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PULLOUT RESPONSES OF STEEL FIBERS IN FIBER REINFORCED MORTAR MATRICES

Manote Sappakittipakorn[1*] and Nemkumar Banthia[2]

[1]Department of Civil Engineering, King Mongkut's University of Technology North Bangkok, Thailand

[2]Department of Civil Engineering, The University of British Columbia, Canada

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**Corresponding Author,*
Email address:
manotes@kmutnb.ac.th

ABSTRACT :

In fiber reinforced concrete (FRC), a flexural toughness is enhanced by the inclusion of fibers. The enhancement primarily depends on bond-slip characteristics between fibers and matrices. Recently, the concept of fiber hybridization is recognized as it synergizes the toughness performance. In the case of the hybridization between finer and coarser fibers, the finer fibers alter the properties of the matrices, which may affect the bond-slip response of the coarser fibers. Such influence was studied experimentally through a single fiber pull out test in this study. A series of tests was conducted to test the pullout resistance of two different types of steel fibers (i.e. hooked-end fibers and dead-drag fibers) inserted in four different cement mortar matrices (i.e. plain mortar, cellulose fiber reinforced mortar, 6-mm polypropylene fiber mortar, and 12-mm polypropylene fiber reinforced mortar). Four replicates were investigated in each combination. Results of the test show that the fibers in the matrices improve the bond-slip responses of the dead-drag fiber but only slightly change the bond-slip responses of the hooked-end fiber.

KEYWORDS : fiber reinforced concrete, single fiber pullout test, steel fiber, cellulose fiber, polypropylene fiber

1. Introduction

Concrete is prone to crack in general and so brittle. Yet, it can be toughened by many means. Fiber reinforced concrete (FRC) is one of them and currently has been used widely [1]. The FRC gains toughness due to the pullout resistance of the fibers. In FRC, reinforcing fibers are dispersed thoroughly in the mix to capture and hold a crack whenever occurred until they fail. Depending on the bond-slip responses between the fibers and the matrices, the failure can be either the breaking or the complete pullout of the fibers. The fibers however are only effective if the fibers themselves do not break but are slowly pulled out of concrete matrix [2] [3].

Those fibers, which toughen concrete and bridge large cracks, may be considered as macro fibers. Other smaller fibers that function as a crack arrester dealing with smaller cracks like shrinkage cracks may be classified as micro fibers. To achieve both above-mentioned advantages, a combination of these two fiber types is possible, so-called the fiber hybridization. However, it is not certain if the addition of the micro fibers into the matrices will always benefit the behavior of the macro fibers. Thus, to assure the performance of the fiber hybridization, the good bond-slip interaction between the macro fibers and the matrices blended with micro fibers is of most interest.

Extensive testing has been done on straight macro fibers. However, in the industries, deformed macro fibers are almost always used [4]. In this study two types of deformed steel fibers were then investigated – one is called Dramix fiber and another is DD (Dead-Drag) fiber. The reason the deformed fibers perform better than straight fibers is because the deformability at the ends of each fiber act as an anchor, holding the fiber in cement matrix. These deformed fibers have an increased resistance against pullout thus improving the concrete's ability to withstand tensile and flexural loading. In the case of the micro fiber, the cellulose and polypropylene fibers are often used and they were also examined concurrently. These micro fibers are very fine so that at a certain dosage they provide a very large number of fibers thoroughly spreading in concrete and may affect the property of concrete matrices [5].

2. Research Significance

The purpose of this test is to compare the pullout resistance of two different kinds of steel fiber from several different kinds of cellulose reinforced mortar matrices. The characteristics of the concrete mix have a significant effect on the ultimate load that the steel/concrete interface can achieve, particularly when considering the addition of cellulose or polypropylene fibers to the concrete mix. The purpose of this experiment was to examine the properties of concrete mixes including various combinations of DD/Dramix fibers and cellulose/polypropylene fibers, and determine which combinations are more suitable for engineering purposes.

3. Experimental Program

3.1 Preparation of Samples

In this study, a test specimen for the test of single fiber pull out comprises of two cylindrical mortar samples bridged with an individual fiber as shown in Figure 1. Two steel fibers were tested in the experiment: Dramix fibers (having the length of 35 mm) and DD fibers (with the length of 30 mm) as illustrated in Figure 2-4.

The DD reinforcing fiber is a fiber specifically designed to partially fail before it reaches its pullout capacity [6]. The fibers drag anchor is designed to break off once a maximum axial force is attained, following this the remaining portion of the fiber is dragged through the concrete until it is completely pulled out, or in the case of many of our tests, fractures in the middle of the fiber.

In contrast to the DD fiber the Dramix fiber does not involve any material failure. Dramix fiber resistance comes from the straightening of the fibers end as it is pulled from the concrete. As the fiber is pulled from the concrete it goes through two stages of bending. Stage one bending, provides added pullout resistance that results in an initial peak in the plotted data. The majority of the fibers pullout resistance comes from the stage two bending, were the fiber is bent at a near 90° angle. The combined effect of stage one and stage two bending results in the first peak value. Following the initial pullout the resisting force load plateaus. When stage two bending reaches its end the resistance force dives toward a minimum value where the only resistance comes from the friction between the straightened fiber and the concrete.

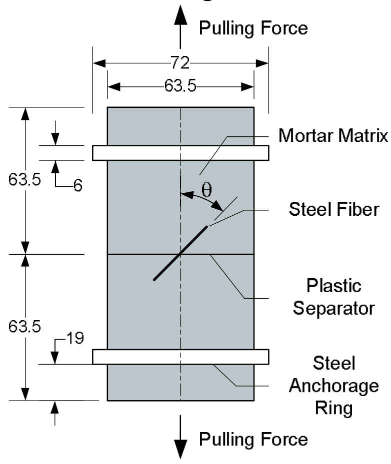
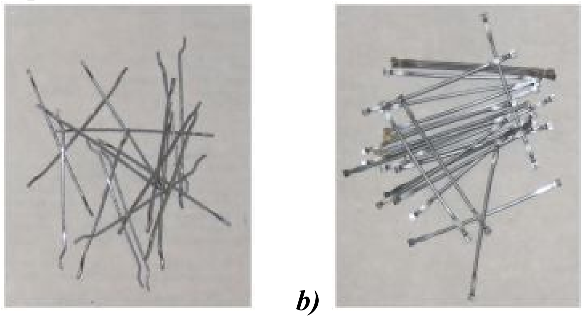


Figure 1 A schematic of the specimen in the single fiber pull out test



a) ***b)***

Figure 2 Steel fibers tested in the study; a) Dramix fiber and b) DD fiber

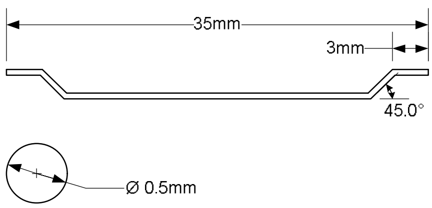


Figure 3 Dimensions and Cross Section of the Dramix Fiber

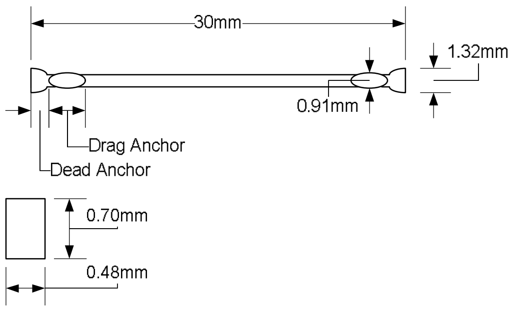


Figure 4 Dimensions and Cross Section of the DD Fiber

The steps in the sample preparation are quite similar to those found in the study of Chanvillard and Aïtcin [7]. The fibers were placed at 45 degrees from vertical and held in cylindrical plastic casings, with small sheets of cellophane against the face of the plastic casings. Metal casings were then tightened around one end of the symmetric plastic casings. The metal casings were cylindrical in shape, and held a steel anchorage ring inside (refer to Figure 5). The casing was filled with mortar. The specimens then sat for approximately three days under plastic sheeting at room temperature. At this stage, a half of the specimen was achieved. The specimens were then turned over; the cylindrical plastic casings were removed, and then replaced by metal casings identical to the first half of the specimen. The same mortar mix was then added to make the complete specimen. The specimens then sat for approximately three days before all the casings were removed. Subsequently, the specimens were moist cured in a saturated calcium hydroxide solution for 28 days.

3.2 Mix proportions of Mortar and Sample Designation

A Type 10 cement mortar mixed with water at the w/c ratio of 0.5 and mixed with river sand at the s/c ratio of 2 was prepared. The mixing was done in a mechanical mixer until the mix reached the consistency of a thick paste. The cement mortar was then poured into the metal casings on a vibrating table – but not over vibrated which would cause segregation of the mix. Cement mortar was mixed with either: cellulose fibers, 6-mm polypropylene (PP) fibers, 12-mm polypropylene (PP) fibers, or no fiber matrix (see the photos of these fibers in Figure 6). Two sets of the four mortar mixes were made: one for the test of the DD fiber and another one for the test of the Dramix fiber, and were designated as shown in Table 1. Four replicates were tested, yielding a total of 32 samples. Three 75x150-mm cylinders made of each of the mortar mixes (excluding the steel fibers) were also cast for a compression test.

a)
b)


Figure 5 a) casting molds (metal casing and rings) and b) testing apparatus

a)
b)
c)


Figure 6 Micro fibers in the matrix: a) cellulose fiber, b) 6-mm PP fiber, and c) 12-mm PP fiber

Table 1 Proportion of Fiber in DD Mixes and Dramix mixes

Mix No.	Fibers being pulled	Fibers mixed in mortar matrices (% by volume fraction)		
		Cellulose Fiber	6-mm PP Fiber	12-mm PP Fiber
#1-1	Steel DD Fiber	-	-	-
#1-2		0.5%	-	-
#1-3		-	0.5%	-
#1-4		-	-	0.5%
#2-1	Steel Dramix Fiber	-	-	-
#2-2		0.5%	-	-
#2-3		-	0.5%	-
#2-4		-	-	0.5%

3.3 Single Fiber Pull Out Testing

The single fiber pull out test simulates a state of a fiber when it bridges a crack in cement-based matrices to determine the pullout responses of the fiber. As the test specimen was prepared as shown in Figure 1, a crack was created by the insertion of the cellophane so that the specimen was divided into two portions. A fiber was embedded in both portions to bridge the crack. To perform the test, the test apparatus as shown in Figure 5b were assembled and attached to the specimen before they were placed in a tension testing unit (refer to Figure 7). The test apparatus was pulled at the rate of 0.6 mm/min and the tensile force was transferred to the specimen through the steel anchorage rings. Simultaneously, the corresponding bond-slip displacement was measured by using two LVDT transducers. The tensile load and the displacement were recorded at the 2 Hz frequency. The load-displacement results were reported and analyzed further on to examine the bridging performance of the fibers.

4. Test Results and Discussion

4.1 Compression Test Results

Figure 8 represents the compression test results conducted on the four different mortar matrices used in the pull out test. Among these four mortar mixes, the plain mortar has the highest compressive strength. At the high dosage of 0.5% volume fraction, the fibers decrease the compressive strength of the plain mortar and such decrease is dependent on the type of the fibers. It is found that the polypropylene fiber decreases the compressive strength at a greater amount than the cellulose fiber does. Since these fibers have low elastic modulus compared to mortar, it is expected that the fibers would also decrease the elastic modulus of the mortar matrices. But the effect of the fiber length on the compressive strength is insignificant as the results between the 6-mm and 12-mm polypropylene fibers are quite similar. According to these changes in the mortar matrices due to the fiber inclusion, the pullout responses of the DD fiber and Dramix fiber from these mortar matrices would be different, which are discussed in the subsequent section.

Figure 7 Mini-Instron testing unit with a specimen installed

4.2 Pullout Responses of DD Fibers and Dramix Fibers

This section summarizes the results of the pull out test that was conducted on the 32 samples, using the two different fibers with the four different fiber reinforced mortar matrices. Please note that some of the results were not available due to some of the test samples had defects and were unsound before testing. The ends of the DD fiber are designed to have a unique double anchored shape called dead and drag anchor. They function differently. While the fiber is pulled, the dead anchor provides an end bearing to hold the fiber in place. That increases the peak load until the dead anchor is broken off the fiber. Then, there is only the drag anchor left at the end. The fiber subsequently starts to slip off the matrix while the drag anchor further provides additional friction force. These complete pullout processes are the ideal failure mechanism of the DD fiber. So, to achieve its most efficiency, the fiber breakage where the breaking of the fiber takes place in the middle portion should be avoided.

The test results of the DD fiber in all four mortar matrices as shown in

Figure 9 indicate at least 50% chance of the fiber breakage. As the plain mortar matrix is very stiff, all of the test samples had fiber breakage. When the mortar matrices were blended with the fibers, they were less stiff and yielded more fiber pullout failure. However, a half of the samples still showed the fiber breakage. It is also found that the fibers were broken mostly at the slip displacement of about 4 mm and lower. Clearly, the pullout responses of the DD fibers were altered mainly by the variation of the mortar strength. It obscures the influence of shrinkage reduction and bond improvement due to the addition of the cellulose and the polypropylene fibers in the matrices.

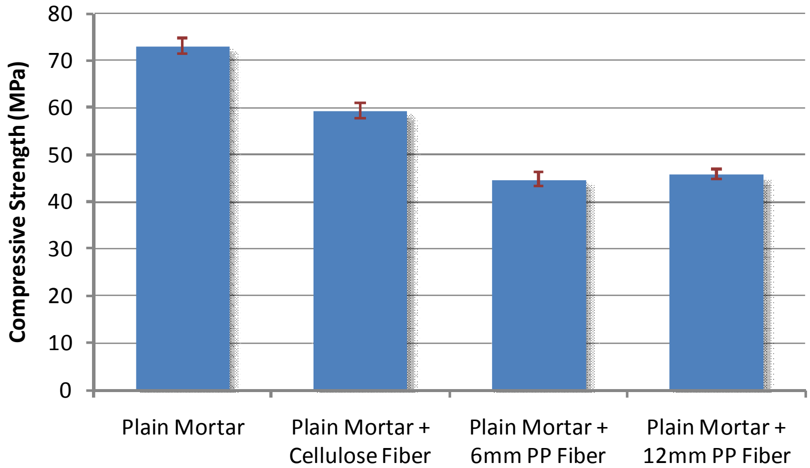


Figure 8 Compressive strength results of mortar mixes (w/c = 0.5 and s/c = 2) reinforced with the fibers at the volume fraction of 0.5% (tested at the age of 28 days)

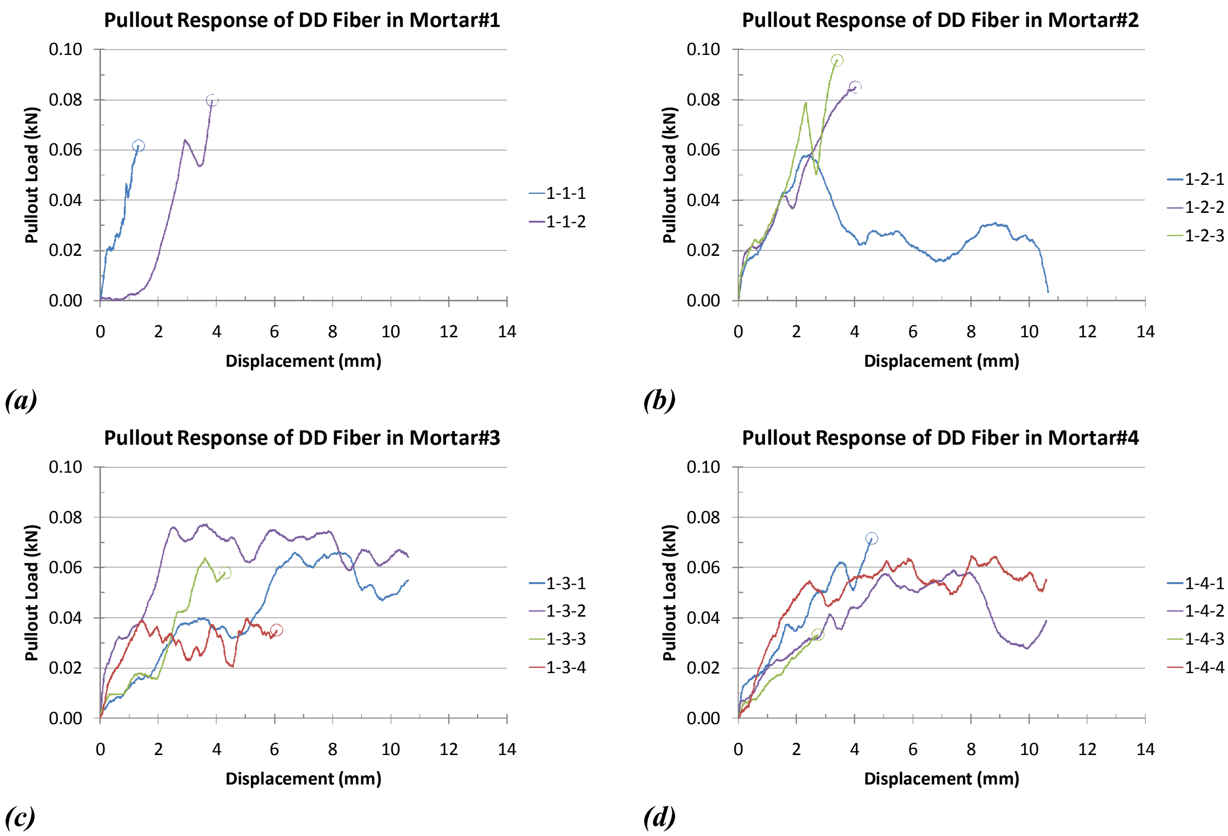


Figure 9 pullout load and bond-slip displacement results of DD fiber in fiber reinforced mortars

The Dramix fiber improves the pullout response through its hooked ends. When pulled out, its ends are flexed along its curved print providing an extra bearing load to increase a peak load. After the peak load, the hooked end was stretched out and slightly curled. The curled end resists the further movement of the fiber through a friction force it created against the mortars. The round section makes the Dramix fiber rather flexible so that it follows the complete pull out failure easily. Almost all the Dramix fiber samples failed in the fiber pullout mode as seen in the test results of the Dramix fiber shown in

Figure 10. Only one sample had a fiber fracture. Comparing among the various matrices, the plain mortar yields the maximum peak load. The peak load in the other mortar matrices was less according to the decrease of the compressive strength.

The post-peak pullout resistance also plays an important role in providing toughness to fiber reinforced concrete. In all of the Dramix samples, the post-peak load is gradually decreased and then approached at a certain load until a complete pullout. Although the variation of the mortar matrices does not have much influence on the response of the Dramix fiber, it does affect the response of the DD fiber. There is no post-peak response in the plain mortar matrix as the DD fiber fractures at the peak load. It is also seemed that the cellulose fiber mortar causes the same post-peak response between the Dramix and DD fiber. In the polypropylene fiber mortars, it is surprised that the post-peak response of the DD fiber is perfectly plastic, which will make the DD fiber very useful for toughness enhancement. But, due to the high chance of fiber fracture failure, such efficiency is not reliable.

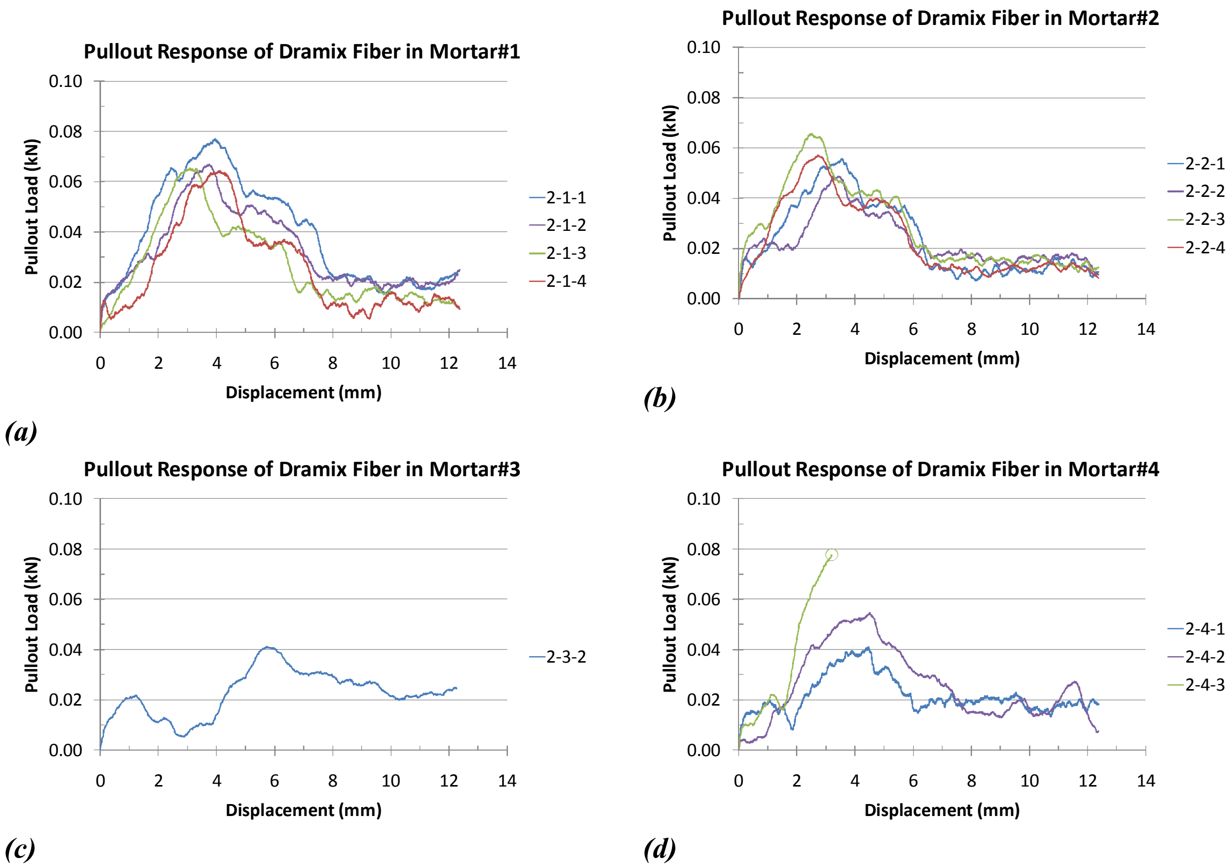


Figure 10 pullout load and bond-slip displacement results of Dramix fiber in fiber reinforced mortars

5. Conclusions

In this study, the influence of cellulose and polypropylene fibers added to mortar matrices on the bond-slip responses of steel fibers was examined. The DD and Dramix steel fibers were tested in the single fiber pullout test with the mortar matrices blended with cellulose and polypropylene fibers. Based on the test results, it can be concluded as follows.

- The high dosage of cellulose and polypropylene fibers lowered the mortar strength considerably that influenced the pull out responses of the fibers, especially the DD fiber. In the plain mortar where the strength was high, the DD fiber performed poorly as it was broken too soon. On the contrary, the low strength mortar matrices favored the performance of the DD fibers by allowing the fiber pullout failure. For the Dramix fiber, the effect of the strength is minimal. The fibers seldom failed in fracture. Only a slightly decrease of the peak load was observed.
- In the mortar reinforced with the cellulose fibers, the chance of the fiber fracture failure was decreased for the DD fibers but was none for the Dramix fibers. The post-peak load profile of both fibers was typical – the load drops from the peak and then gradually approach a certain load. However, it is seemed that, if the pullout failure takes place, the DD fiber is more effective than the Dramix fiber.
- In the case of the DD fibers in the mortar reinforced with the polypropylene fibers (both 6 mm and 12 mm long fibers) where the pullout failure was occurred, they produced the superior post-peak load bearing until they were pulled out completely. The load was as high as the peak that would promote great toughness energy. Yet, there is only 50% chance of such beneficial pullout failure. Unlike the DD fibers, the Dramix fibers yielded lower post-peak load bearing capacity and so did the lower toughness. However, their response is more consistent.

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