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PULLOUT BEHAVIOR OF STEEL FIBERS FROM CEMENT-BASED COMPOSITES

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ABSTRACT

A comprehensive experimental program on pullout tests of steel fibers from cement based matrices is described. A specially designed single fiber pullout apparatus was used to provide a quantitative determination of interfacial properties that are relevant to toughening brittle materials through fiber reinforcement. The parameters investigated included a specially designed high strength cement based matrix called Densified Small Particles system (DSP), a conventional mortar matrix, fiber embeddment length, and the fiber volume fraction. The mediums from which the fiber was pulled included a control mortar mix without fibers, a mortar mix with 3, and 6 percent fibers by volume. The results indicate that: (1) The dense DSP matrix has significantly improved interfacial properties as compared to the conventional mortar matrix. (2) Increasing the fiber embeddment length and the fiber volume fraction in the cement matrix increase the peak pullout load and the pullout work. (3) The major bond mechanism in both systems is frictional sliding. © *1997 Elsevier Science Ltd*

Introduction

Cement-based materials are brittle and have an inherent weakness in resisting tension. They are known to crack under low levels of tensile strain. It has long been recognized that the behavior of such materials can be dramatically improved by the addition of discontinuous fibers. The improvement in composite properties is largely attributed to the bond between the fiber and matrix.

The fiber-matrix interface bond strongly affects the ability of fibers to stabilize crack propagation in the matrix. When a large crack is allowed to form in a matrix containing fibers, debonding and sliding at the interface have a significant influence on total energy consumption during crack propagation. The resistance to crack propagation provided by the fibers depends on the mechanical properties of the matrix, the fibers, and the fiber-matrix interface; as well as the fiber length, orientation, volume content, and spacing (1-5).

The strength of the composite interface is commonly measured using a pullout test. In this test, a fiber is cast into a cement-based matrix and loaded in tension until the fiber debonds and is withdrawn. Pullout of a fiber from a cement based matrix is used to characterize the interface bond between the matrix and the fiber.

Using different testing techniques, many researchers have conducted fiber pullout tests to characterize the interfacial properties in fiber-reinforced cementitious composites, [Naaman et al. (3), Pinchin et al. (6), Gray et al. (7), Wang et. al. (8), Morrison et al. (9), Stang et al. (10), Li et al. (11), Gopalaratnam et al. (12), Banthia and Trottier, (13)]. The experimental results obtained from the above researchers, are not always in agreement.

The main objective of this research is to generate a comprehensive experimental database for characterizing the bond in high performance fiber reinforced cementitious composites like DSP. The results obtained from this investigation are important for better understanding of the role of steel fibers in improving the tensile properties of very high strength, brittle cement-based composites.

Experimental Program

The experimental program was focused on studying the interfacial bond in fiber-reinforced cementitious composites. The effect of the following parameters on the fiber pullout characteristics was considered; fiber embeddment length, fiber volume fraction, interfacial crack (slit) length, and matrix strength. Three different fiber embeddment lengths, 6 mm, 12 mm, and 18 mm were tested. Two different fiber volume fractions, equal to 3% and 6%, were used within the matrix. Interfacial crack lengths of 0 and 6 mm were selected. Two different matrices were used in the program. The composition of these matrices and their mix proportions is shown in Table 1. A hardened stainless steel piano wire, 0.19 mm in diameter, was used as the fiber. The mechanical properties of the pullout wire and the fibers used in the matrix are shown in Table 1.

TABLE 1

Details of the Experimental Program for Pullout Tests

Matrix type		**Fiber Embeddment Length (mm)**		
DSP		6	12	18
Designation: D		**Series Designation**		
Mix Proportions by Weight		D0 6 0 1	D0 12 0 1	D0 18 0 1
DSP Cement : Sand #13 : Sand #29 : Water		D0 6 3 1	D0 12 3 1	D0 18 3 1
1 : 0.36 : 0.86 : 0.20		D0 6 6 1	D0 12 6 1	D0 18 6 1
Sand #13: 0-0.18 mm, Sand #29: 0.18-0.5 mm		D6 6 0 1	D6 12 0 1	D6 18 0 1
Compressive Strength: 150 MPa		D6 6 3 1	D6 12 3 1	D6 18 3 1
Modulus of Elasticity: 51,000 MPa		D6 6 6 1	D6 12 6 1	D6 18 6 1
Conventional Mortar				
Designation: M		M0 6 0 1	M0 12 0 1	M0 18 0 1
Mix Proportions by Weight		M6 6 0 1	M6 12 0 1	M6 18 0 1
Ordinary cement : Sand #13 : Sand #29 : Water				
1 : 0.36 : 0.86 : 0.45				
Compressive Strength: 40 MPa				
Modulus of Elasticity: 25000 MPa				
Properties of Pullout fiber		**Properties of steel fibers in the matrix**		
Diameter:	0.19 mm	0.15 mm	Length: 6 mm	
Tensile strength:	2990 MPa	2950 MPa		
Modulus of Elasticity:	200,000 MPa	200,000 MPa		

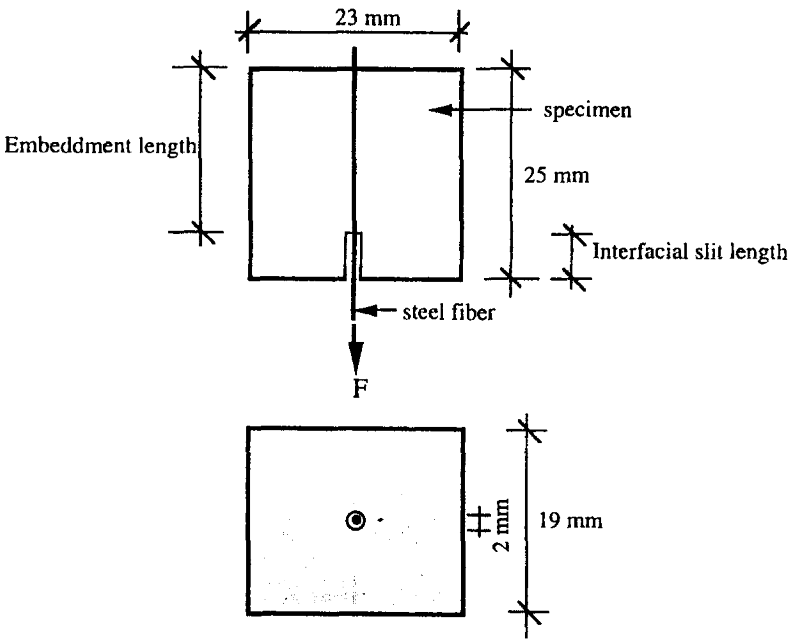

FIG. 1.
Schematic diagram of the pullout specimen.

The experimental program conducted in this study comprised a total of 120 specimens. Each specimen was given a code name. A typical code name consists of the following characters. The first indicates the matrix type (D for DSP or M for conventional mortar), the second indicates the interfacial slit length, the third indicates the fiber embeddment length, the fourth indicates the fiber volume fraction in the matrix, and the fifth indicates the specimen number. For example, D6 12 3 1 refers to a DSP specimen with 6 mm interfacial slit length, 12 mm embeddment length, 3% fiber volume fraction within the matrix and specimen number 1. Table 1 gives details of the experimental program for pullout tests and the series designation of the specimens (14).

Specimen Preparation

The pullout specimens had a prismatic shape of 25 mm × 23 mm × 19 mm, as shown in Fig. 1. The specimens were made using a specially designed steel mold. The schematic diagram of the mold is shown in Fig. 2. The mold was cleaned, oiled and prepared for casting by securely fixing it to a vibrating table. An artificial slit was created along the fiber embedded length by means of a thin siliceous rubber tube of 2 mm in diameter which was fitted around a steel fiber in advance. The slit was introduced by removing the thin siliceous rubber tube 24 hours after casting. The surface of the steel wire was cleaned with acetone and embedded at the center of the specimen. The steel fibers were kept in a straight position in the mold, using a special arrangement without any significant pretensioning prior to casting. Due to some practical difficulties the properties of the pullout fiber were slightly different than the properties of the Bekaert fibers used in the matrix.

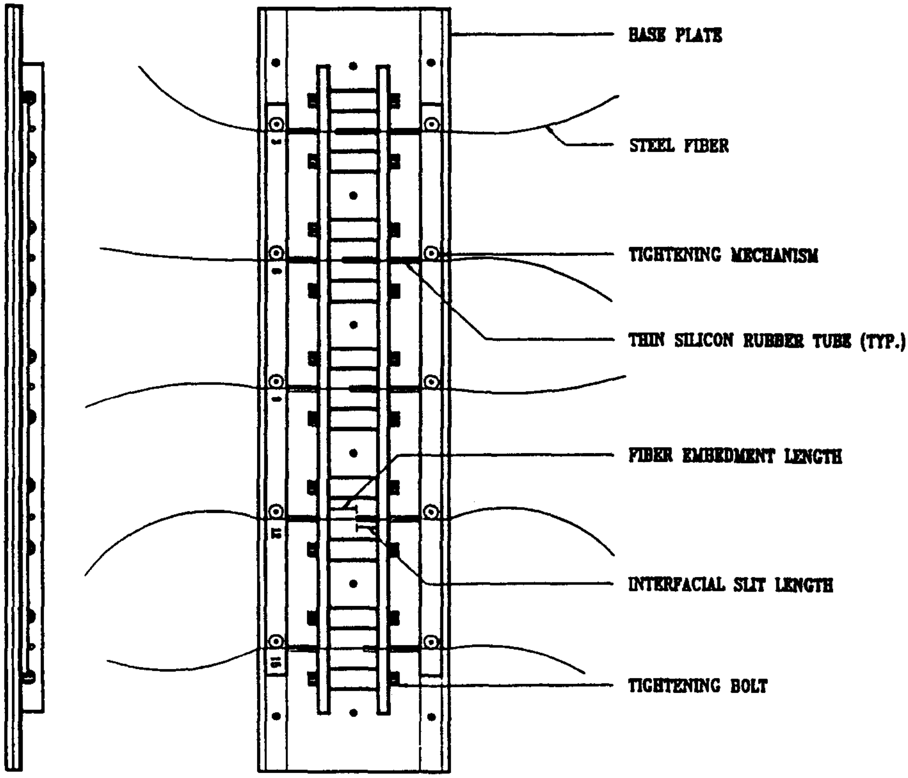

FIG. 2.
Schematic diagram of the pullout mold.

The specimens were cast horizontally, with the embedded fiber perpendicular to the direction of casting. They were vibrated simultaneously, using a vibrating table with a frequency of about 75 Hz. The specimens were then covered with plastic sheets and cured at room temperature for 24 hours prior to demolding. They were then placed in hot water at 80°C for an additional 24 hours, and finally were kept at room temperature for testing. All specimens made in this study were tested in a dry condition at an age of one week.

Testing Procedure

A schematic diagram of the pullout apparatus used in this investigation is shown in Fig. 3. The top end of the wire was clamped in a slotted block which allowed free movement of the specimen until load was applied. The bottom end of the wire was held by a specially designed grip attached to a 200 N load cell. While manually applying the load at a constant rate the top end displacement of the fiber was monitored with two linear variable differential transducers (LVDTs) attached 3 mm above the top of the specimen. This length, known as the free fiber length, was kept constant in all tests. The displacement of the bottom end of the wire was monitored by another LVDT. Preliminary tests were conducted to ensure that no slip occurred between the specimen and the grips at maximum pullout loads.

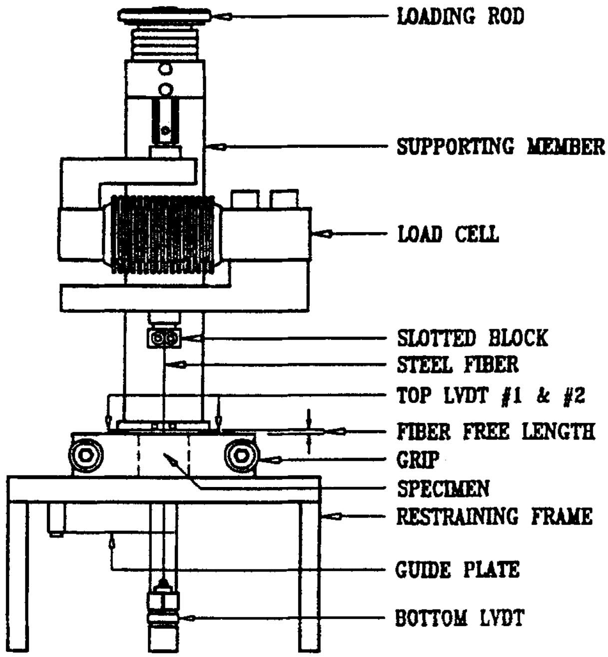

FIG. 3.
Schematic diagram of the single fiber pullout apparatus.

TABLE 2

Typical Interfacial Properties of DSP and Conventional Mortar

Specimen Designation	frictional bond stress (MPa)	debonding energy (N/m)	average bond stress (MPa)	peak load (N)	peak disp (mm)	debonding disp.(mm)
D0 18 0 1	3.87	22.50	3.91	42.00	0.078	0.085
D0 18 0 2	3.81	26.10	3.89	41.75	0.053	0.074
D0 18 0 3	4.30	30.90	4.37	47.00	0.085	0.091
D0 18 6 4	4.20	27.70	4.24	45.50	0.094	0.123
D0 18 6 5	4.37	56.20	4.37	47.00	0.075	0.118
D0 18 6 6	4.80	49.90	4.84	52.00	0.086	0.127
D0 18 6 7	3.40	44.40	3.44	37.00	0.061	0.076
D0 12 3 8	6.58	46.90	6.63	47.50	0.075	0.089
D0 12 3 9	6.01	49.30	6.04	43.25	0.039	0.053
D0 12 3 10	5.79	20.60	5.90	42.25	0.053	0.054
M0 6 0 11	4.56	9.60	4.68	16.75	0.007	0.013
M0 6 0 12	4.60	8.10	4.75	17.00	0.006	0.011
M0 6 0 13	4.56	8.10	4.68	16.75	0.010	0.017
M6 18 0 14	2.08	12.60	2.09	22.50	0.068	0.081
M6 18 0 15	1.41	6.30	1.44	15.50	0.048	0.06
M6 18 0 16	1.49	7.60	1.54	16.50	0.053	0.07

TABLE 3

Typical Interfacial Properties
(Comparison Between DSP Matrix and Conventional Mortar Matrix)

	DSP Matrix		Conv. Mortar Matrix	
embedded length (mm)	frictional bond stress (MPa)	debonding energy (N/m)	frictional bond stress (MPa)	debonding energy (N/m)
6	8.3	8.1	4.56	9.6
6	7.18	5.4	4.6	8.1
6	2.47	1.3	4.56	8.1
6	5.24	3.9		
12	4.05	6.3	1.71	8.6
12	5.13	5.3	0.74	3.4
12	4.54	2.4	0.54	0.09
18	3.87	22.4	2.08	12.6
18	3.81	26.1	1.52	6.3
18	4.55	32.9	1.96	7.6
18	4.29	30.9	1.41	9.6

The value of the force, as well as the movement at both ends of the fiber, were graphically monitored and recorded by a data acquisition system, then stored in computer files. The pullout load versus top and bottom displacement was obtained and plotted, using such data files.

Test Results

The pullout load and the displacement at the top end of the fiber were used to develop pullout load versus end slip curves. The displacement at the bottom end of the fiber was used to determine the load at which complete debonding occurs and frictional pullout starts. The debonding process in single fiber pullout tests was analyzed using a new model (15). This model is based on evaluating the part of the area under the pullout curve corresponding to pure debonding. This model provides a direct estimation of the debonding energy and the frictional bond strength of the interface from the experimental pullout curve.

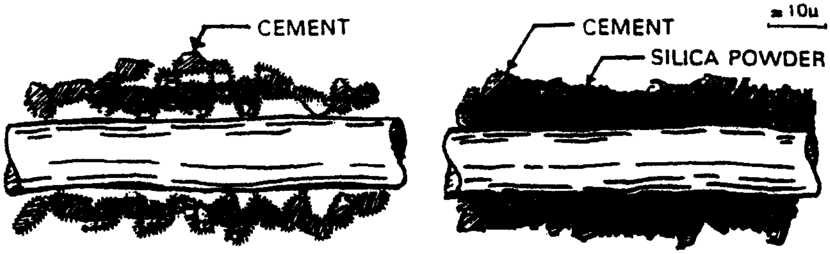

FIG. 4.
Schematic representation of the interfacial particle packing in the case of fiber embedded in conventional cement mortar matrix (left), and in DSP matrix (right), (17).

Typical results on single fiber pullout tests are presented in Tables 2, and 3. The effect of matrix strength, fiber embeddment length, and fiber volume fraction on the pullout response of steel fibers from cement based matrices was investigated by varying the parameter concerned while keeping all other parameters fixed. Typical trends observed for the load-slip behavior for both DSP and conventional mortar matrices are shown in Fig. 5, and 6. The maximum fiber pullout load for most of the specimens is plotted versus fiber embeddment length as shown in Fig. 7. The interfacial properties determined in this study were analyzed considering the effects of the parameters mentioned previously, and the results are shown in Fig. 8. The fiber volume fraction effect is shown in Fig. 9. To better understand the effect of the investigated parameters on overall energy consumption, dissipated bond energy (also termed "pullout work") up to peak load and up to 1 mm displacement, was investigated as shown in Figure 10.

Discussion of Test Results

Pullout tests such as those described here are capable of generating a great deal of data. The experiments were performed to provide: 1) an estimate of the frictional bond strength and debonding energy of the fiber/matrix interface, 2) some knowledge of the factors affecting the bond strength and the pullout characteristics, such as matrix strength, fiber embeddment length, fiber volume fraction, and interfacial crack length.

The pullout curves, shown in this study can be divided into three main stages: (1) linear elastic stage, (2) partial fiber debonding stage, and (3) complete fiber debonding stage followed by frictional pullout. The results listed in Table 2 indicate that the frictional bond strength for DSP range from 3.4 to 6.58 MPa, and from 1.41 to 4.60 MPa for conventional mortar. The debonding energy of the fiber/matrix interface for DSP ranges from 20.6 to 56.2 N/m and from 6.3 to 12.6 N/m for conventional mortar. The frictional bond strength values presented in Table 2 were slightly less than the average bond strength values calculated as

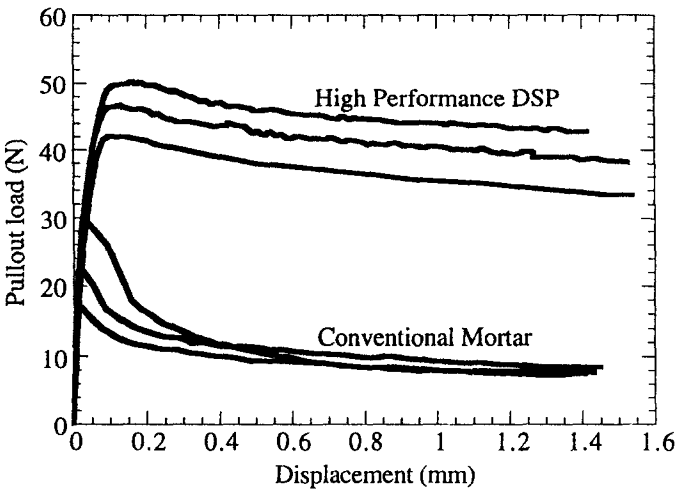

FIG. 5.
Effect of matrix strength on the pullout behavior of steel fibers from cement based matrices.

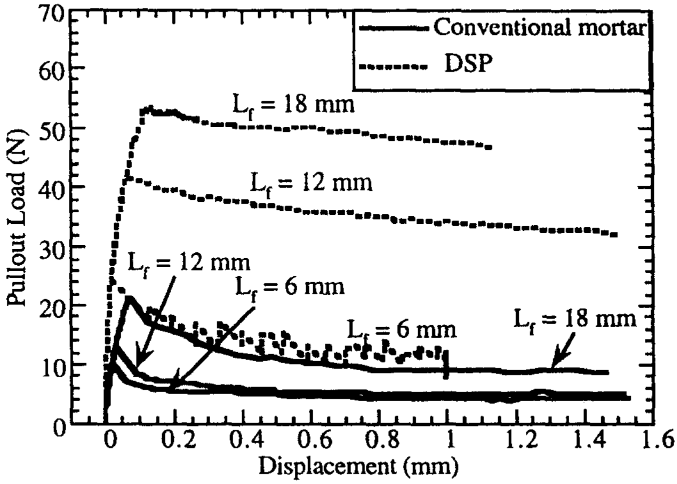

FIG. 6.

Effect of embeddment length on the pullout behavior of steel fibers from cement based matrices.

the maximum pullout load divided by the embedded fiber surface area. It can also be observed that the peak displacements were higher for larger embeddment lengths. The experimental results reported in the present study were consistent and in good agreement with those reported in the literature by other investigators (3, 5, 9, 10, 11, 16, 18, 20).

Effect of Matrix Strength. The densified systems of mortar and concrete containing homogeneously small particles, now known as DSP, were first described by Bache (17) in the early 1980's. This system makes use of large amounts of superplasticiser and silica fume to give a densely packed cement paste as illustrated in Fig. 4, with extremely low water to binder ratios ranging from about 0.15 to 0.23 with strengths from 150 to 250 MPa (21). The DSP cement matrix used in the present investigation was specially designed to achieve a compressive strength of 150 MPa with 0.2 water to binder ratio.

The effect of the compressive strength of the matrix is shown in Fig. 5. It can be observed that the peak pullout load increases in direct relation to the compressive strength. Thus it almost doubled when the compressive strength of mortar increased from 40 MPa to 150 MPa. It can also be observed that the frictional decay following the peak load was eliminated for the system with the higher matrix strength. The improved response of DSP system is attributed to the improved interfacial microstructure, as shown in Fig. 4.

Effect of Fiber Embeddment Length. All of the specimens with the embedded fiber length up to and including 18 mm failed by fiber debonding and pull-out. It can be observed from Fig. 6, that increasing the fiber embeddment length from 6 to 18 mm, while keeping other parameters fixed, resulted in a significant increase in the peak pullout loads. This can be due to the increase in the fiber debonded surface area. However, the maximum pullout load does not appear to be directly proportional to embedded fiber length as shown in Fig. 7.

The frictional bond strength values shown in Fig. 8, seem to be more stable for 12, and 18 mm embeddment lengths. The difficulties in obtaining results for 6 mm embeddment lengths

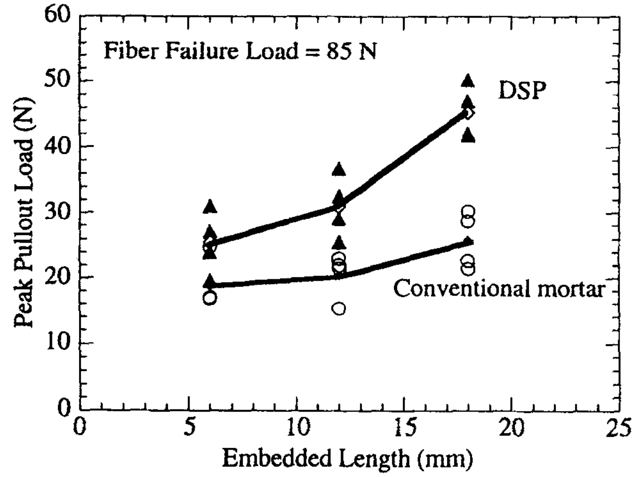

FIG. 7.
Effect of fiber embeddment length on peak pullout load.

are visible. An average frictional bond strength of about 4.4 MPa was obtained for the DSP system and an average value of about 1.9 MPa was obtained for the conventional mortar system (19).

Effect of Fiber Volume Fraction. Within the 3 to 6% range of the fiber volume fractions added to the matrix in this study, it can be observed that increasing the fiber volume fraction in the matrix, while keeping other parameters fixed, caused an increase in peak pullout load and the pullout work as shown in Fig. 9 and 10. The increase in the pullout resistance can be attributed to fiber interlock. At 6% fiber volume fraction, a stick-slip phenomenon has occurred in the post peak region as shown in Fig. 9. The presence of fibers in the matrix at such

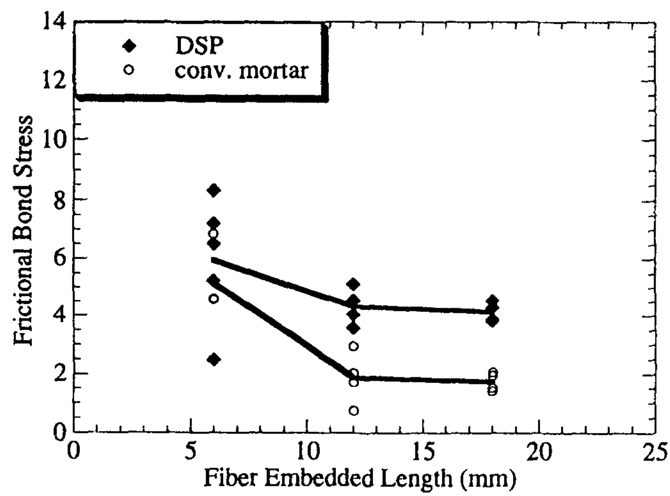

FIG. 8.
Effect of fiber embeddment length on frictional bond strength for cement based matrices.

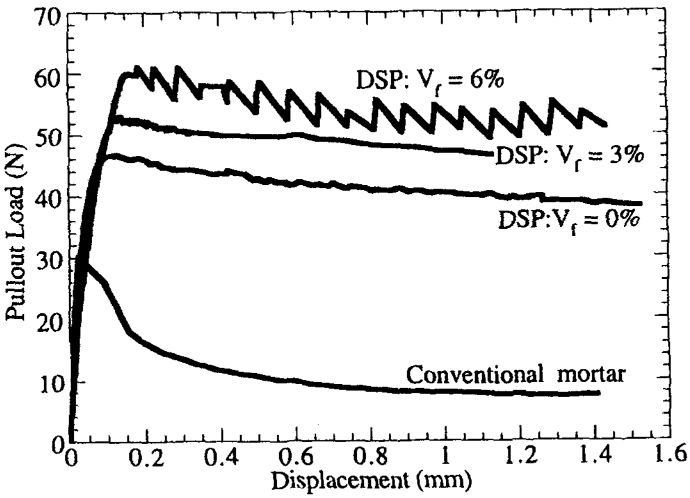

FIG. 9.

Effect of fiber volume fraction on the pullout behavior of steel fibers from cement based matrices.

a high percentage seems to provide additional resistance to pullout, and thus reduces frictional decay in the descending branch of the curve.

Pullout Work. Pullout Work or the dissipated bond energy, is defined as the area under the pull-out load versus end slip curve (22). The peak pullout work indicated approximately the amount of energy absorbed during the debonding process in a single fiber pullout test. The pullout work up to 1 mm displacement demonstrated the total amount of energy consumed during debonding and frictional sliding of a single fiber from a cement based matrix. It can be observed from Fig. 10 that the pullout work significantly increased as fiber embeddment

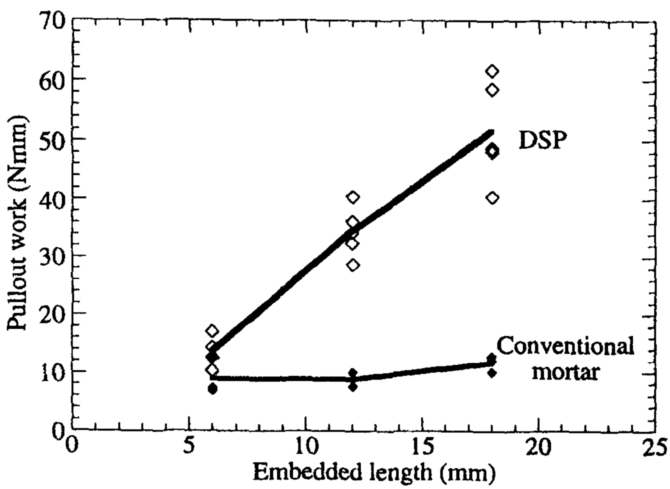

FIG. 10.

Pullout work up to 1 mm displacement for DSP and conventional mortar.

length increased and was much larger for DSP as compared to conventional cement mortar. Analysis of bond energy due to pullout show that the pullout energy in DSP and conventional mortar was dominated by frictional sliding (19).

Effect of Interfacial Crack Length. The matrix surface effects on the interfacial properties at the fiber exit point from the matrix was investigated by introducing a 2 mm diameter by 6 mm long interfacial crack (slit) around the fiber. The interfacial properties were estimated for an interfacial crack length of 0 and 6 mm. The results showed no noticeable matrix surface effects on the pullout characteristics of steel fibers from cement based matrices (14). This may be due to the size of the crack introduced, (i.e., being small) relative to the size of the specimen. Another factor may have been the extreme care taken in keeping the pullout fibers in a straight position in the molds, during casting without introducing any significant pretensioning of the fibers.

Conclusions

Based on the complete experimental data obtained and prior discussions, the following conclusions can be stated:

1. Observed values for interfacial properties indicate a significant improvement (up to three times) in the frictional bond strength and debonding energy of DSP. This is due to its dense microstructure as compared to conventional mortar.
2. The major mechanism of energy absorption in a single fiber pullout test is the interfacial friction during fiber pullout.
3. While keeping other parameters constant, (a) Increasing the fiber embeddment length caused a significant increase (2 to 3 times) in the peak pullout load and the pullout work. (b) Increasing the fiber volume fraction within the pullout medium caused up to a 20% increase in the peak pullout load and pullout work.

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