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Rate Effect on Pullout Behavior of Steel Fibers Embedded in Very-High Strength Concrete

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Abstract: Problem statement: Rate dependence of the newly developed Very-High-Strength-Concrete (VHSC) composites has received little or no attention so far. **Approach:** In this research, the bond-slip mechanisms of four types of steel fibers embedded in VHSC matrices were investigated through single-fiber pullout tests with the loading rates and matrix strengths are the primary variables. This study presented the experimental results of steel fiber-matrix bond characteristics and discussed the influence of loading rates on the pullout behavior. **Results:** The results were measured in terms of peak loads and total fiber pullout work or dissipated bond energy. Results indicated that the increase in pullout rate increases both peak load and total pullout work for all deformed fibers but had no effect on smooth, unreformed fibers. **Conclusion/Recommendations:** De formed and smooth fibers exhibit different rate sensitivities. The variation in response was attributed to the fiber end conditions. It is recommended that (1) additional experimental tests should be performed at other loading rates and (2) an analytical model should also be developed to analyze the rate effect on the interfacial deboning process of VHSC composites.

Key words: VHSC, fibers, rate sensitivity, pullout rate, matrix strength, interface, mechanical properties

INTRODUCTION

Fiber-reinforced Very High Strength Concrete (VHSC) composites are promising materials for use in a wide variety of civil and structural engineering applications. As compared to conventional concrete, the primary improvements of VHSC include packing through gradation of particle sizes, porosity and the similar modulus of elasticity of its constituents. The compressive strength of VHSC could reach 200 MPa or greater, approximately 7 times that of conventional concrete (O'Neil *et al*., 1999). This breakthrough in concrete technology is generally achieved by using the particle-packing method, elimination of the coarse aggregates, lowering of w/c ratio, lowering of carbon silica fume ratio and applying heat during curing (O'Neil *et al*., 1999; Olivier *et al*., 2000).

Studies on fibers' interaction with the cementitous matrix (Naaman and Najm, 1991; Chan and Chu, 2004; Kim *et al*., 2009; Zhouhua *et al*., 2002) have shown that good interfacial bond provides high resistance to fiber pullout during tensile-cracking and greatly increases the material's toughness. However, the vast majority of theses and other studies have dealt with static loading conditions. Very few studies have investigated the fiber pullout behavior under various loading rates. Kim *et al*. (2009) investigated the correlation between rate sensitivity in single fiber pullout behavior and rate sensitivity at the corresponding High Performance Fiber Reinforced Cementations Composites (HPFRCC). Their results included the effect of loading rate on the first cracking strength, post cracking strength and strain capacity as a function of fiber type, fiber volume fraction and matrix strength. Zhouhua *et al*. (2002) Performed dynamic fiber push-out experiments on model single fiber composite systems. They studied the effect of loading rate, fiber length and surface roughness on the push-out behavior and concluded that the maximum push-out force increases with increasing loading rate. Khanna and Shukla (1994) performed fiber pull-out test on copper/polyester model composite and observed that the maximum pull-out load increased by about 25% when the pull-out rate was increased from 4.2×10^{-4} to 0.42 cm sec^{-1}. Gokoz and Naaman

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(1981) performed fiber pullout tests on three types of fibers (smooth steel, glass and polypropylene) subjected to quasi-static rate (4.2×10^{-3} cm sec^{-1}) and very high loading rates (300 cm sec^{-1}). They observed that while polypropylene fibers were very sensitive to the loading velocity, smooth steel fibers were insensitive to it.

It is expected that the response of fiber reinforced VHSC composites is rate dependent. However, the rate-dependent response of this newly developed material has received little or no attention so far. The primary objective of this study is to provide experimental test data of the effect of loading rate on the pullout behavior of steel fiber reinforced VHSC composites. To achieve this goal, the present study uses single-fiber specimens to perform a series of pullout tests. The main variables in the experimental program were the loading rates, VHSC mixtures and fiber types and geometries (smooth, hooked, flat end and helical). The pullout loads versus slips, peak loads and the pullout work (or dissipated bond energy) were evaluated and reported. The results of this experimental investigation are important to better understand the effects of fiber geometry, matrix properties and loading have on bond-slip characteristics, as well as the effectiveness of steel fibers on improving tensile properties and toughness of VHSC.

MATERIALS AND METHODS

Four types of steel fibers (Table 1) were embedded in six different concrete matrices, leading to fifty-one basic series of pullout specimens. Each specimen consisted of six fibers, producing six single-fiber pullout tests. The steel fibers, namely Dramix 80/30, ZP305, Fibercon and Polytorx were embedded as deformed, hooked, or smooth. The smooth fibers were prepared by clipping off the end of both the hooked and the flattened end fibers. The matrices consisted of two normal concretes (42.5 and 54 MPa) and four very-high strength concretes ranging from 133-196 MPa. Table 2 provides the mixture proportions for the VHSC used in this investigation. Two loading rates were applied to study the effect of pullout rates on the pullout mechanism of steel fibers/VHSC matrices: (1) quasi-static rate at 0.021 mm sec^{-1} and (2) seismic rate at 25.4 mm sec^{-1}.

Specimen preparation: The components of the VHSC mixture Table 2 were dry-mixed at a low rate for 10 min and then the water/HRWRA was slowly added and observed for several minutes. Each batch was quantified to produce two pullout specimens and three 2 in. cubes for compression testing. After casting and adequately vibrating, the specimens were covered for 36 h before the 7 days curing at room temperature in a lime saturated water tank. After the 7 days curing, the VHSC specimens and cubes were placed in a water filled tank which was placed in an oven set at 90°C for four days (oven-wet curing). After four days, they were removed from the filled tank and returned to the oven at 90°C for an additional 2 days (oven-dry curing). On the other hand, the normal concrete specimens were cured in the lime saturated water tank for 7 days.

Test setup and testing procedures: MTS 858 Bionix II testing machine Fig. 1 was used to carry out the fiber pullout tests for both the quasi-static tests and seismic loading tests. The pullout load speed for the quasi-static test was 0.021 mm sec^{-1}, while loading rate of 25.4 mm sec^{-1} was used for seismic rate. The ratio of the high rate to low rate is 1200, or three orders of magnitude. The testing procedures involve securing the pullout specimen to the platen and carefully center each fiber between the grip faces. Each fiber was griped by extending the hydraulic actuator to the maximum extension possible without touching the pullout specimen. The values of the load and the corresponding movement of the actuator (displacement) were recorded using MTS Test works 4.0 software. The recorded data were then adjusted by subtracting the elastic elongation of the fiber from the corresponding displacement.

Table 1: Types and properties of the steel fibers

Fiber profile	Fiber type	Mechanical deformation	Length (mm)	Cross section area (mm^2)	Coating	Tensile strength (MPa)
	Dramix ZP 305	Hooked-end	30	0.250	None	1109
	Flat end	Flattened-end	50	1.080	None	1110
	Polytorx	Helix	25	0.190	Zinc	1728
	Dramix 80/30	Hooked-end	30	0.116	Brass	2094

Table 2: VHSC Mix proportions

	Cement	Sand	Silica flour	Silica fume	HRWRA	Water
Proportion	1.00	0.97	0.28	0.39	0.0206	0.22
Specific gravity	3.15	2.65	2.65	2.22	1.3000	1.00

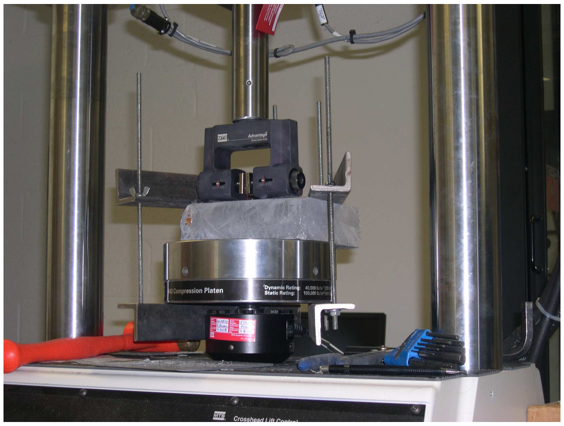


Fig. 1: Specimen and test setup

RESULTS

Effects of loading rate on pullout behavior of steel fibers/VHSC matrices are tabulated in Table 3 and illustrated in Fig. 2-11. Specimens designated by High Rate or "HR" were pulled out at a seismic rate of 25.4 mm sec^{-1}; all other fibers were pulled out of the matrix at a static rate of 0.021 mm sec^{-1}. Results of peak load, displacement at peak, pullout work at peak and total work (or total pullout energy) were averaged from six tests and reported here. Pullout mechanisms of different types of steel fibers are as follows:

Dramix 80/30 high carbon fibers: Results of smooth Dramix 80/30 (DS) fibers pulled from VHSC and from the standard grout matrices are illustrated in Fig. 2. Results indicated that for fibers embedded in VHSC with embedment lengths of 6.35 and 12.7 mm, the peak loads and pullout works are higher for the higher pullout rate. Comparing low pullout rate to high rate, the percent difference in peak load is 69 and 28% for embedment lengths of 6.35 and 12.7 mm, respectively. The corresponding increase in the total pullout work is 108 and 44% respectively. Also, the test results show that both the pullout energy at peak and displacement at peak load are also higher for the fibers pulled out at the high rate. Further, as shown in Fig. 2a the High Rate (HR) fibers' initial slope is linear, while the low rate fibers' entire pullout curve is oscillatory. However, for the 12.7 mm embedment length Fig. 2c, the initial slope of both high rate and low rate curves are very similar. Moreover, in contrast to VHSC, pullout from the standard grout indicated that the peak load is 49.4% less and the pullout work is 33.2% less when the smooth D-fibers pulled out from standard grout at high rate comparing to the lower rate Fig. 2d.

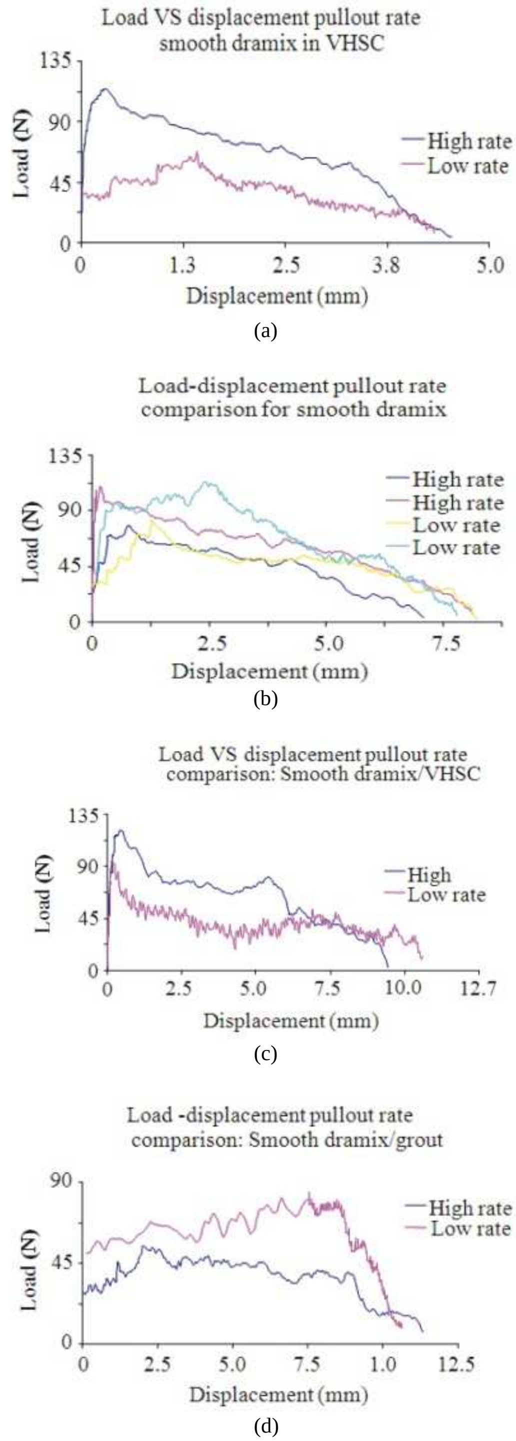


Fig. 2: Effect of pullout rate on Smooth Dramix (DS) fibers at different embedment lengths. (1 in = 25.4 mm; 1 N = 0.225 lb) (a) 6.35 mm/VHSC (b) 9.5 mm/VHSC (c) 12.7 mm/VHSC (d) 12.7 mm/standard grout

Pullout behavior of Hooked Dramix (DH) fibers is shown in Fig. 3. Both the peak load and total pullout work increase with the pullout rate. For an embedment length of 6.35 mm, the peak load difference between the HR and low rate is 12.7% and the pullout work difference is 38%. The corresponding difference for the 12.7 mm fibers is 28.2 and 49.4% respectively. The displacement and pullout work at peak load are also higher at higher rate. As illustrated in Fig. 3a and c the pullout behaviors of the High Rate (HR) and low rate fibers are very similar. However, the post peak behavior of fibers with the 9.5 mm embedment length Fig. 3b causes the total pullout work at low rate to be greater than high rate fibers. Behavior of deformed Dramix fibers embedded in standard grout is shown in Fig. 3d. From Fig. 2 and 3, it can be seen that the maximum pullout load values (for the smooth and hooked Dramix fibers pulled from VHSC) increased with pullout rate. This suggests that the pullout resistance of these fibers is rate dependent.

Further, as shown in Fig. 4a, pullout curve of fiber/VHSC exhibits linear behavior until the peak load is reached. The post peak behavior of the hooked D fiber does not appear to be influenced by matrix strength. On the other hand, the initial incline of the smooth D fibers pulled from VHSC medium Fig. 4b is very steep and terminates at the peak load. After the peak, the load drops sharply and then oscillates until the final sharp descent.

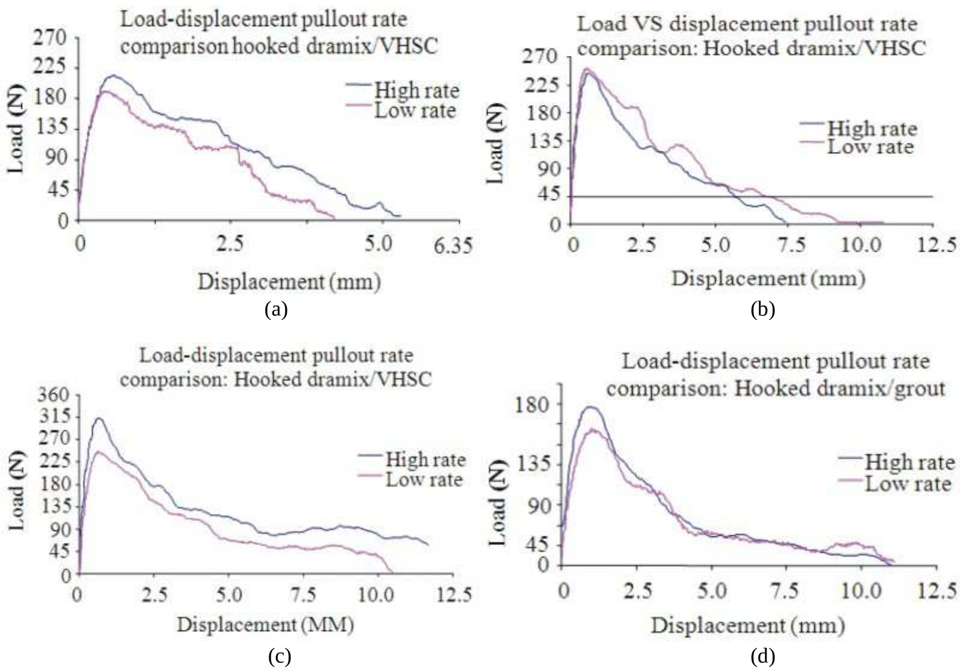


Fig. 3: Effect of pullout rate on Deformed Dramix (DH) fibers at different embedment lengths. (a) 6.35 mm/VHSC (b) 9.5 mm/VHSC (c) 12.7 mm/VHSC (d) 12.7 mm/standard grout

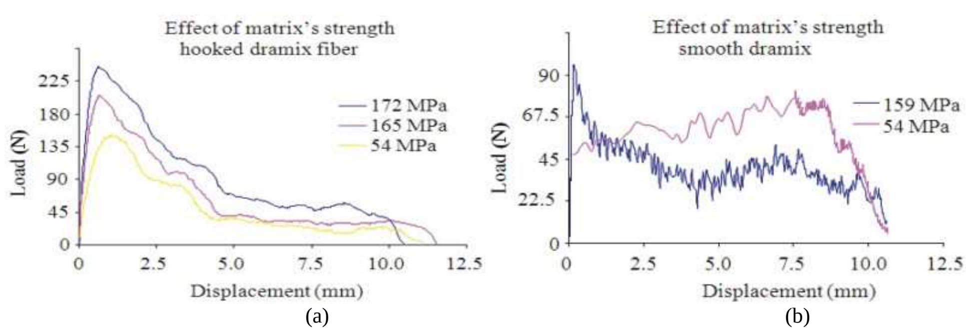


Fig. 4: Hooked and smooth Damix fibers embedded in different matrixes' strengths with 12.5 mm embedment length. (a) Hokked Dramix (D) Fiber (b) Smooth Dramix (D) Fiber

Table 3: Effect of pullout rate

Fiber	Pullout rate (mm sec^{-1})	Embed. length (mm)	f'_c (MPa)	P_{peak} (N)	Δ_{peak} (mm)	W_{peak} (N-m)	W_{total} (N-m)
	25.400	6.35	196.0	112.40	0.280	0.025	0.3180
	0.021	6.35	196.0	66.50	1.450	0.065	0.1530
	25.400	9.50	196.0	76.90	0.760	0.040	0.3290
	0.021	9.50	196.0	81.10	1.300	0.063	0.3770
Smooth dramix 80/30	25.400	9.50	157.6	107.90	0.170	0.011	0.4970
	0.021	9.50	157.6	112.10	2.480	0.223	0.5050
	25.400	12.70	159.0	119.90	0.430	0.024	0.6520
	0.021	12.70	159.0	94.00	0.170	0.009	0.4530
	25.400	12.70	54.0	53.80	2.060	0.073	0.4110
	0.021	12.70	54.0	80.40	7.680	0.457	0.5480
	25.400	6.35	178.0	211.90	0.580	0.084	0.5900
	0.021	6.35	178.0	188.10	0.460	0.060	0.4270
	25.400	9.50	172.0	240.70	0.640	0.105	0.8270
Hooked dramix 80/30	0.021	9.50	172.0	247.80	0.560	0.098	1.0780
	25.400	12.70	172.0	69.77	0.680	0.146	1.6610
	0.021	12.70	172.0	310.40	0.660	0.107	1.1120
	25.400	12.70	54.0	175.00	1.000	0.124	0.5140
	0.021	12.70	54.0	150.90	1.030	0.104	0.6220
	25.400	9.50	147.0	152.90	0.630	0.070	0.7160
	0.021	9.50	173.0	135.30	0.440	0.045	0.6400
	25.400	12.70	156.6	168.60	1.610	0.191	1.1320
Smooth ZP 305	0.021	12.70	156.6	272.90	2.230	0.237	0.9650
	25.400	15.90	134.5	183.40	5.590	0.375	1.3040
	0.021	15.90	134.5	189.40	1.930	0.279	1.7180
	25.400	12.70	42.5	70.40	0.254	0.009	0.2640
	0.021	12.70	42.5	66.20	0.254	0.010	0.3310
	25.400	6.35	157.3	117.30	0.614	0.054	0.5160
	0.021	6.35	157.3	119.20	0.236	0.021	0.4040
Hooked ZP 305	25.400	12.70	164.7	273.80	0.996	0.177	1.4610
	0.021	12.70	178.1	272.30	0.460	0.088	1.2760
	25.400	12.70	42.5	232.10	0.830	0.155	1.2580
	0.021	12.70	42.5	172.40	1.280	0.173	0.7850
	25.400	6.35	191.0	298.80	1.030	0.517	0.9900
	0.021	6.35	191.0	242.60	0.470	0.090	0.7280
	25.400	9.50	191.0	409.70	2.220	0.716	2.1420
Smooth fibercon	0.021	9.50	191.0	271.50	1.280	0.205	1.2750
	25.400	12.70	168.3	575.60	1.250	0.528	3.8060
	0.021	12.70	168.3	603.20	2.370	1.084	4.4830
	25.400	25.40	133.0	721.90	3.310	1.937	11.034
	0.021	25.40	133.0	871.00	6.890	4.863	14.405
	25.400	6.35	152.6	1061.00	2.950	2.224	3.7120
	0.021	6.35	152.6	775.30	1.620	1.050	3.3400
	25.400	12.70	152.6	1375.00	1.710	1.778	2.1700
Flattened end fibercon	0.021	12.70	152.6	1189.00	2.210	2.096	2.8110
	25.400	25.40	157.3	1181.00	1.840	1.469	3.6850
	0.021	25.40	157.3	1135.00	2.060	1.791	8.6750
	25.400	25.40	54.0	389.60	0.180	0.035	8.7270
	0.021	25.40	54.0	256.60	0.220	0.026	2.4810
	0.021	12.50	154.0	350.40	0.680	0.180	0.2300
Polytorx	0.021	12.50	147.0	330.40	0.640	0.170	0.2200
	0.021	12.50	42.5	280.40	1.050	0.230	1.5600

(1 in = 25.4 mm; 1 N = 0.225 lb; 1 MPa = 145 psi; 1 N-m = 8.85 lb-in)

ZP 305 low carbon fibers: Similarly, the pullout test results of the smooth ZP 305 fibers pulled out from VHSC matrix Fig. 5 indicated that both the peak load and total pullout energy increases with pullout rate. Figure 5a shows that the pre peak pullout behaviors of the HR and low rate fibers are somewhat similar. However, the difference in post peak behaviors suggested varying tunnel damage. Figure 5b illustrates the erratic behavior of the fiber at high pullout rate. Fibers, at both rates, exhibit a load drop after the initial incline, but the HR fiber exhibits a significant second incline in contrast to the low rate fibers. Further, the pullout behavior of ZP 305 embedded in standard grout Fig. 5d show that the post peak behaviors are slightly different which contributes to the higher total work of the fibers pulled at the low rate.

Pullout test results of the deformed ZP 305 embedded in VHSC Fig. 6a and b indicated that the loading rate has no effect on the peak load. However, the displacement at peak load and the post peak behaviors contribute to the higher total work of the high rate fibers. On the other hand, when the deformed ZP

305 is pulled out from standard grout Fig. 6c, the high loading rate resulted in 34.6 and 60% increase in peak load and total pullout work, respectively. As shown in Fig. 6c, the high rate fibers' initial slope is linear up to the peak load. In contrast, the low rate fibers' initial slope changes from linear to nonlinear well before the peak load. Moreover, the post peak decline of the HR curve is gradual and consistent in contrast to the oscillatory behavior of the low rate curve.

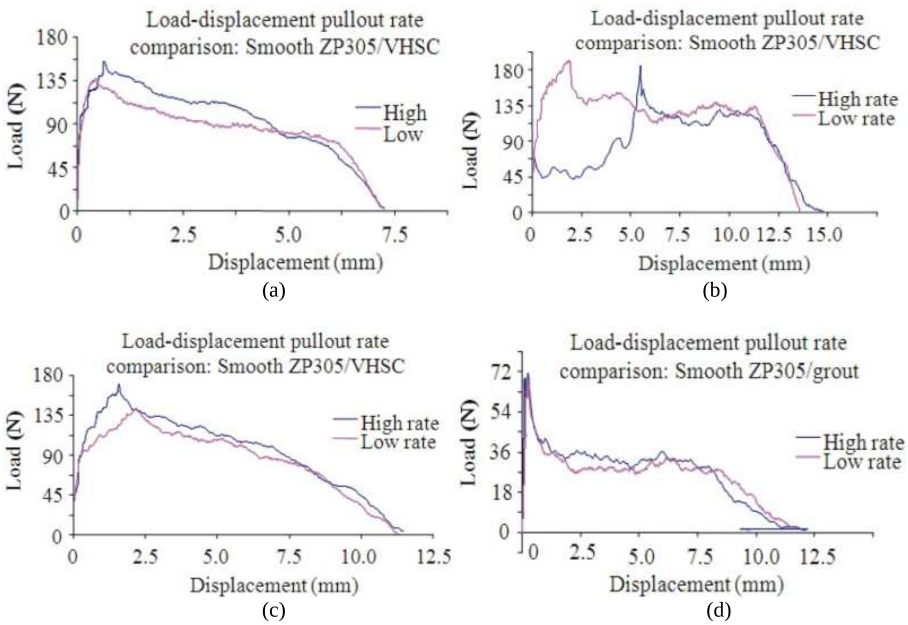


Fig. 5: Effect of pullout rate on smooth ZP 305 (ZS) fibers embedded at different lengths. (a) 9.5 mm/VHSC (b) 15.9 mm/VHSC (c) 12.7 mm/VHSC (d) 12.7 mm/standard grout

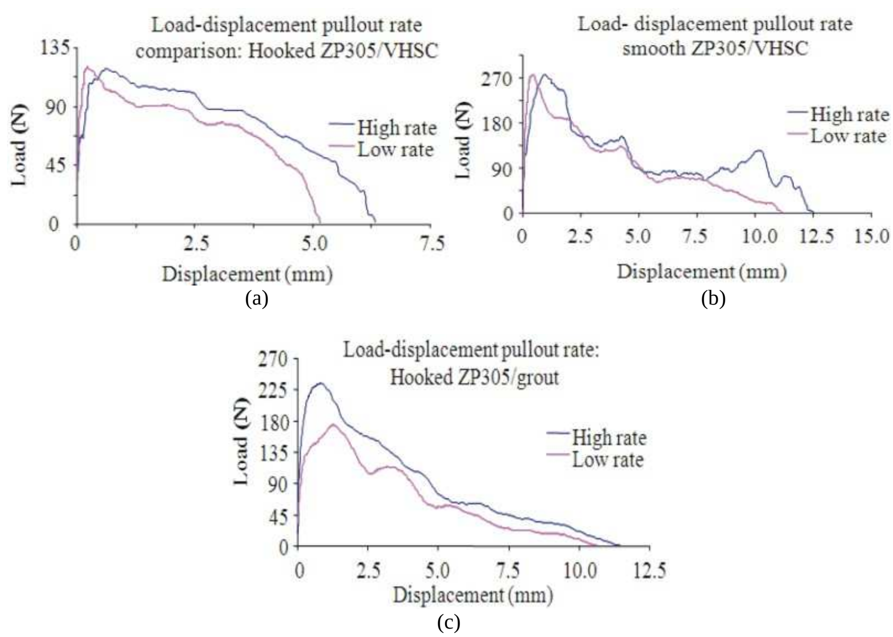


Fig. 6: Effect of pullout rate on hooked ZP 305 (ZH) fibers embedded at different lengths. (a) 6.35 mm/VHSC (b) 12.7 mm/VHSC (c) 12.7 mm/standard grout

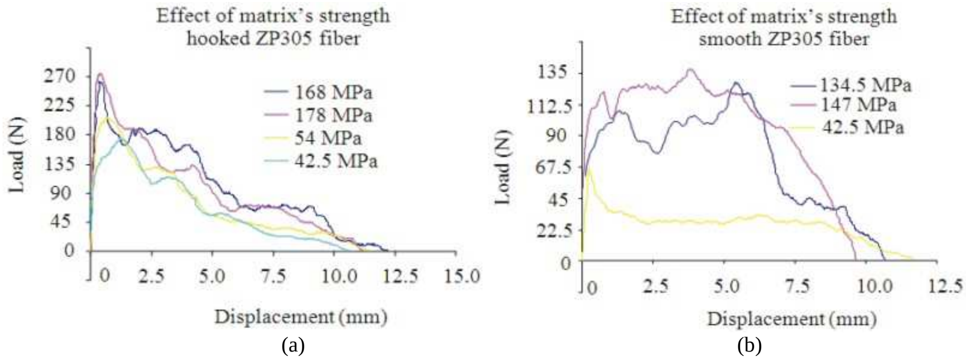


Fig. 7: Hooked and smooth ZP 305 fibers embedded in different VHSC matrixes with 12.5 mm embedment length. (a) Deformed ZP 305 fiber (b) Smooth ZP 305 fiber

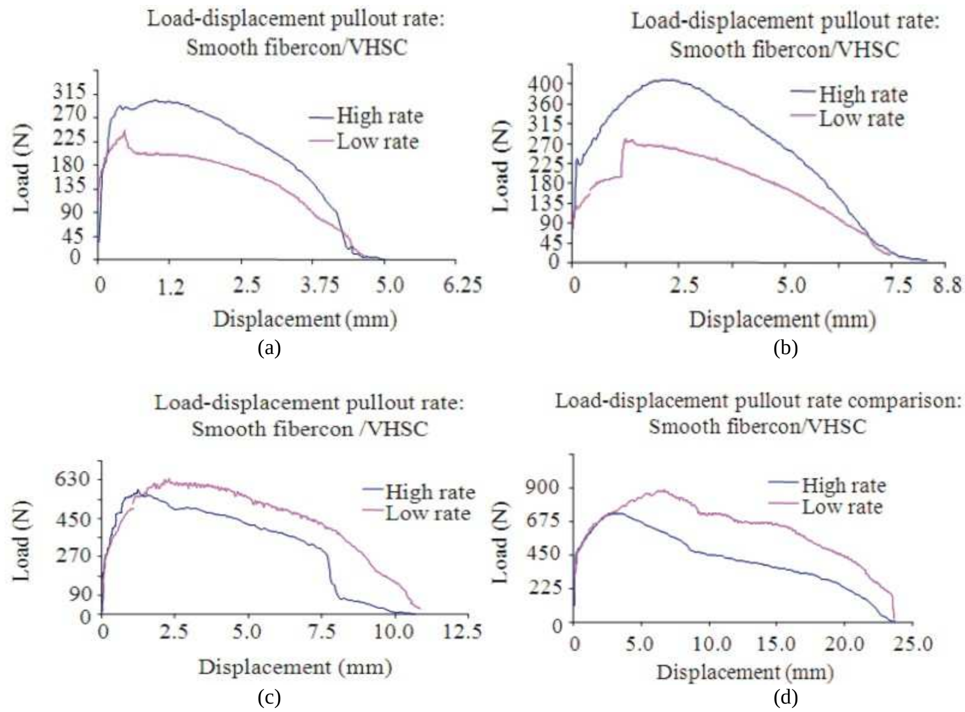
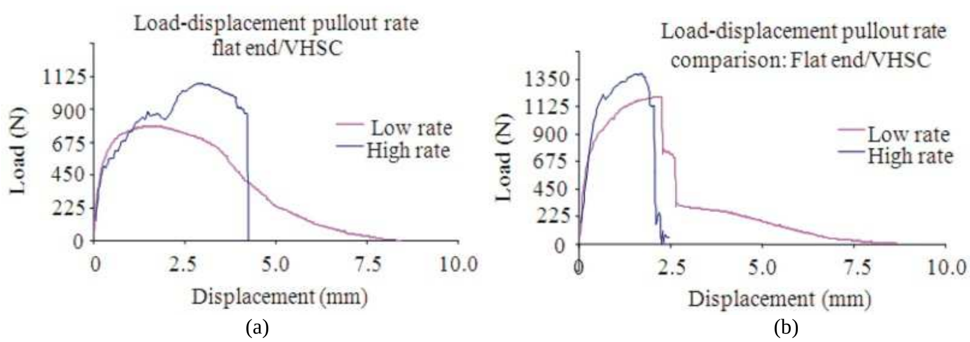
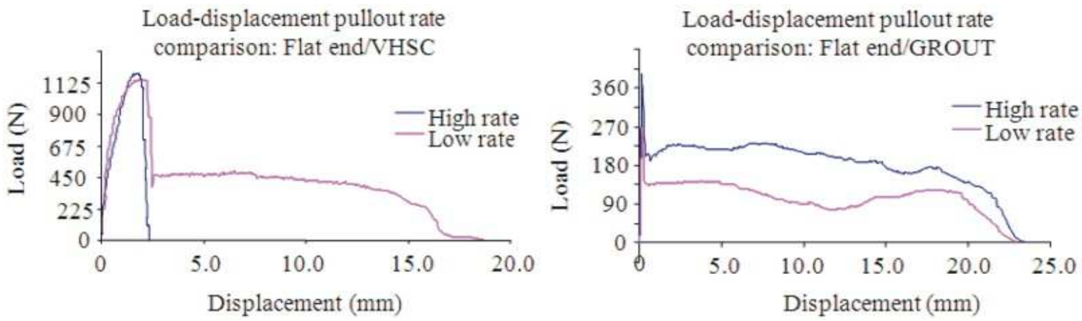


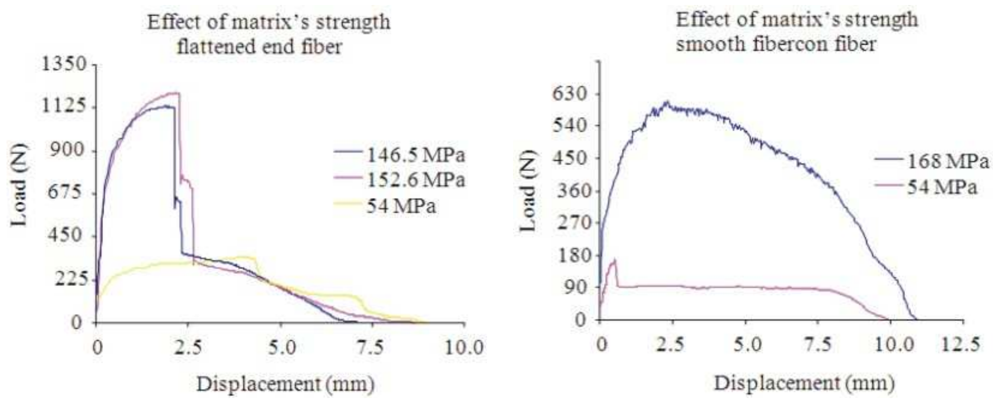
Fig. 8: Effect of pullout rate on Smooth Flat end (FS) fibers embedded at different lengths. (a) 6.35 mm/VHSC (b) 9.5 mm/VHSC (c) 12.7 mm/VHSC (d) 25.4 mm/VHSC





(c) (d)

Fig. 9: Effect of pullout rate on flattened end (FH) fibers embedded at different lengths. (a) 6.35 mm/VHSC (b) 12.7 mm/VHSC (c) 25.4 mm/VHSC (d) 25.4/standard grout



(a) (b)

Fig. 10: Load-displacement curve averages for (a) flattened end and (b) Smooth F-fibers embedded in varying strength matrixes

The pullout behavior of hooked and smooth ZP 305 (Z) fibers pulled from matrixes of varying strengths is illustrated in Fig. 7. It can be seen that both the peak load and total pullout work increases with matrix's strength.

Fibercon "flattened-end" fibers: Pullout behavior of the Smooth Fibercon (FS) fibers is tabulated in Table 3 and illustrated in Fig. 8. Pulling 6.35 mm at high rate causes the peak load to increase by 23% and the total pullout work by 36% in comparison with the low pullout rate. The increase at an embedment length of 9.5 mm is 51 and 68% respectively. In contrast, at embedment lengths of 12.7 and 25.4 mm the pullout parameters are greater for the low pullout rate. On the other hand, behavior of the Flattened end (FH) fibers embedded in VHSC Fig. 9 indicated that the end condition of these fibers improves their pullout resistance. This increase in the resistance may, however, cause fiber ruptures and thus reduce the energy absorption capacity. It should be noted that the vast majority of the fibers with embedment lengths of 12.5 and 25.4 mm ruptured inside the matrix when pulled out at both high rate and low rate. However, as indicated in Fig. 9b and c, the responses to the rupture are significantly different. While the HR fiber offered no additional pullout resistance once the rupture occurred, the low rate fiber behaves like smooth fiber. The pullout behavior of the flattened end fiber embedded in standard grout Fig. 9d indicated that both the peak load and total work at the high rate are greater than the corresponding values at the low rate. Further, after deboning, the flattened end is pulled through the matrix wearing down the end deformation of the fiber which results in behavior similar to a smooth fiber.

The effect of matrix's strength on the behavior of the flattened end F-fibers embedded in VHSC is shown in Fig. 10. As shown, when the matrix strength increases from 54-153 MPa, the peak load and total pullout work increases by 248 and 156% respectively. For the smooth F-fibers, the corresponding percent increases were 262 and 425% respectively.

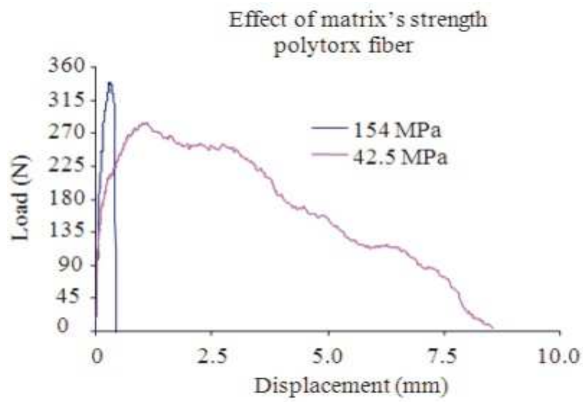


Fig. 11: Load-displacement curve averages for polytorx fibers embedded in VHSC and standard grout

Further, the behavior of the flattened end fibers pulled from VHSC was very consistent Fig. 10a. The initial incline is linear up to the P_{crit} point then increases nonlinearly to the point of rupture (the embedded flattened end shears off). Once the fiber ruptures, there is a significant load drop, then a gradual descent until total pullout. On the other hand, the pullout behaviors of the smooth F-fibers Fig. 10b are significantly different depending on which matrix they are pulled from. The initial incline of both are similar with linear branches followed by nonlinear branches ending at the peak load.

Polytorx fibers: The Polytorx P-fibers pulled out from VHSC ruptured at all embedment lengths. However, when the compressive strength of VHSC is 263% greater than the compressive strength of the grout, the peak loads increase only 25%, but, due to fiber rupture, the pullout work is significantly lower. Fig. 11 illustrates the pullout behavior of the P-fiber embedded in VHSC and standard grout.

DISCUSSION

Dramix 80/30 high carbon fibers: Effects of loading rates on pullout mechanism of smooth and hooked Dramix fibers show that pullout rate has greater effect on total work than the peak load. In case of smooth Dramix 80/30 (DS) fibers, the loading rate effect on pullout energy is greater than in the peak loads, but the displacement at peak load is significantly lower at high pullout rate. The hook end of the Dramix 80/30 (D) fiber substantially increases the peak load and total pullout work in both VHSC and grout matrixes. Further, the pullout curve line of the hooked D fiber is fairly smooth indicating that the fiber traveled through the tunnel and did not significantly rip or tear the matrix while bending around the curves of the tunnel.

ZP 305 low carbon fibers: Pullout test results of the deformed ZP 305 embedded in VHSC indicated that the loading rate has no effect on the peak load. However, the post peak behavior contributes to the higher energy of the high rate fibers. Additionally, comparing the two ZP 305 fibers embedded in VHSC, the hooked fibers' peak load is 1.9 times that of the smooth fibers but the pullout work of the hooked fibers is only 32% greater than the smooth fibers. Both the smooth and hooked Z fibers pulled out without damaging the tunnel. However, some of the fibers ruptured internally at the base of the hook, the others ruptured at the fiber/concrete interface.

Fibercon "flattened-end" fibers: behavior of the Flattened end (FH) fibers embedded in VHSC indicated that the end condition of these fibers improves their pullout resistance. This increase in resistance may, however, cause fiber ruptures and thus reduce the energy absorption capacity. That is, the high loading rate ruptures these fibers causing sudden drop (at low displacement) in the pullout curve, which in turn resulted in lower pullout energy or area under the pullout curve. However, the peak loads remain higher at high loading rate. The mode of fiber failure changes from a complete pullout under quasi-static loading to fiber rupture under seismic loading rate.

Also, it was observed that the F fibers pulled out of the grout were significantly worn down, almost matching the diameter of the body of the fiber. Further, it was noticed that when the deformed flat end fiber pullout from the grout, it held its peak load for an extended displacement. This appears to be the result of the flattened end cutting through the grout until the flattened end was worn smooth. While being pulled from the VHSC matrix, the internal flattened end broke, hence the sharp drop in load.

Polytorx fibers: The Polytorx (P) fibers embedded in VHSC ruptured at all embedment lengths. However, the peak loads for the fibers pulled from the VHSC are higher than those pulled from the standard grout but due to fiber rupture, the pullout work is significantly lower.

CONCLUSION

The effect of pullout rates, using single fiber pullout test, is helpful for understanding the rate sensitivity of interfacial bond behavior of VHSC composites. This experimental study investigated the effect of loading rate on the pullout behavior of steel fibers embedded in very high strength concrete mediums. Quasi-static and seismic loading rates, different types of steel fibers and different matrices of VHSC were used. The following conclusions can be drawn from the findings of this research:

- Increasing loading rate was seen to produce increasing peak load and pullout energy for the deformed fibers
- For a given fiber's type, the deformed and smooth fibers exhibit different rate sensitivities. The variation in response is attributed to the fiber end conditions
- The flattened end steel fiber ruptured at all embedment lengths when pulled out at high rate; however, the peak loads were the highest among all other fibers. The mode of fiber failure changes from a complete pullout under quasi-static loading to fiber rupture under seismic loading
- Results show that both pullout work and peak load increase as matrix strength increases for all deformed fibers that did not rupture. Moreover, while the smooth Fibercon and the smooth ZP 305 fibers' pullout work and peak loads increase as matrix strength increases, the smooth Dramix fibers do not appear to be affected by matrix strength

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