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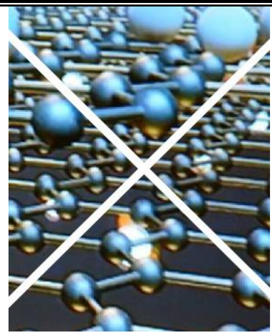

ESTIMATION OF INTERFACIAL FRICTION PROPERTY BETWEEN SINGLE FIBER AND NORMAL CONCRETE

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Abstract

Due to the challenges of measuring the interfacial properties of "Fiber Reinforced Concrete (FRC)" by direct methods using measurement devices, it is important to find alternative methods such as special micro or macro-experiments in concrete laboratories in addition to theoretical computations. This study introduces an alternative method that can be used to find the friction factor between the fibers and the concrete in the composites of FRC. In this method, different types of fibers can be used 'such as (steel, glass, carbon, polymer and aramid)'. A pull-out test will be conducted for several laboratory samples of a single fiber embedded into a normal concrete matrix. From this laboratory pull-out test a curve of stress-displacement can be drawn for each sample, where the average one will be used to estimate the interfacial-friction factor between the fiber and the concrete. Using the same materials properties and dimensions, computer simulations can be prepared. In these computer simulations, different values of friction factor will be applied, and a curve of stress-strain can be drawn for each applied value of friction factor. The sliding part of the stress-strain curve, that has been prepared from the laboratory pull out test, will match one of the several stress-displacement curves of computer simulations. Then the value of the friction factor that was used in the matched curve can be assumed as an expected value of the friction factor between the fiber and the concrete. The results showed that the use of fiber with a smaller diameter would improve the frictional bond strength at the interface in FRC composites. Also, the results showed that the use of fiber with a smaller diameter will decrease the required quantity of bonging materials 'such as the required quantity of cement in FRC composites'. This technique can be applied also to find other interfacial-properties 'such as poisson's ratio and bond strength'.

Keyword: Steel Fiber, Glass Fiber, Friction, Concrete, Sliding, Interface, Pull-out, FEM.

1. Introduction

"Fiber Reinforced Concrete (FRC)" is classified as a composite material, where the concrete occupies the place of material with high compressive strength property and the fiber occupies the place of material with high tensile strength property. Generally, the strength of FRC can be evaluated using the interfacial properties of contacted surfaces between the concrete and the fibers.

The shape of fiber usually affects the bond strength and sliding mechanism of fibers in concrete matrix [1-3]. In case of sophisticated forms of fiber (with hooked ends), the results showed enhancing in bond strength between the fiber and the concrete, even using same concrete mix components [4]. Evolution in bond strength also can be found in case of fibers with corrugates along its length [5]. Different types of fibers with different shapes are usually used in FRC 'such as glass fiber, steel fiber, carbon fiber and aramid fiber' [6-8]. Improvements in the design of FRC can be conducted when the properties of the concrete and the fibers are used in suitable values 'such as Poisson’s-ratio and elasticity modulus' [9-14]. Pull-out tests in concrete and materials laboratories are usually used to observe the mechanical behavior at the interfacial surfaces between the concrete and the fiber 'such as bonding, debonding and sliding [15-21]. Computer simulations and finite element modeling can be used to compare and validate the laboratory results [22-28]. In literature some properties of FRC can be obtained by direct methods or experiments such as compressive strength, tensile strength, splitting strength and flexural strength. However, some other properties are not possible to be obtained by the same direct methods or measurements; one of these important properties is the interfacial properties 'such as friction coefficient or Poisson’s-ratio'. Therefore, in this paper, an alternative method will be introduced to extract some interfacial properties at the surfaces between the concrete and the fiber using laboratory experimental results and computer aids including modern technique. This technique will be implemented by a comparing between the results of real life pull-out tests and the results of computer simulations.

2. Materials and Methods

In general, bond strength at the interfacial surfaces along the fiber in concrete composites comes from three sources. First one because of the chemical reaction of cement past along the total area of outer surfaces of the fiber. Second one because of fiber shape and connecting joints between the fiber and the concrete matrix, such as hooked ends or corrugates along the length of the fiber. Third source is the sliding movement of the fiber inside the concrete matrix when the fiber is exposed to tensile forces trying to extract this fiber from the concrete 'such as flexural stresses in case of beams'. The third source can be considered as sliding-mechanism, which is controlled by the value of friction at the interfacial surfaces between the fiber and the concrete. Generally, to evaluate the sliding strength against tensile or compressive forces, which might be applied on the fiber inside the concrete, equations of equilibrium at the interface between the two materials should be applied. Theoretically, the sliding mechanism can be controlled by its governing equations. Therefore, we have to define and extract the related governing equations in this section. To obtain experimental stress-strain curves, a real-life pullout test has to be conducted by using a single fiber embedded into concrete matrix, and several samples will be prepared to cover this part of the study. On other hand, computer simulations will be used to draw ideal stress-strain curves for different values of the friction factor. Then, by comparing the results of laboratory pull-out test and the computer simulations, the friction factor can be estimated.

The sliding mechanism can be analyzed using governing equations, which will be prepared theoretically in the next section.

2.1 Sliding-Mechanism governing equations

Tensile or compressive forces might apply on the fiber in concrete members, in this case, the chemical bond resists until breaking, after that, the debonding strength works to resist the sliding movement until become not sufficient to resist the applied forces, then the friction at the interfacial surfaces starts to resist the sliding movement. The speed and the strength of this sliding movement are related to the smoothing at the interface, what means, in other words, the friction governs this movement.

The applied tensile force, F_t, on each fiber (or compressive force) usually transferred to the interface as shear stresses, τ_s, along the embedded length of the fiber inside the concrete, l_{emb}, (See Figure 2.1.1).

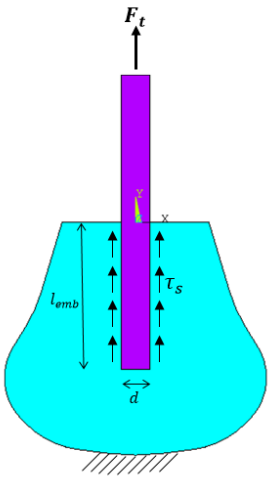

Figure 2.1.1 Applied shear stresses at the interface.

The concrete resists the fiber sliding movement by frictional stresses, τ_{fr}, which are distributed along the embedded length at the interface as well but in the opposite direction. The resultant of these stresses can be called as, S, which must be under balance with the applied tensile force, F_t, (See Figure 2.1.2), these frictional forces are produced because of concrete pressure in (x) direction on the interface, which can be called as σ_x.

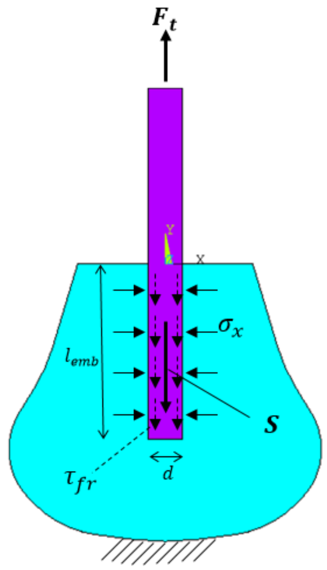

Figure 2.1.2 Resistance stresses at the interface

In both cases, if we assume the friction factor at the interface between the fiber and the concrete is, $Fri_{(f.c)}$, the governing equations will be as the following:

$$\tau_s = \frac{F_t}{\pi \times d \times l_{emb}} \qquad (1)$$

$$\tau_{fr} = \sigma_x \times Fri_{(f.c)} \qquad (2)$$

To obtain sufficient resistance against sliding movement, the produced frictional stresses, τ_{fr}, must be greater than the applied shear stresses, τ_s. Therefore, the concrete pressure in (x) direction, which is applied on the interface, σ_x, should satisfies the balance equation (3) as the following:

$$\sigma_x \geq \frac{F_t}{Fri_{(f.c)} \times \pi \times d \times l_{emb}} \qquad (3)$$

2.2 Laboratory pull-out test

The experimental program of this research was prepared to conduct pull-out tests, in aiming to monitor the mechanical behavior of the fiber in the concrete when applying an extracting tensile force on the fiber, and also for obtaining stress-displacement curves, which can be used to find the interfacial properties along the fiber 'such as the friction factor or Poisson's ratio'.

The samples of single fiber have been prepared using the metallic molds as shown in Figure 2.2.1. Two types of fibers have been used (steel fiber and glass fiber). In order to grow the fiber, 50% of required fresh concrete should be casted in the mold, and then the fiber should be placed with a suitable embedded length into the concrete, after that the mold should be completed by fresh concrete as in the figure. These samples will be cured by moist method in the normal temperature of the lab.

The density of steel fiber is $7850\ kg/m^3$, the modulus of elasticity is $200000\ N/mm^2$, the ultimate strength is $1200\ N/mm^2$, the length is $50\ mm$, the diameter is $0.8\ mm$, Poisson's ratio is 0.28.

The elasticity modulus of glass fiber is $70000\ N/mm^2$, and for the concrete is $30000\ N/mm^2$.

Poisson's ratio of the used glass fiber and concrete is 0.20. In all cases, the embedded length of the fiber will equal to 50% of its total length.

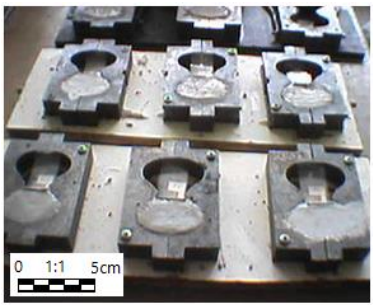

Figure 2.2.1 Preparation of samples of single steel and glass fibers embedded into normal concrete.

Figure 2.2.2 Pull-out experiment of single steel and glass fiber embedded into normal concrete.

For pull-out test the machine in Figure 2.2.2 has been used, where the bottom head is fixed and used for catching the hardened concrete part of the sample, and the top one can move up for applying a tensile force on the free edge of the fiber through the experiment. In front of these two heads, there is a camera for monitoring and recording the movement of the fiber during the experiment as well.

2.3 Finite element modeling (FEM)

Computer simulations are prepared using same dimensions of laboratory samples and same properties of materials. In these simulations, a finite element model was prepared (Figure 2.3.1). The FEM is a widely used technique in this century [29-34]. In general, experimental results are employed to validate the numerical approaches. However, the author claims a validation of experimental results by numerical approaches. In all cases, these finite element simulations are prepared with a mesh of quadratic finite elements. For concrete matrix, the connection is node to node by full bond and for the fiber body as well. At the interface, a sliding connection was prepared, as contact line to contact line, using different values of friction factor between the fiber and the concrete, with respect to the type of the used fiber. The scope of friction factor in case of steel fiber is 0.05 to 0.2, and in case of glass fiber from 0.1 to 0.3.

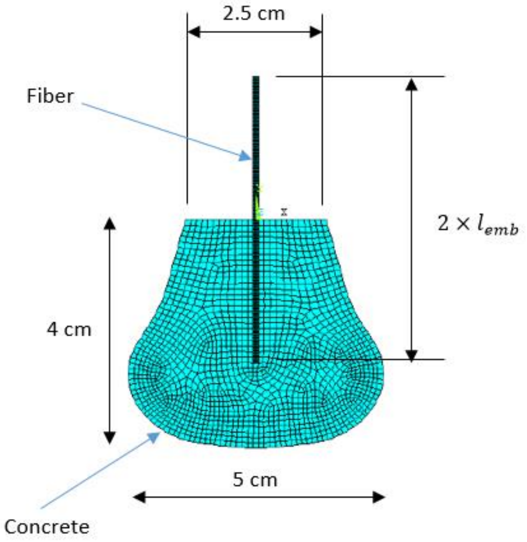

Figure 2.3.1 Finite element modeling (FEM) and meshing of single fiber in concrete matrix.

The type of element selected in creation process of the finite element models is PLANE182, which can be used for 2-D modeling of solid structures. The element can be used as either a plane element (plane stress, plane strain or generalized plane strain) or an axisymmetric element. It is defined by four nodes having two degrees of freedom at each node: translations in the nodal x and y directions. The element has plasticity, hyperelasticity, stress stiffening, large deflection, and large strain capabilities. It also has mixed formulation capability for simulating deformations of nearly incompressible elastoplastic materials, and fully incompressible hyperelastic materials [35]. This element has two Degrees of Freedom (Horizontal displacement, Vertical displacement), and the maximum degree of freedom value is equal to (0.26×10^{-4} m) in case of fully bond connected nodes at the interface and (3.63×10^{-3} m) in case of using node-to-node contact element at the interface between the fiber and the concrete.

3. Results and Discussion

The results of laboratory pull-out tests show that the capacity of full-bond interfacial strength may reach about 120 N in case of steel fiber samples (See Figure 3.1). For comparing purposes, the average force-displacement curve will be used, and the force will be converted into stress. Therefore, a stress-displacement curve for the average sample can be drawn as in Figure 3.2. In this curve, the maximum stress is about 240 MPa. Splitting in the full bond at the interface will start after the point, and then the fiber will move out of the concrete by a sliding movement. This sliding part of the curve will be used to find out the value of the friction factor at the interface.

In computer simulations, by using different values of interfacial-friction factor between the fiber and the concrete 'such as (0.05, 0.1, 0.15 and 0.2)', stress-displacement curves can be drawn for each value of friction factor (See Figure 3.3).

The expected value of friction factor between the fiber and the concrete can be found now by placing the stress-displacement curve, which was extracted from the laboratory samples, above the stress-displacement curves, which were drawn by the computer simulations (See Figure 3.4). In this figure the curve of laboratory samples matches the curve of friction factor equal to 0.1. Therefore, 0.1 can be considered as the target value of friction factor between the straight steel fiber and the normal concrete. In literature, there are no measurements for the friction factor between the steel fiber and the concrete. This extracted value is acceptable compared to steel-steel in literature, which is 0.11, or 0.1 in case of steel-graphite and 0.14 in case of steel-carbon [36].

Using to this extracted value of friction factor and the governing equation (3), the required pressure of concrete on the embedded length of the fiber, σ_x, can be estimated. If the concrete pressure is sufficient, according to equation (3), the sliding movement of the fiber inside the concrete can be prevented depending on only the frictional stresses at the interface. According to the calculations of this sufficient pressure, the required quantity of bonding materials 'such as cement' might be reduced.

Repeating the same procedure by the same steps, the friction factor between the glass fiber and the concrete can be found as well. In Figure (3.5), a stress-displacement curve of single glass fiber embedded into concrete has been drawn using the laboratory results of a pull-out test. The maximum stress is about 1000 MPa, what means high full-bond strength between the glass fiber and the concrete. Comparing the laboratory pull-out test results and the computer simulations results using different values of friction factor (0.1, 0.2 and 0.3), the stress-displacement curve of laboratory samples is matching the computer simulation curve with the friction factor equal to 0.2 (See Figure 3.6). Therefore, the expected value friction in case of single glass fiber can be considered as 0.2. This friction is acceptable compared to literature, where the friction factor is equal to (0.1-0.6) in case of glass-glass, and (0.5-0.7) in case of glass-metal.

The friction factor in case of glass-concrete (0.2) is greater than its value in the case of steel-concrete (0.1), and this finding is justified because of the greater stresses that can be applied in the case of glass-concrete compared to steel-concrete.

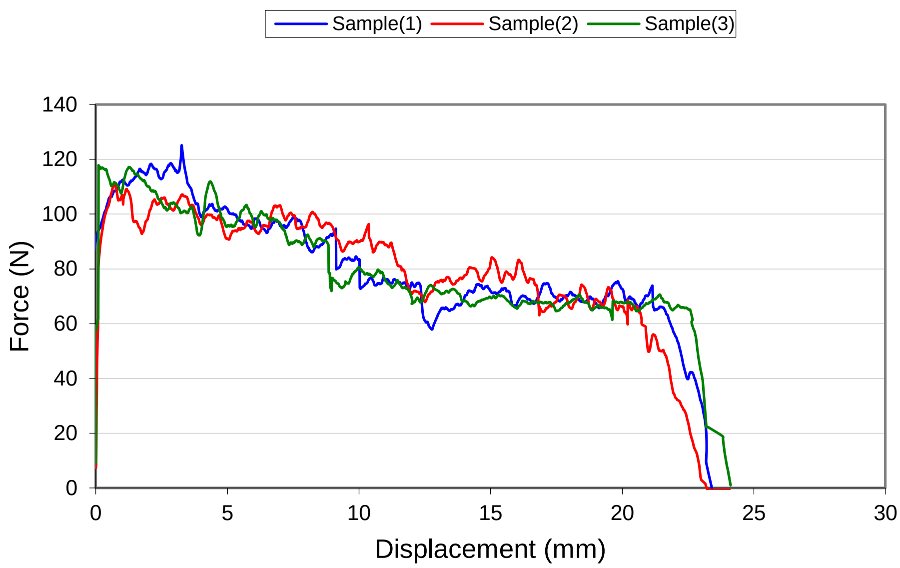

Figure 3.1 Force-displacement curves of steel fiber embedded into normal concrete, obtained from laboratory pull-out test.

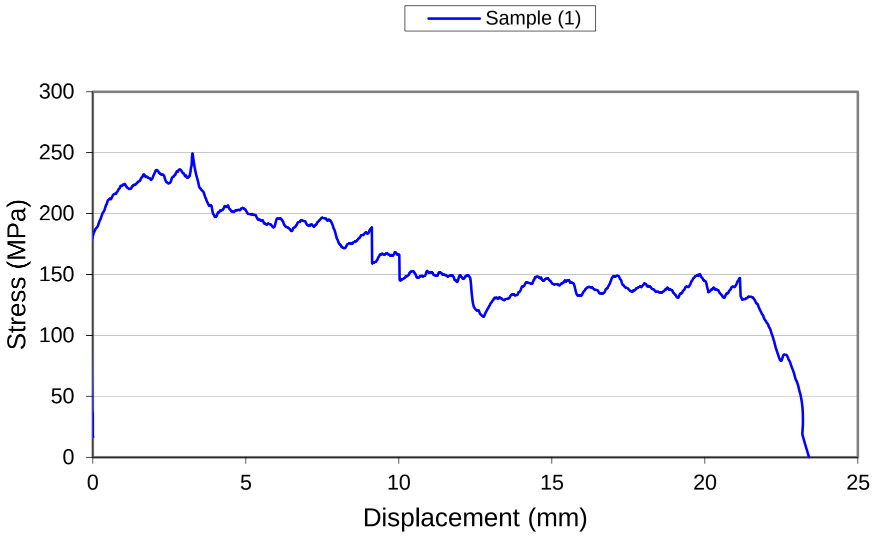

Figure 3.2 The selected stress-displacement curve of steel fiber embedded into normal concrete, obtained from laboratory pull-out test curves.

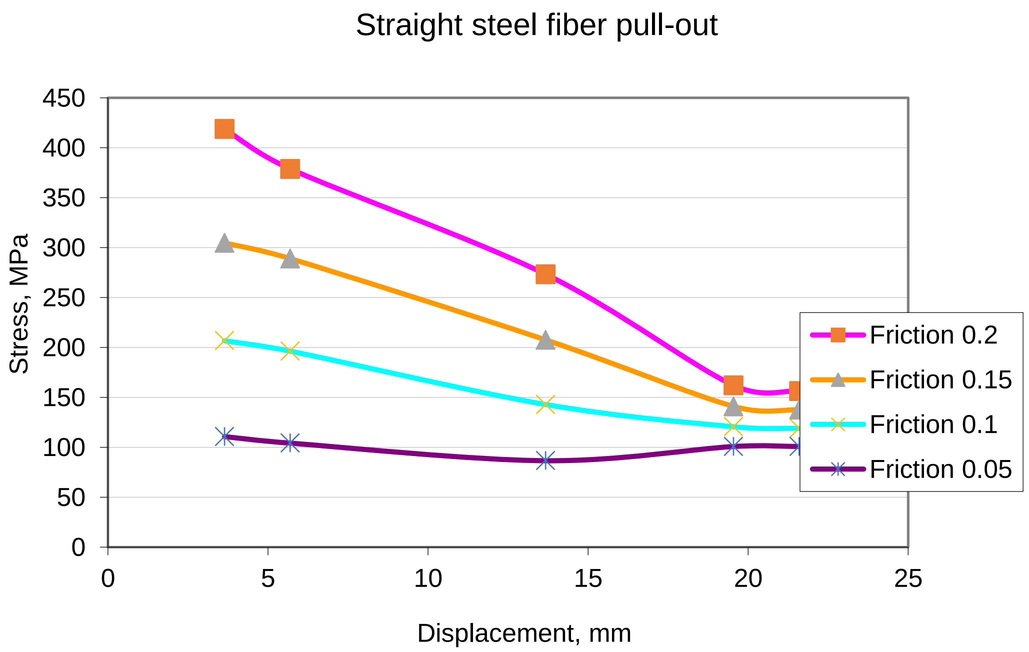

Figure 3.3 Stress-displacement curves of straight steel fiber embedded into normal concrete, obtained from computer simulations.

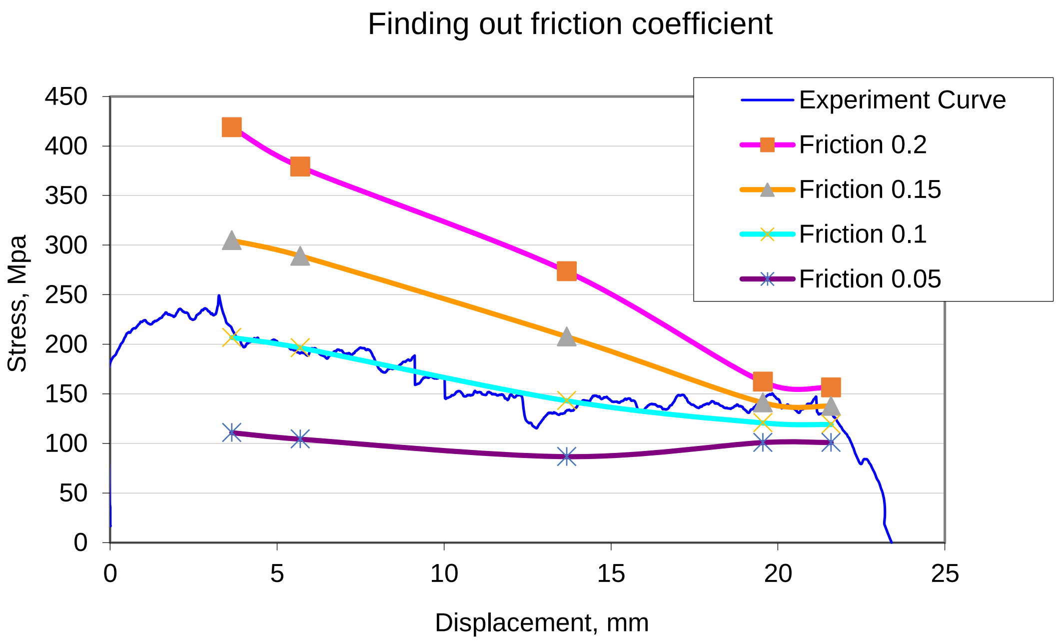

Figure 3.4 Comparison between the experiment stress-displacement curve and the curves of computer simulations to find the value of friction factor of straight steel fiber, $Fri_{(f.c)} = 0.1$.

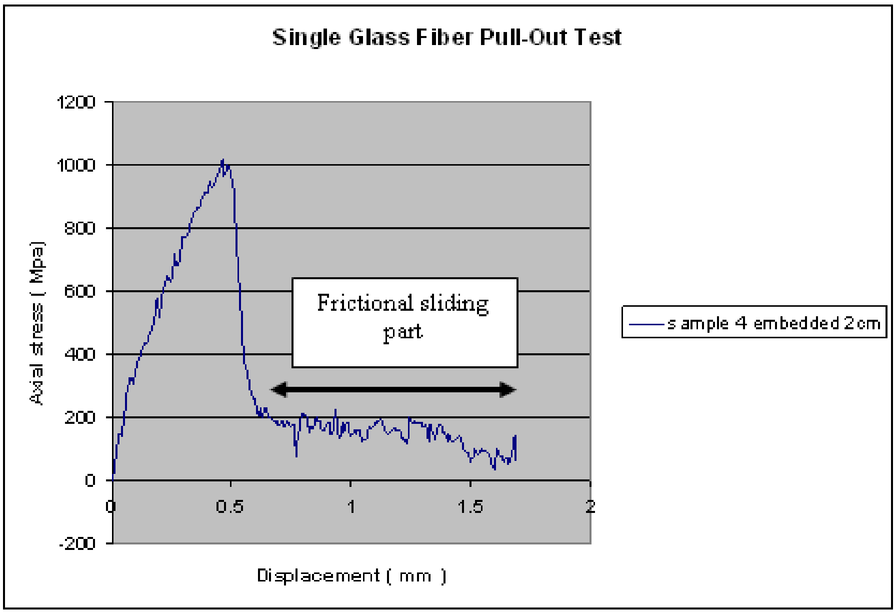

Figure 3.5 A selected stress-displacement curve of single glass fiber embedded into normal concrete, obtained from laboratory pull-out test.

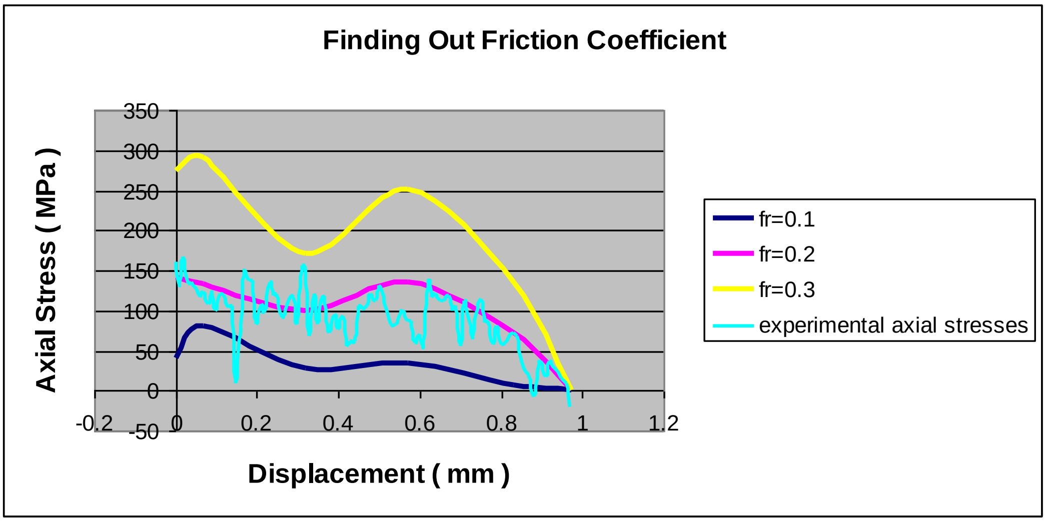

Figure 3.6 Comparison between the experiment stress-displacement curve and the curves of computer simulations to find the value of friction factor of glass fiber, $Fri_{(f.c)} = 0.2$.

4. Conclusions:

This paper introduced a new method using a modern technique for estimating some of the main properties at the interface of composite materials such as "Fiber Reinforced Concrete (FRC)". According to this study, the friction factor between the straight steel fiber and the normal concrete was expected to be 0.1, and between the single glass fiber and the concrete was expected to be equal 0.2 as well. This method can be applied to find the value of friction factor in case of carbon fiber, aramid fiber and polymer fiber or any other type of fiber that may be used in fiber reinforced concrete composites.

Numerical computer simulations using different values of interfacial-friction factor have been prepared to monitor the sliding movement of the fiber inside the concrete. The results showed that the interfacial friction bond can be improved by increasing the concrete pressure on the embedded part of the fiber inside the concrete. Greater pressure might be obtained when a smaller diameter of fiber is used, where the maximum applied stresses are increased from 240 MPa in case of steel fiber by diameter equal to 0.8mm to 1000 MPa in case of glass fiber by a diameter ranging from 5 to 24 µm. Therefore, it can be concluded that the required quantity of bonding material such as cement can be reduced when the fiber is used by a smaller diameter.

These results have been validated by the laboratory results and by the governing equations, which have been extracted in this study. The introduced technique in this study may give different values of friction factor according to the methods of concrete mix design and preparation, therefore the values of friction factor, which have been found in this study, can be used only as a practical example, and to have a knowledge about the main steps of the introduced technique. Using the same technique, other interfacial-properties can be found 'such as Poisson's ratio and bond-strength in addition to debonding-strength'.

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