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The Effect of Freeze-Thawing on Steel Fiber-Matrix Bond Characteristics of Cement Based Composites

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Abstract— **A frost resistance is required for the concrete and reinforced concrete elements such as girder bridges, dams, concrete paving and airport runways in cold climatic zones. The water in the capillary spaces of concrete is freezes and expands when subjected to frost effect water-saturated hardened concrete. The expansion amount at the end of re-freezing subsequent dissolving increases cumulatively. If the stress caused by expansion exceeds the tensile strength of concrete, distortion such as cracking, disintegration are occurred in concrete. In this study; the freeze-thaw effects on bond strength of reactive powder concrete (RPC), normal concrete and mortar were studied. The effect of maximum aggregate diameter, chemical additives, water/binder ratio, steel fiber and curing conditions on bond strength were determined. The fiber-matrix bond strength and mechanical properties of control samples compared with specific freeze-thaw cycle exposed samples.**

Keywords— ***Freeze-Thawing, Pull-out, cement based composites, steel fiber, fiber-matrix bond characteristics***

Introduction

It has long been recognized that the poor behavior of cement based materials under tensile loads can be improved by the addition of steel or various discontinuous fibers. The bond between fiber-matrix provides the stress transferring between the fiber–matrix phases (Fig. 1).

In the past decades, many researchers have dealt with the bond characteristics of steel fibers embedded in cement-based composites. However, there is a lack of information about the effect of durability issues like freeze-thaw cycles on the pull-out behavior of steel fibers. Freeze–thawing resistance of concrete is a critical parameter in terms of the structural elements in the cold climates. Freeze–thawing (F-T) cycles may cause major deterioration in the critically saturated and unprotected concrete (For example, non-air entrained concrete). Beglarigale & Yazıcı (2013) [1] have investigated the effect of a common durability problem, alkali silica reaction (ASR), on steel fiber-matrix bond characteristics. Surprisingly, the test results indicate that the ASR gel congestion in the fiber-matrix interface increased the bond strength significantly during alkali exposure.

It can be summarized from many researches that the steel fiber-matrix bond characteristics depend on the properties of cementitious matrix as well as the geometry of the steel fibers. An increasing in the matrix strength leads to higher bond strength [2, 3, and 4]. On the other hands, studies showed that the pull-out peak load of the hooked-end steel fiber was significantly higher than the smooth steel fiber. [2, 3, and 5]. In addition, the pull-out peak load and the debonding toughness increased by an increasing in the embedment length of the smooth and hooked-end fibers [2 and 6].

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Experimental

A. *Materials*

CEM I 42.5 R type cement was used for this research. A polycarboxylic ether based superplasticizer (SP) was used to reach the target workability. Two types of aggregate were used in experimental program. Crushed lime stone (0–5 and 5-8 mm) and quartz aggregate (0.5-1 and 0-0.4 mm) were used in this study. A single type of steel fiber with 1.05 mm diameter, 50 mm length, and 48 aspect ratio was used in the pull-out tests. Furthermore, brass-coated steel-micro fiber with 0.16 mm diameter, 6 mm length, and 37.5 aspect ratio was used in micro reinforced mixtures.

B. *Preparation and production of mortars*

In this study, three different main mortars were designed. An ordinary mortar (OM) with 0.5 water/cement (W/C) ratio, a high strength mortar (HSM) with 0.35 W/C ratio, and a reactive powder concrete (RPC) mixture with 0.18 water to binder (W/B) ratio. These mixtures were prepared with and without 2% (by volume) steel micro-fiber reinforcement. The reinforced mixtures were abbreviated by "F" (e.g. RPC-F). In other to investigate the effect of maximum aggregate diameter, an ordinary mixture with 8 mm maximum aggregate size prepared (OM-D). In addition, a series of the OM (Air-OM) and HSM (Air-HSM) mixtures were prepared by an air-entraining admixture. The air-entraining admixture dosage was adjusted to achieve a mixture with 6-8% air content. Also, a different OM mixture was prepared by 7.5% (by weight of cement) styrene–butadiene rubber latex admixture.

The experimental study was carried out in two different curing conditions. After casting, specimens were kept for 24h in 20 ±2°C and after that, were demolded and then, were cured in water for 28 days. The temperature of curing water was fixed in 20 ±2°C. A series of RPC and RPC-F specimens were put in autoclave cabin. The temperature was adjusted to 210°C and steam pressure was adjusted to 2 MPa. Mix designs of the main mixtures are presented in Table 1.

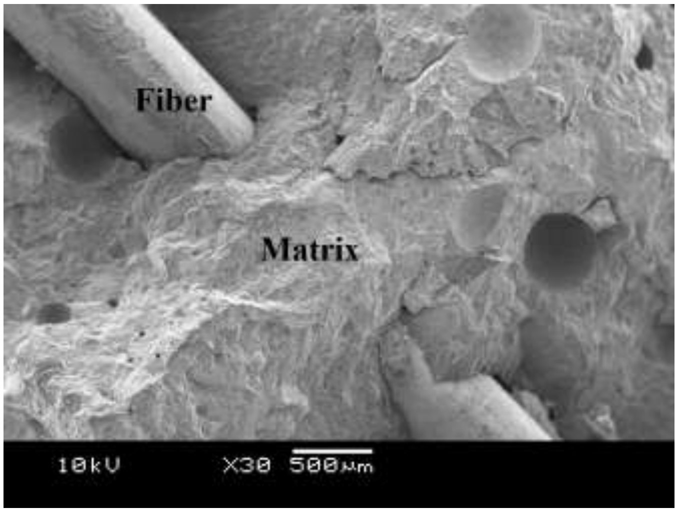

Figure 1. SEM image of steel fiber embedded in mortar

Table I. Mix designs of the main mixtures.

Component	OM	HSB	RPC
Cement (kg/m³)	500	500	785
Silica Fume (kg/m³)	-	-	196
Water (kg/m³)	250	175	174
0-5 mm Limestone (kg/m³)	1470	1675	-
0.5-1 mm Quartz (kg/m³)	-	-	684
0-0.4 mm Quartz (kg/m³)	-	-	455
Superplasticizer (l/m³)	5	9	35
Water/cement	0.5	0.35	0.22
Water/binder	0.5	0.35	0.18
Flow (mm)	155	155	200

Mixtures were mixed by a Hobart mixer. Dry ingredients of ordinary mixtures were premixed for two minutes and RPC for five minutes to achieve homogeneous dry components. Then, half of the mixing water was added to the dry mixture, while the remaining water was being mixed with the required amount of superplasticizer and then, poured into the mixer. After normal speed for about 1 minute for OM/HSM and 5 minutes for RPC mixtures, mixing continued for another 3 min for OM/HSM and 10 min for RPC in high speed. The workability of each mixture was controlled with mini-flow table test. The required amount of superplasticizer was used to achieve 155 ±10 mm flow table values for OM/HSM mixtures and 200 ±10 mm for RPC mixture. The mixtures that were prepared for the pull-out test were poured into 50x50x50 mm cubic molds in two layers with 30sec applying vibration for each layer. After placing final layer, single steel fiber was centrally embedded into the fresh mixture by an apparatus which allowed the fiber becomes perpendicular to the surface of the specimen and adjusts the desired embedment length into the matrix and then, vibration was applied for 30sec. In addition, the flexural and compressive strength of the matrices were determined in 40x40x160 mm prismatic specimens.

The specimens were subjected to the freeze–thawing cycles in accordance with ASTM: C666 standard.

C. *Test procedures*

The fiber-matrix bond characteristics were determined by applying single-fiber pull-out test that is a common method used and analyzed by many researchers [8-11, 14-24]. The Schematic diagram of pull-out test setup used in this study is presented in Fig. 2. Capacity of the load-cell was 6 kN. The pull-out test specimen was fixed to the frame on the bottom platen while the free end of the fiber was held by the fiber mounting plate. The matrix remained rigid while, the fiber mounting plate moved upward with a rate of 1 mm/min under closed loop control test. During the slip of fiber from the matrix, corresponding load values were recorded by the load-cell that was connected to a computer. Some important parameters such as peak pull-out load, displacement at the peak load and, debonding toughness (slip energy) were found out by analyzing the pull-out load versus end displacement curves plotted using the data from the test.

Each one of the data presented here is the average test result of three specimens for the three point flexural strength and the average test result of four specimens for the pull-out test values. Compressive strength results are the average of six samples that were left from bending test. After flexural tests, the broken half-prisms were tested in uniaxial compression (loading area is 40x40 mm).

Results and discussion

D. *Mechanical properties of mixtures*

Compressive and Flexural strength of mixtures are shown in Fig. 2 and 3. As expected the compressive and flexural strength of RPC mixture are higher than the other mixtures. The autoclaving have a positive effect on both flexural and compressive strength. This positive effect is more obvious in the case of the steel-micro fiber reinforced RPC (AC-RPC-F). It is well known that micro fibers improve the mechanical strength of cement based composites. This behavior is also valid in the case of OM and HSM mixtures (OM-F and HSM-F mixtures).

The compressive strength of OM mixture was slightly decreased by using the SBR latex, while the flexural strength increased. Generally, the compressive strength of cement based composites can be decreased as a result of air entraining effect of polymer based admixtures. However, they can have a positive effect on flexural strength of concrete and mortar. This positive effect of polymers on flexural strength can be explained by the better bond strength between aggregate and matrix as a result of film formation [7 and 8].

As expected, the air-entraining admixture decreased the mechanical strength of the OM and HSM mixtures (Air-OM and Air-HSM mixtures).

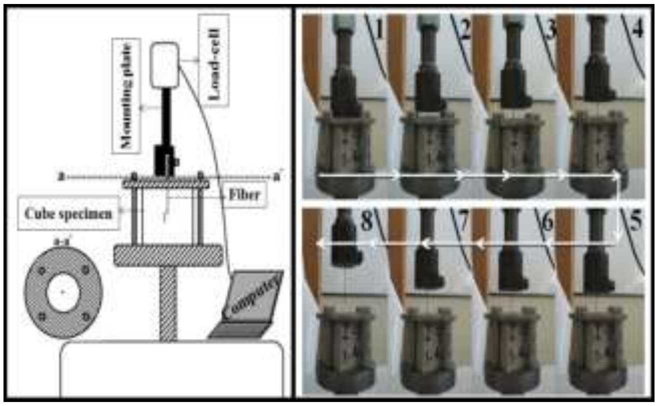

Figure 2. Pull-out test setup and procedure.

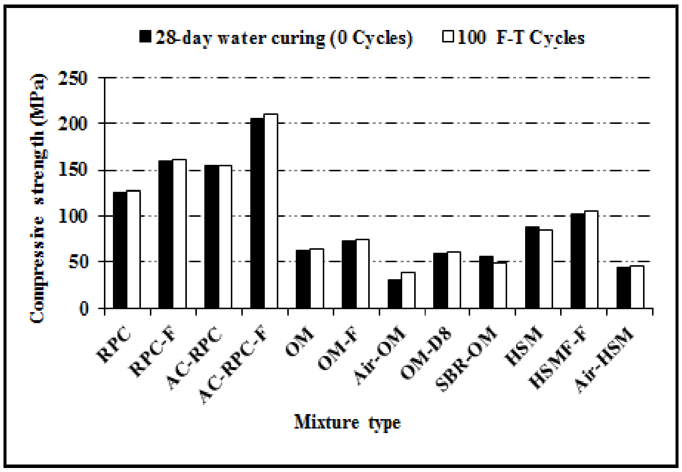

Figure 2. Compressive strength test results.

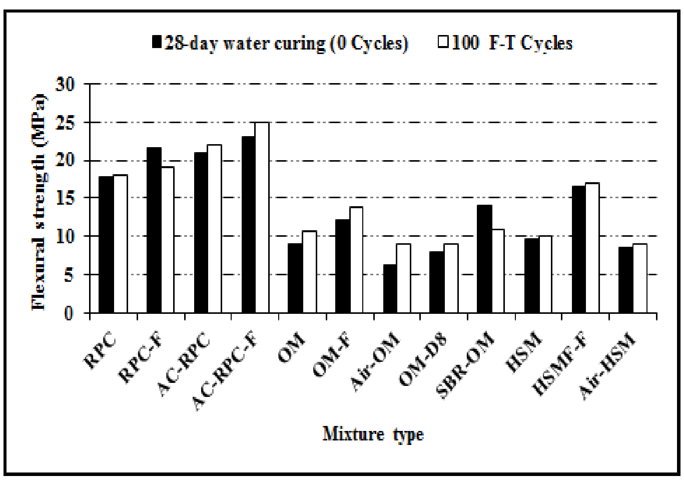

Figure 3. SEM image of steel fiber embedded in mortar.

E. *The effect of W/C ratio and matrix type on pull-out behavior*

The pull-out load – displacement curves of steel fiber embedded in the RPC, OM, and HSM mixtures are presented in Fig. 4. It can be seen from curves that the combination of two different mechanisms constitutes the pull-out behavior: debonding of the surround interface and frictional slip of the fiber. Firstly, the embedment length of fibers is fully debonded (from outer surface to the interior of specimen), then the fiber pull-out occurs under frictional resistance. High pull-out peak load illustrates the good bond between matrix and steel fiber. It can be stated that fiber shows elongation until the peak load without the initiation of a considerable debonding. Second peak point in the descending part of hooked-end fiber is related to the mechanical interlock of hooked end. The additional peak points were also observed in the load-displacement graphs of some mixtures. It may be related to the frictional effect of aggregate, especially for coarser than1 mm.

As can be seen from the figure the pull-out peak load and deboning toughness of HSM mixture is higher than the OM mixture. Lower W/C ratio improves the mechanical properties and fiber-matrix bond characteristics. In addition, the pull-out behavior of RPC mixture is much better than the other mixtures. Dense microstructure and low W/B ratio leads to better bond characteristic of steel fiber and RPC matrix compared to the OM and HSM mixtures. Furthermore, the existence of silica fume has a positive effect on bond characteristic between steel-fiber and RPC matrix [9].

Reinforcing the mixtures by 2% steel micro-fiber improved both the peak load and the debonding toughness somewhat. However, it seems that the properties of the matrix phase (W/B ratio) are more important.

F. *The curing condition (Autoclaving)*

The Pull-out load–displacement curves of steel fibers embedded in the RPC and AC-RPC mixtures are presented in Fig. 5. As can be seen from the figure the pull-out peak load and of RPC mixtures increased remarkably after the autoclave curing. Steel fiber was ruptured during the pull-out test without considerable debonding values. This behavior shows that the bond strength is higher than tensile strength of the steel fiber itself. This behavior can be explained by congestion of tobermorite gel in the fiber-matrix interface (observed in the microstructural investigation) and low W/B ratio which increased the bond strength strongly. By using the SiO_2 components such as finely ground quartz (quartz powder) or silica fume in mix design of mixture, a pozzolanic reaction takes place during the autoclave curing, and the crystalline 1.1 nm tobermorite yield. This behavior leads an increase in mechanical strength [10]. It can be seen from the Fig.6 that the tobermorite gel spread throughout the fiber-matrix interface of autoclave cured specimens. This phenomenon was not observed in the water cured specimens (Fig. 6). The congestion of the hydration products in the fiber-matrix interface increased the bond strength.

G. *The effect of maximum aggregate size on pull-out behavior*

The Pull-out load–displacement curves of steel fibers embedded in the OM and OM-D8 mixtures are presented in Fig. 7. As can be seen the pull-out behavior of steel fibers embedded in both OM and OM-D8 is similar.

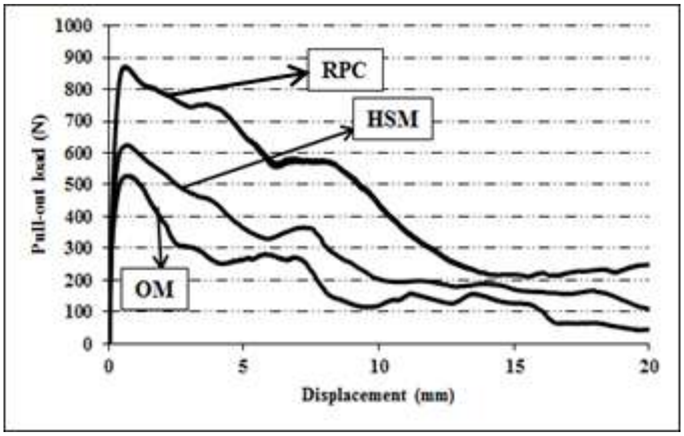

Figure 4. The Pull-out load–displacement curves of steel fibers embedded in the OM, HSM, and RPC mixtures.

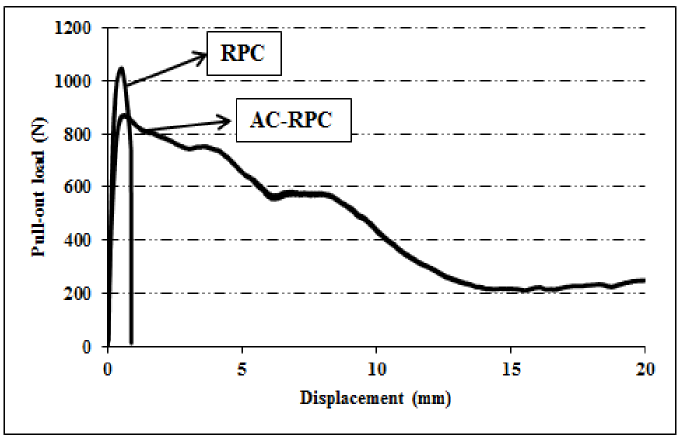

Figure 5. The Pull-out load–displacement curves of steel fibers embedded in the RPC and AC-RPC mixtures.

H. *The effect of SBR latex on pull-out behavior*

The Pull-out load–displacement curves of steel fibers embedded in the OM and SBR-OM mixtures are presented in Fig. 8. The SBR admixture slightly improved the pull-out behavior of the OM mixture. This can be explained by the film formation in the fiber-matrix interface. The polymer based admixtures improves the bond strength between aggregate and matrix as a result of film formation [7 and 8].

I. *The effect of air-entraining admixture on pull-out behavior*

The Pull-out load–displacement curves of steel fibers embedded in the Air-OM and Air-HSM mixtures are presented in Fig. 9. The pull-out behavior was affected negatively by using the air-entraining admixture. Micro air bubbles decreased the matrix-fiber bond slightly.

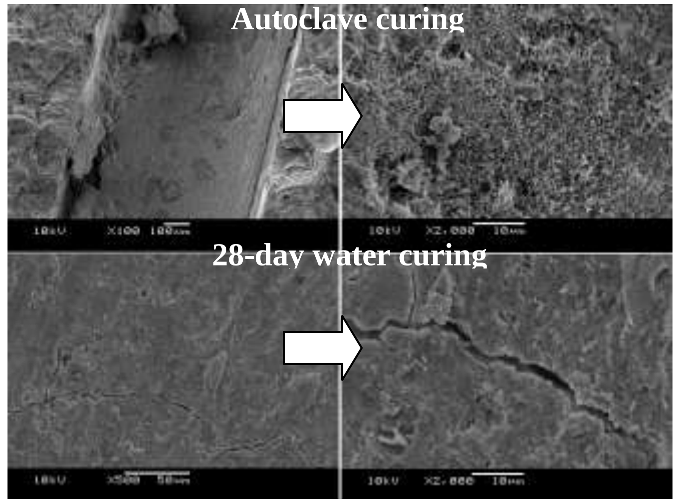

Figure 6. SEM images of the steel fiber-RPC matrix interface.

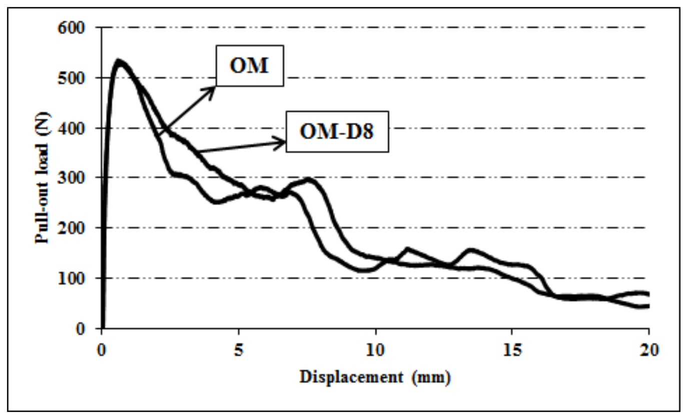

Figure 7. The Pull-out load–displacement curves of steel fibers embedded in the OM and OM-D8 mixtures.

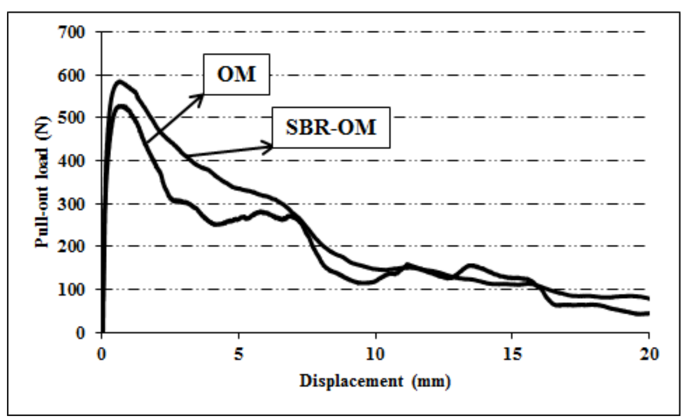

Figure 8. The Pull-out load–displacement curves of steel fibers embedded in the OM and SBR-OM mixtures.

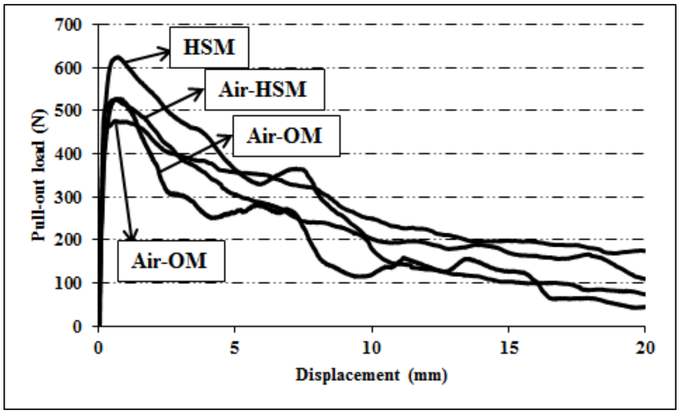

Figure 9. The Pull-out load–displacement curves of steel fibers embedded in the Air-HSM and Air-OM mixtures.

J. *The effect of 100 Freeze-Thawing cycles on the mechanical strength and pull-out behavior*

The mechanical strength of matrix phase did not affect negatively due to 100 Freeze-Thawing cycles (Figs. 2 and 3). This behavior is also valid in the case of pull-out test results. For example, Figs. 10 and 11 shows the pull-out load–displacement curves of steel fibers embedded in the HSM, RPC, OM, and SBR-OM mixtures. It can be seen from curves that curing effect is still predominant and there is not any significant differences between the pull-out behavior of mixtures before and after the 100 Freeze-Thawing cycles. This paper is the part of an ongoing study and the mechanical strengths and pull-out behaviors will be tested after 300 Freeze-Thawing cycles (In accordance with ASTM: C666 standard).

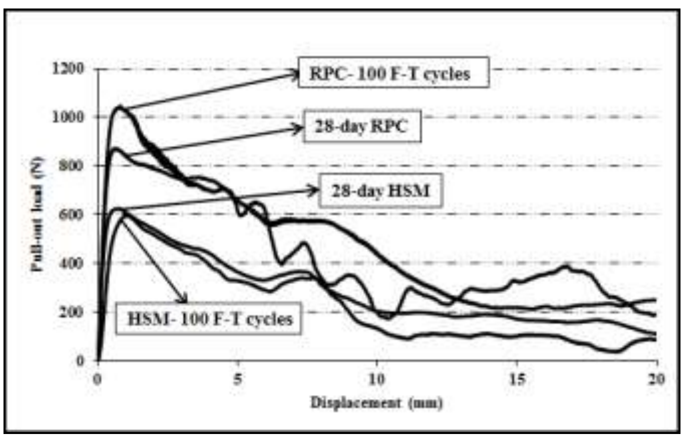

Figure 10. The Pull-out load–displacement curves of steel fibers embedded in the HSM and RPC mixtures subjected to 100 F-T cycles.

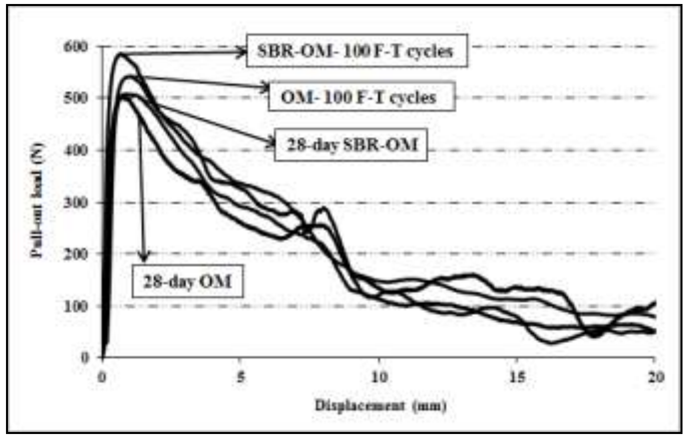

Figure 11. The Pull-out load–displacement curves of steel fibers embedded in the OM and SBR-OM mixtures subjected to 100 F-T cycles.

III. Conclusions

Test results showed that the steel fiber-matrix bond behavior depended on many parameters W/B ratio, matrix type, air entraining, curing condition, chemical admixture etc. On the other had differences between the F-T resistance of mixtures are not clear after 100 F-T cycles. All mixtures showed good durability under this condition and 300 F-T cycles will be tested ongoing testing program.

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