amplified this air entrainment phenomenon, and that a proper analysis of the influence of micro-fibers on frost resistance thus required the preparation of mortars with a very significantly reduced volume of air. The tests reported in this paper were performed to achieve this objective.

Test Program

As explained in the following section, to reduce the volume of entrapped air, all mixtures for these tests were batched under vacuum. To allow a better analysis of the influence of fibers, and since it is easier to reduce the volume of air in pastes than in mortars, both paste and mortar mixtures were prepared. Two series of four pastes and two series of four mortars were made. One series of pastes and one series of mortars had a water/binder ratio of 0,35 and the other series had a water/binder ratio of 0,45. In each of the two series of pastes, the first mixture contained no fibers (as a reference), the second contained 2% (by volume) steel fibers, the third 5% steel fibers and the last 2% carbon fibers. In each of the two series of mortars, the first mixture contained no fibers, the second contained 1% steel fibers, the third 2% steel fibers and the last 1% carbon fibers. Both rapid freezing and thawing cycle tests and deicer salt scaling tests were performed to evaluate the durability.

Materials, Mixture Composition and Experimental Procedures

The same normal portland cement and the same silica fume were used for all mixtures. The mortars were made using a fine sand (ASTM C190) with a 24 hour absorption of 0% and with 100% of particles passing the 1.25 mm sieve. 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 fibers have a tensile strength of approximately 600 MPa. The elastic modulus of the carbon is equal to 30 GPa, i.e. much lower than that of the steel (200 GPa). The relative density of the carbon is 1,65, versus 7,85 for the steel. A naphtalene based superplasticizer was used for most mixtures. Table 1 presents the composition of the pastes and mortars, together with the values of the mass per unit volume measured on the fresh mixtures. For a few mixtures, particularly those containing carbon fibers, a fairly large superplasticizer dosage was required.

Figure 1 shows the set up used for batching under vacuum. This set up simply consists of a large cylindrical cover placed over the mixer and connected to a vacuum pump. A container for the mixing water is also connected to the set up as shown in the Figure. The

TABLE 1
Mix Composition

Code	Water kg/m^3	Cement kg/m^3	Silica Fume kg/m^3	Sand kg/m^3	Sp L/m^3	SF/B %	S/B	Fiber Volume %	Unit Weight kg/m^3
					Pastes				
N-0-0.35	493	1274	142	-	6.8	10	-	0.0	1918
St-2-0.35	468	1218	135	-	9.0	10	-	1.9	1984
St-5-0.35	474	1244	137	-	15.5	10	-	5.1	2280
C-2-0.35	465	1219	136	-	15.0	10	-	2.0	1870
N-0-0.45	562	1125	124	-	0.0	10	-	0.0	1812
St-2-0.45	555	1111	123	-	0.0	10	-	2.0	1946
St-5-0.45	537	1082	120	-	5.4	10	-	5.1	2147
C-2-0.45	566	1145	127	-	13.4	10	-	2.1	1889
					Mortars				
N-0-0.35	241	619	68	1375	6.0	10	2	0.0	2310
St-1-0.35	224	587	65	1305	7.9	10	2	1.0	2268
St-2-0.35	215	568	63	1261	10.7	10	2	1.9	2272
C-1-0.35	207	558	62	1240	17.0	10	2	1.0	2104
N-0-0.45	292	585	65	1300	0.0	10	2	0.0	2242
St-1-0.45	280	560	62	1245	0.0	10	2	1.0	2225
St-2-0.45	274	548	60	1217	15.0	10	2	2.0	2268
C-1-0.45	263	545	61	1212	17.3	10	2	1.0	2118

Code: Fiber type-Fiber %-W/B
St: Steel, C: Carbon, Sp: Superplasticizer, SF: Silica fume, S: Sand, B: Binder, W: Water

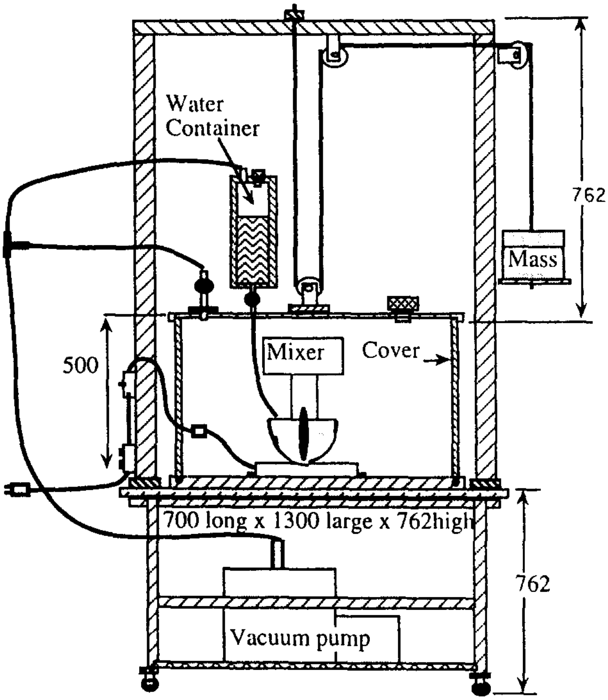

FIG. 1.
Set up for Batching Under Vacuum (dimensions are in mm).

batching procedure was the following. After all the dry materials had been placed into the mixer, the cover was fixed and the vacuum pump was started for 20 minutes. After this period, the pump was then stopped, the water (containing the superplasticizer if any) was added and mixing could proceed. The specimens required for the various tests were prepared using a vibrating table, except for a few particularly stiff mixtures for which rodding was needed.

Two 23 x 36 x 195 mm prisms for the freezing and thawing cycle tests (ASTM C666 procedure A), two 110 x 300 x 25 mm slabs for the deicer salt scaling tests (ASTM C 672) and three 50 mm in diameter and 100 mm in length cylinders for the compressive strength measurements were made from each mixture. An additional specimen was also prepared from each mixture for the determination of the characteristics of the air void system (ASTM C457 modified point count method). For the deicer salt scaling tests, a 3% sodium chloride solution was used. As required by the standard, the specimens for the C666 tests were moist cured for 14 days and then tested immediately, whereas those for the C672 tests, again as required by the standard, were cured for 14 days and then dried at 23°C and 50% relative humidity for 14 additional days before the tests. The strength measurements were performed after 28 days of moist curing.

TABLE 2
Air Void System Characteristics

Code	Air Content in Paste (%)	Specific Surface (mm^{-1})	Spacing Factor (mm)
		Pastes	
N-0-0.35	0.2	25.3	1192
St-2-0.35	0.1	45.3	859
St-5-0.35	0.2	16.0	2096
C-2-0.35	0.3	16.0	1730
N-0-0.45	0.3	22.2	1171
St-2-0.45	0.5	10.7	2093
St-5-0.45	0.3	10.7	2611
C-2-0.45	0.2	12.0	2515
		Mortars	
N-0-0.35	4.1	11.1	864
St-1-0.35	10.0	8.9	703
St-2-0.35	14.1	6.6	782
C-1-0.35	12.0	10.0	529
N-0-0.45	3.4	11.1	933
St-1-0.45	5.2	12.0	717
St-2-0.45	6.5	7.7	1015
C-1-0.45	5.0	9.5	820

Test Results

The air void characteristics of the pastes and mortars are shown in Table 2. For the pastes, it is very clear that batching under vacuum almost completely prevented air from being entrapped during the mixing process. The air content is equal to or lower than 0,5% in all cases, and the air void spacing factor varies between 859 µm and 2611 µm. For the mortars, batching under vacuum also prevented air from being entrapped, but not as completely as for the pastes. The air content in the paste fraction varies between 4,1% and 12%, and the spacing factor between 529 µm and 1015 µm. For similar mortars not batched under vacuum, values of air content ranging between 12,7% and 42,7% (with spacing factors ranging between 176 and 544 µm) were observed [1]. Probably because of the increased viscosity of the paste, the air content is higher in the 0,35 than in the 0,45 water/binder ratio micro-reinforced mortars.

Table 3 presents the results of the compressive strength measurements after 28 days of moist curing.

The strength of the reference (non-reinforced) pastes (50,8 MPa and 41,3 MPa) and mortars (54,3 MPa and 49,0 MPa) are normal for such mixtures made with silica fume cement at water/binder ratios of 0,35 and 0,45. For the pastes, the strength increases very significantly with the use of steel fibers, but only at a volume fraction of 5%. For the mortars, the use of steel fibers also appears to enhance the strength to some degree, but only in the 0,35 mixtures. Surprisingly, the use of carbon fibers was found to have a negative influence on the strength of the mortars, particularly for the 0,45 mixture, and also on the strength of the 0,45 paste. This negative influence could be due in part to the high superplasticizer dosages that

TABLE 3
Compressive Strength

Code	Air Content in Paste (%)	Compressive Strength (MPa)
	Pastes	
N-0-0.35	0.2	50.8
St-2-0.35	0.1	51.6
St-5-0.35	0.2	70.0
C-2-0.35	0.3	51.9
N-0-0.45	0.3	41.3
St-2-0.45	0.5	45.5
St-5-0.45	0.3	58.6
C-2-0.45	0.2	35.8
	Mortars	
N-0-0.35	4.1	54.3
St-1-0.35	10.0	64.5
St-2-0.35	14.1	62.1
C-1-0.35	12.0	49.3
N-0-0.45	3.4	49.0
St-1-0.45	5.2	52.4
St-2-0.45	6.5	47.4
C-1-0.45	5.0	30.6

were used in all mixtures containing carbon fibers, since such large dosages can reduce very significantly the rate of hydration of cement. However, the 0,35 paste with 5% steel fibers, which was prepared with 15,5 L/m^3 of superplasticizer, has the highest strength. The presence of microstructural flaws due to fiber dispersion problems (which has been observed by other investigators [3]) could also partly explain this negative influence of the carbon fibers.

Length change is generally considered as the best indicator of the internal microstructural damage that freezing and thawing cycles can cause [4]. Normally, a length change significantly higher than 200 μm/m indicates the onset of significant damage. According to this criterion, all pastes and all mortars but one (that having the lowest air void spacing factor, 529 μm) were severely deteriorated during the freezing and thawing tests (Table 4). However, the use of fibers, and particularly carbon fibers, was found to reduce the observed deterioration. The reference pastes and mortars were all completely destroyed before the end of the tests (i.e. before 300 cycles), but the micro-reinforced pastes and mortars were not. At the dosages that were selected for these tests, the use of carbon or steel micro-fibers thus appears to slow down the rate of deterioration due to internal microcracking during freezing and thawing cycles, but it can not prevent the formation of microcracks. It is interesting to note, in this respect, that the frost resistance of the pastes and the mortars is quite similar.

Scaling due to freezing and thawing cycles in the presence of deicer salts is a progressive phenomenon which slowly (or sometimes rapidly!) destroys successive surface layers of paste or mortar. The results in Table 5 clearly show that micro-fibers can reduce, and in certain cases almost totally prevent, this type of deterioration. For the 0,35 pastes and mortars, which are normally more resistant to scaling than their 0,45 counterparts, the amount of scaling residues is very significant in the non-reinforced mixtures, but quite small in all reinforced mixtures. For the 0,45 pastes and mortars, however, the influence of the fibers is

TABLE 4
Freezing and Thawing Test Results

Code	Spacing Factor (mm)	Length Change (after 300 cycles) (mm/m)
	Pastes	
N-0-0.35	1192	*
St-2-0.35	859	5945
St-5-0.35	2096	5472
C-2-0.35	1730	880
N-0-0.45	1171	*
St-2-0.45	2093	7103
St-5-0.45	2611	5636
C-2-0.45	2515	2841
	Mortars	
N-0-0.35	864	*
St-1-0.35	703	4759
St-2-0.35	782	3382
C-1-0.35	529	279
N-0-0.45	933	*
St-1-0.45	717	4536
St-2-0.45	1015	4340
C-1-0.45	820	2669

* Specimen destroyed before the end of the test

not as pronounced. The amount of residues is small only for the pastes containing 5% steel fibers or 2% carbon fibers, and it is relatively high for all mortars. These scaling test results thus confirm that the use of micro-fibers can reduce the rate of deterioration due to freezing phenomena, but that it can not generally totally prevent damage.

Discussion

The mechanical behavior of pastes and mortars reinforced with steel micro-fibers is different than that of similar cementitious systems reinforced with carbon fibers [3]. Probably because steel is much more rigid than cement paste, the presence of steel fibers appears to enhance the resistance to microcrack opening (due to the so-called "pinching action" described by Bentur and Mindess [5]), and the increase in bending strength due to the fibers occurs before the bend-over-point on the load versus deflexion curve[3]. However, the use of steel micro-fibers does not enhance very significantly the toughness and the ductility of the composite and there is generally a sharp decrease of load immediately after the bend-over-point. On the opposite, because carbon fibers have a modulus of elasticity similar to that of cement paste, they can not exert this "pinching action", and sufficent crack opening is required to mobilize the fibers. The increase in bending strength due to the presence of carbon fibers therefore occurs past the bend-over-point, and it has been found that these fibers also enhance very significantly the toughness and the ductility of the system. An indication of the difference

TABLE 5
Deicer Salt Scaling Test Results

Code	Spacing Factor (mm)	Mass of Residues (after 50 cycles) (kg/m^2)
	Pastes	
N-0-0.35	1192	2.7
St-2-0.35	859	0.29
St-5-0.35	2096	0.09
C-2-0.35	1730	0.14
N-0-0.45	1171	8.5
St-2-0.45	2093	1.61
St-5-0.45	2611	0.52
C-2-0.45	2515	0.31
	Mortars	
N-0-0.35	864	0.81
St-1-0.35	703	0.05
St-2-0.35	782	0.05
C-1-0.35	529	0.35
N-0-0.45	933	9.7
St-1-0.45	717	2.5
St-2-0.45	1015	3.1
C-1-0.45	820	5.1

between the mechanical behavior of steel and carbon fiber composites is given in Table 3 which indicates that only steel fibers had a significant influence on compressive strength.

Surprisingly, the deterioration processes due to freezing action (with or without deicer salts), which are due to the formation of microcracks, were found to be quite similarly influenced by the presence of steel or carbon fibers. Both types of fibers were observed to reduce the rate of deterioration, but neither was found to be able to completely prevent damage. The cracking phenomena due to freezing thus appear to be somewhat different from those due to mechanical loads. It can be hypothecized that the tensile stresses due to freezing in frost susceptible systems can always be at some point higher than the tensile strength, and thus that cracks will always finally be formed. The role of the fibers would thus mostly be to reduce the rate of crack propagation, and carbon fibers would be at least as effective as steel fibers in this respect, and most probably better as the freezing and thawing test results seem to show.

Conclusion

The tests results reported in this paper were obtained from pastes and mortars batched under vacuum in order to reduce the volume of air and thus verify the influence of micro-fibers on cementitious systems susceptible to frost damage. These results show that the use of steel and carbon microfibers in pastes and mortars tends to reduce the rate of deterioration due to freezing and thawing cycles, as well as to scaling due to freezing in the presence of deicer salts. It does, however, appear that these fibers can not totally prevent frost damage. Proper air-entrainment is therefore required in micro-reinforced cementitious systems, unless, as shown in various recent publications [6, 7], the water/binder ratio is sufficiently low.

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