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BOND-SLIP CHARACTERISTICS OF STEEL FIBERS IN HIGH REACTIVITY METAKAOLIN (HRM) MODIFIED CEMENT-BASED MATRICES

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ABSTRACT

Pull-out tests were carried out on deformed steel fibers embedded in cement-based matrices. Four matrices including plain cement paste, cement paste with 10% silica fume, cement paste with 10% high reactivity metakaolin (HRM), and cement paste with a combination of 5% silica fume and 5% HRM in the same mix were investigated. Based on the resulting bond-slip curves, HRM was found to be more effective in improving the pull-out performance than silica fume. However, when silica fume and HRM were combined in the same mix, an excessive improvement in the bond occurred which led to undesirable fiber fractures, and consequently, a brittle behavior.

Introduction

As in any composite with a 3-D random distribution of short fibers, the influence of fiber-matrix bond on the mechanical properties and microfracture processes of cement-based composites is fundamental. However, unlike composites based on ductile polymeric matrices, the brittle matrix in a cement-based composite cracks at relatively low strains early in the process, and fibers are required to bridge cracks and hinder further widening and propagation. The strength of the bond between the matrix and the fibers, therefore, is of great importance in the case of cement-based composites.

The effectiveness of a given fiber in transmitting stresses across a crack may be assessed by conducting single fiber pull-out tests on bonded fibers, where the fiber slip is monitored as a function of the applied pull-out load. These tests are routinely conducted as a means of optimizing fiber and matrix characteristics and to understand toughening mechanisms in these composites. Pull-out characteristics of steel fibers embedded in cementitious matrices are known to be influenced by variables such as rate of load application (1,2), temperature of the environment (2), fiber inclination (3,4), and so on. In addition, a number of fiber surface modifications such as coatings, surface indentations, and notches have been examined as ways of improving the bond-slip characteristics of fibers in a cementitious matrix (5,6). The most important fiber modification for the purpose of improving the bond-slip behavior, however, is mechanical deforming such as placing a hook or a crimp at ends or along the length (7).

TABLE 1

Properties of Typical HRM and Silica Fume

Property	HRM	Silica Fume
Average Particle Size, μm	1.5	0.1
SiO_2+Al_2O3+Fe_2O_3, minimum percent	97	95
Specific Gravity	2.5	2.2

Properties of the matrix, such as the water/binder ratio, or the presence of silica fume and polymers, also play a critical role in determining the bond-slip behavior of steel fibers (7,8,9). This dependence is even more pronounced in the case of deformed fibers where the matrix in the vicinity of a fiber is much more severely stressed during pull-out and a number of additional bulk properties of the matrix such as the compressive and tensile strengths and poisson's ratio, become important.

Lately, there has been much interest in the use of High Reactivity Metakaolin (HRM) as a supplementary cementing material (10, 11). Produced by calcining purified kaoline clay in the temperature range of 700 to 800°C, HRM is a poorly crystallized white powder with a high pozzolanic reactivity. Typical HRM and silica fume are compared in Table 1.

So far as the bond between a steel fiber and cement-based matrix is concerned, a number of properties of HRM modified mixes may be of a significant advantage. The rate of compressive strength development in HRM mixes is significantly higher than mixes without HRM (10) and is manifested by a higher adiabatic temperature rise in the mix. Similar accelerating trends are also observed in the flexural strength and the static modulus of elasticity. Morphological features of the fiber-matrix interface in the presence of HRM may also be expected to reflect the lack of calcium hydroxide at the interface and the related densification. Additionally, given the reduced bleeding and drying shrinkage in concrete with HRM, one can expect a lack of shrinkage related cracking at the interface and hence a further improvement in the bond-slip behavior. Very little information, however, exists on the effects of HRM on the bond-slip behavior of deformed steel fibers.

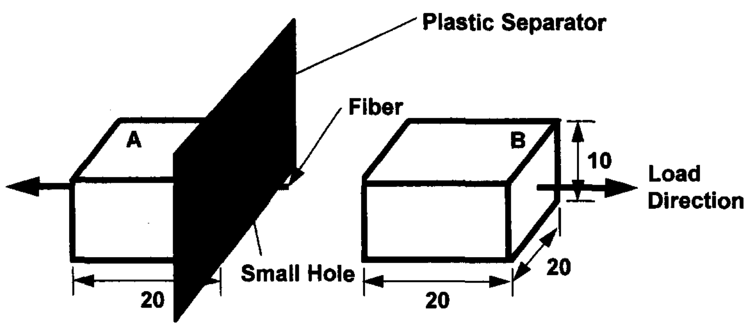

FIG. 1.
Pull-out specimen (dimensions in mm).

TABLE 2

Matrices Investigated

Matrix	W/B	HRM/C	SF/C	HRWR (% C)
Cement Paste (M1)	0.35	-	-	2
HRM Cement Paste (M2)	0.35	0.10	-	3
SF Cement Paste (M3)	0.35	-	0.10	3
HRM + SF Cement Paste (M4)	0.35	0.05	0.05	3

B: Binder; C: Cement; W: Water; HRM: High Reactivity Metakaoline; SF: Silica Fume

Experimental Program

Pull-out tests were performed using rectangular specimens as shown in Figure 1. A very thin plastic separator with a hole slightly smaller than the steel fiber kept the fiber in place while the cementitious matrix in the plastic state was poured in the mould. The separator prevented the two parts of the specimen, A and B, from bonding and thus provided an artificial crack. Fibers investigated were 30 mm long and 0.5 mm in diameter with hooked ends. Four matrices M1 to M4 with mix proportions given in Table 2 were investigated. Notice that in the matrix M4, HRM was combined with silica fume in equal proportion with the premise that HRM particles, being finer than cement but coarser than those of silica fume, would provide a more efficient packing resulting in favorable rheological and interfacial characteristics. Three specimens of each type were prepared.

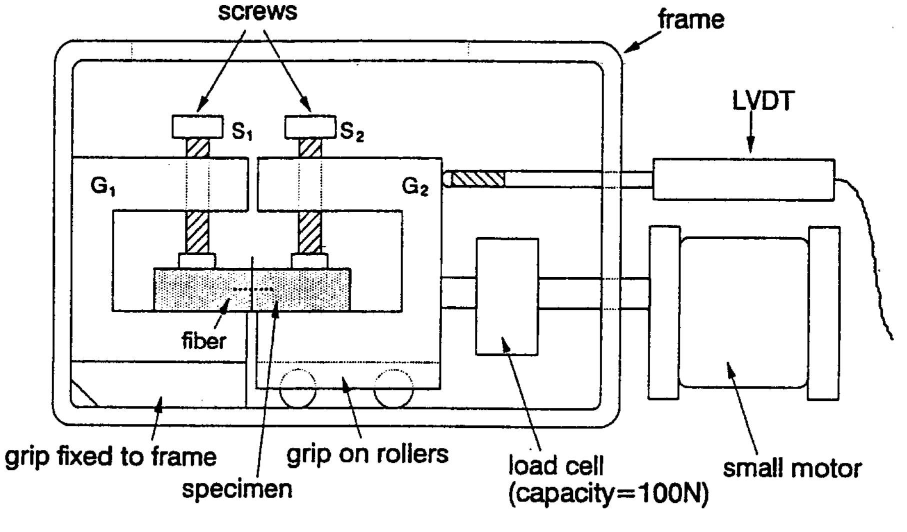

FIG. 2
Pull-out test set-up.

Pull-out tests were carried out 7 and 28 days after casting in a specially designed table mounted test apparatus shown in Figure 2. In a typical test, the pull-out specimen was held between two grips G_1 and G_2 using two vertical screws S_1 and S_2. Grip G_1 is fixed while G_2 is mounted on rollers such that it could be moved in the horizontal direction by a small motor. An LVDT monitored the displacement of grip G_2 and a load cell (445 N capacity) measured the applied load. In a pull-out test, G_2 was pulled away from G_1 and the applied load vs. fiber slip curves were recorded.

Results and Discussion

Some representative pull-out load vs. pull-out displacement curves are given in Figures 3 and 4 for pull-out tests at 7 and 28 days respectively in the four matrices. These curves were analyzed and the results in the form of peak load, average bond strength, energy absorbed to a displacement of 9.75 mm and the peak stress in the fiber as a percentage of the ultimate strength are given in Table 3. The fiber failure mode (fiber pull-out or fracture) is also noted in Table 3.

The high average bond strengths for all the matrices is apparently the result of the very low (0.35) water/binder ratio. The general improvement in the bond strength due to the addition of silica fume or HRM is also noticeable at both 7 and 28 days. However, HRM appears to be somewhat less effective initially, but exceeds silica fume at 28 days. The combination of HRM

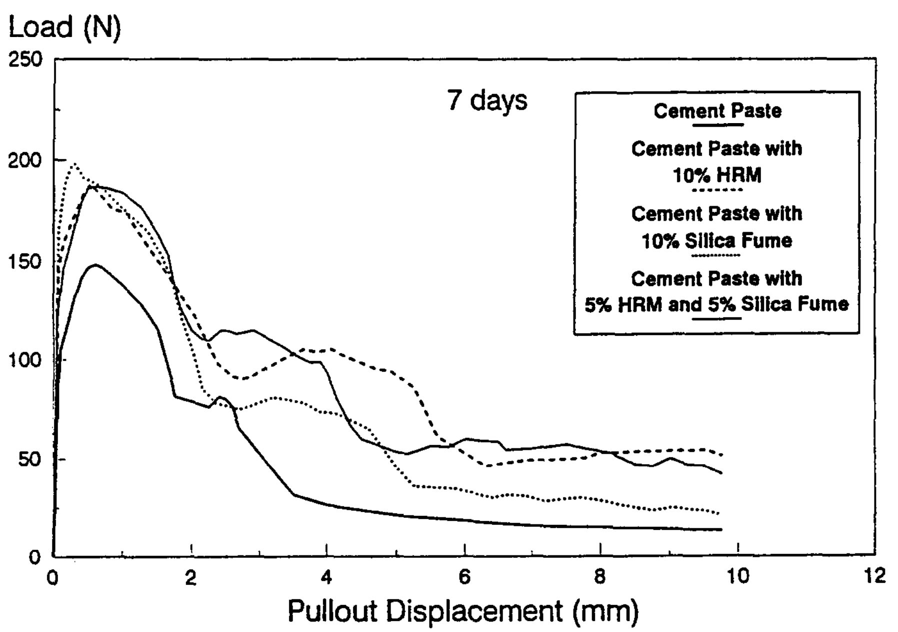

FIG. 3
Load-pullout displacement curves (7 days).

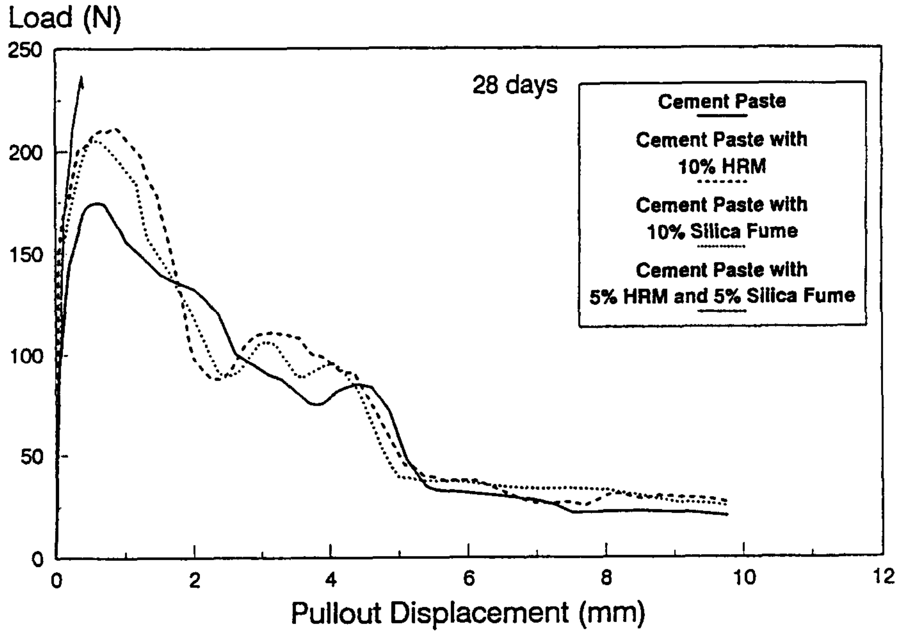

FIG. 4.
Load-pullout displacement curves (28 days).

and silica fume in the same mix appears to follow a similar trend; however, the bond improvements beyond 7 days are too good and in all of the specimens the fiber stress attained the ultimate fiber strength and the fibers fractured.

As far as the absorption of energy is concerned, averages indicate that both HRM and silica fume improved the absorption of energy to a slip of 9.75 mm; but, HRM additions were more effective in this regard. Notice, however, that the fiber stress in the case of HRM matrices came to within 98.5% of the ultimate strength and as such a further increase in HRM content may in fact be deleterious. Along the same lines, one can also conclude that in Mix M4 where HRM and silica fume were combined at 5% each, the optimum had already been exceeded.

Concluding Remarks

Based on the pull-out test data presented here, one could conclude that the addition of High Reactivity Metakaolin (HRM) at about 10% by weight of cement in the mix is very effective in improving the bond-slip behavior of deformed steel fibers, and the improvements even exceed those observed with silica fume. However, this may also be an optimum quantity and an increase in HRM content beyond 10% may in fact be deleterious. Combining silica fume and HRM in the same mix appears to be promising, but at a replacements rates of 5% each of silica fume and HRM, the optimum appears to have already been exceeded.

TABLE 3
Pull-Out Test Results

Matrix	Peak Load (N)		Average Bond Strength (MPa)		Energy Absorbed at 9.75 mm Slip (N-mm)		Stress in Fiber as % of Ultimate Strength**	
	7 days	28 days	7 days	28 days	7 days	28 days	7 days	28 days
Cement paste (M1)	159.4	171.8	6.75	7.30	668.6	680.3	67.8	73.1
Cement paste with 10% HRM (M2)	190.3	231.5	8.08	9.83	819.0	1187.3	81.0	98.5
Cement paste with 10% SF (M3)	207.0	210.0* 229.0***	8.79	8.92*	768.0	945.0*	88.1	89.4
Cement paste with 5% HRM & 5% SF (M4)	190.3	235.0	8.08	fiber fractures	856.0	fiber fractures	81.0	100

Note: *Average of two specimens; the third failed when the fiber fractured.
**The ultimate tensile strength of the fiber is 1197.5 MPa.
***Load supported by the third fiber that fractured.

Acknowledgments

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