Strength and Toughness of Reinforced Concrete with Coated Steel Fibers

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P A P E R   I N F O

A B S T R A C T

The effect of zinc phosphate (ZP) and zinc calcium phosphate (ZCP) coatings on the reinforcing mechanisms of smooth steel fiber in cementitious matrix have been studied. The results of pull out tests illustrated that by coating smooth steel fiber the pull-out load may be increased up to 100%. The effect of zinc phosphate coating on interface bonding was more than zinc-calcium phosphate coating. This could be due to formation of large crystals in zinc phosphate coating and its tendency to react in alkaline environment of cementitious matrix. This behavior was also confirmed by SEM analysis. The obtained results from a mathematical model for pull-out energy were in good agreement with the experimental results. The results indicated that coating of fibers with zinc based ceramics could improve the composite's mechanical properties as well as its chemical stability.

1. INTRODUCTION

In 1910, Porter first suggested the use of Steel fibers (SFs) in concrete. However, the first scientific research on fiber reinforced concrete (FRC) in the United States was done in 1963 [1]. Steel fiber reinforced concrete (SFRC) has the ability of excellent tensile strength, flexural strength, shock resistance, fatigue resistance, ductility, and crack arrest [2].

During the last decades, incredible development has been made in concrete technology. One of the major progresses is Fiber Reinforced Concrete (FRC) which can be defined as a composite material consisting of conventional concrete reinforced by the random dispersal of short, discontinuous, and discrete fine fibers of specific geometry [3].

Two main mechanisms for strengthening short fiber reinforced composite are fiber pull out and fiber bridging [4]. The shape and characteristic of matrix-fiber interface play important roles in governing mechanical properties of the fiber reinforced concrete [5].

Luo et al. studied and conducted test on the mechanical properties and impact resistance on steel fiber reinforced high-performance concrete. It was observed that addition of 2.0 percent by volume of hooked-end steel fibers increased the toughness compared to the plain concrete for by about 19.27%. When the fibers were used in a hybrid form, the increase in above study parameters was about 31.42%, compared to the plain concrete [6].

Abdelmajed et. al., reported another research that when, Young's modulus was205 MPa, aspect ratio varied from 30 to 100, ultimate tensile strength of steel fiber varied from 345 to 1700 MPa, and length varied from 19 to 60 mm for respective fiber[7].

It is believed that the most important influence of the fiber stem is its effects on fracture energy [8-11]. Fibers can bridge the crack and retard the effect of stress concentration at the crack tip, and if not broken, the fibers consume considerable amount of energy when creeping out of cement matrix. From the design stand point, an appropriate balance between pull out force and pull out energy is desirable. Pull-out process increases the plasticity and energy absorption of concrete.

In designing concrete structures, preliminary estimation of compressive and tensile strengths is very important. One of the methods for determining concrete tensile

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strength is to use splitting tensile test (Brazilian method) [12].The behavior of SFRC can be classified into three groups according to its application, fiber volume percentage, and fiber effectiveness. Although adding fibers merely to increase the direct tensile strength is probably not worthwhile, steel fibers, in compression, do lead to major increases in the post-cracking behavior or toughness [13].There are several experimental studies in the literature which have studied the effect of steel fiber on the compressive toughness and considerable improvement in compressive toughness has been reported by them [7, 14].

The characteristic of bonding between fibers and the matrix controls this balance. Therefore new techniques to improve the interface bond between fiber and matrix are of research intents. Attempts have been made to improve the fiber-matrix interface behavior by surface treatment of the fiber such as oxidation [8, 9].The application of steel fiber-reinforced shotcrete (SFRS) avoids these technological problems and additionally creates a possibility of making thinner sprayed layers, which simultaneously are more resistant to cracks [15]. Although different types of steel fibers have been used, hook-ended steel fibers were found to perform better than the other types because of their hooked ends, or high tensile strength, which requires additional loads for pulling out or breaking [16]. Based on the report of intermediate calcium phosphate compounds played important role in (1) improving the cement-fiber interfacial bonds, and (2) repairing the damage of the zinc phosphate (ZnPh) surfaces dissolved by alkali. These processes protected the steel fiber from corrosion [17]. In this work, the effect of zinc phosphate (ZP) coating and zinc-calcium phosphate (ZCP) coating on tensile strength of cementitious matrix containing smooth fibers have been investigated.

2. EXPERIMENTAL PROCEDURES

Uncoated and coated smooth fibers were used for pull-out and tensile tests. Patent steel (DIN1714080) was used for making steel fibers with 30mm length and 0.5mm diameter. Chemical composition and mechanical properties of the steel fibers are given in Tables 1 and 2 respectively.

TABLE 1. Chemical composition of steel fibers

Element	%
Ti	0.01
Mg	0.18
Cu	0.02
S	0.05
P	0.04
Ni	0.01
Cr	0.02
Mn	0.61
Si	0.18
C	0.49

Zinc phosphate and zinc-calcium phosphate coating processes were carried out in a phosphate bath with composition given in Table 3. After washing the fibers with Acetone, coating process was performed in the phosphate bath at 65ºC and pH 2.35 for 7 minutes. The specimens were then washed by water and dried by blowing warm air.

TABLE 2. Mechanical properties of steel fibers

Elasticity Modulus (GPa)	Yield Stress (MPa)	Fracture Strength (MPa)	Diameter (mm)
200	1420	1670	0.5

TABLE 3. The composition of the phosphate baths used for fiber's coating

Type of baths	Bath Composition (g/lit)				
	Na_3N	$Ca(NO_3)_2$	ZnO	HNO_3 (65%)	H_3PO_3 (85%)
Zn Phosphate	0.50	----	3.25	2.24	10.375
Ca-Zn Phosphate	0.50	8.26	3.25	2.24	10.375

The studied matrix characteristics of all specimens were similar. Certain amount of very fine silica fume was added to the cement for improving the compaction. Super plasticizer were also added to decrease porosity. The composition of the matrix in this study is summarized in Table 4.

TABLE 4. Composition of cementitious matrix

Cement (kg/m^3)	500
Silica Fume (kg/m^3)	50
Super plasticizer (kg/m^3)	8.25
Sand(2-4mm) (kg/m^3)	1006.05
Sand(0.1-2mm) (kg/m^3)	670.7
Water (kg/m^3)	190.15

To investigate the effect of surface coating of the fibers on the interface characteristic, pull-out test were carried out. Fig.1 shows the pull-out specimen assembly schematically. After molding, specimens were cured in water bath (21ºC) for 14 days.

All pull out tests were carried out using an MTS testing machine with a load 25 capacity. Since the bond length was set to 50 mm, the pull out load was expected to be around 5 kN, which was about 20% of the capacity of the testing machine. From the 25 pull out failure load measured by the testing machine, the bond strength was 25 calculated by dividing the failure load by the surface area of the bonded length of the 25 reinforcing bar. Tensile rate was 2mm/min in this test. Each test was repeated three times and the average of the two closest

results was plotted. Scanning Electron microscope was used to study the interface between fibers and cementitious matrix.
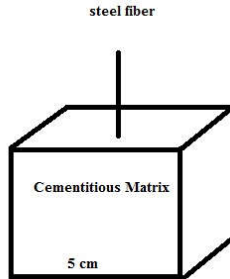
steel fiber

Cementitious Matrix

5 cm

Figure 1. Specimen designed for pull-out test

3. RESULTS AND DISSCUSSION0

Fig.2 shows the average pull-out load versus fiber end displacement curves for coated and uncoated smooth fibers. Curves were linear until the maximum load(to overcome the initial friction) and then decreased rapidly until reaching a certain load level corresponding to the second frictional stress between fibers and the matrix. In the final part of the curves, frictional load decreased gradually due to increasing matrix tunnel damage around the fiber surface and also due to decreasing contact length [10].
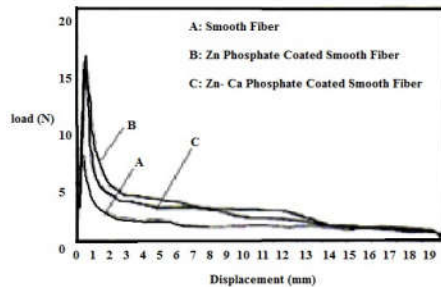
A: Smooth Fiber
B: Zn Phosphate Coated Smooth Fiber
C: Zn- Ca Phosphate Coated Smooth Fiber

Figure 2. Pull-out curves of smooth fibers (A: smooth fiber, B: Z-P coated smooth fiber, C: Z-Ca phosphate coated smooth fiber).

After small slipping (i.e. 2mm), pull-out load reduced to a practically insignificant level. The maximum pull-out load for uncoated fibers was 150.2 N. This is in contrary to some results [7] and agreed well with some others [5]. This is due to dependence of pull-out load to parameters such as matrix and fiber characteristics, environment, and loading condition [18].
The maximum initial frictional bond shear can be calculated using the below equation:

$$\tau_f = \frac{P_{max}}{\pi d_f l_f} \qquad (1)$$

Where: p_{max}maxis the maximum pull-out load, d_f is the fiber diameter, l_f is the fiber embedded length.
Computing τ_f for uncoated and zinc phosphate and zinc calcium phosphate coated fibers yields to the following values, respectively; τ_f = 6.37 MPa, τ_{fzp} = 13.56 MPa, τ_{fzcp} = 12.90 MPa. As can be seen, the interface strength increased by nearly 114% and 100% for fibers coated by zinc phosphate and zinc-calcium phosphate, respectively. The effect of zinc phosphate coating on interface strength was more than the effect of zinc-calcium phosphate coating. This could be due to the formation of large crystals in zinc phosphate coating and their tendency to react in alkaline environment of cementitious matrix [19]. Figure 3, 4, and 5 show interfaces between coated fiber/uncoated fiber and cementitious matrix. As can be seen, there was no significant bonding between uncoated fibers and the matrix, while the interface of coated fibers and the matrix were strongly bonded via chemical reactions at the interface. Since the zinc phosphate crystals were hydrated, therefore it seems there was a strong tendency to interact between the hydrated crystals and cementitious matrix.
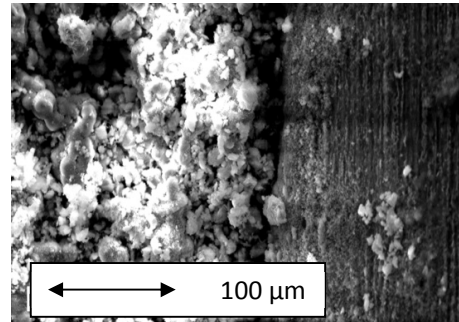
100 μm

Figure 3. Microstructure of interface between uncoated fiber and matrix
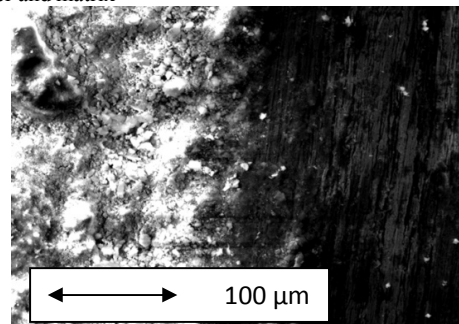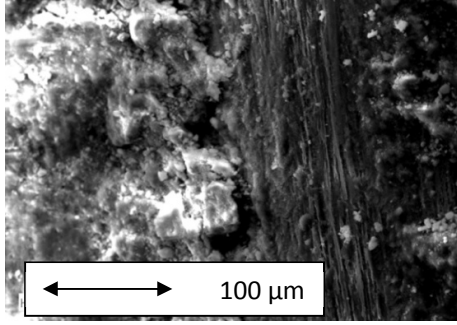
100 μm

Figure 4. Microstructure of interface between zinc phosphates coated fibers and cementitious matrix

Figure 5. Microstructure of interface between zinc-calcium phosphates coated fiber and cementitious matrix

This is encouraging chemical reaction between coated surface and the matrix. In addition, the considerable porous surfaces of coated fibers can a favorable site for crystallization of cementitious matrix.

After the initial peak, the load-displacement of coated fibers revealed higher stress for a certain displacement, and the effect of ZP coating was more significant than ZCP coating. It was obvious that the original smooth surface of the steel fiber was changed into a rough topographical feature by precipitating Zinc phosphate crystals on the fiber. The weak peak of EDX results for the Zinc phosphate treated and untreated fibers did not indicate light (Hydrogen to phosphor) elements but numerous gutters oriented along the fibers axis could indicated that elements. The slops of the curves prior to the peak for coated fibers ewer greater than that of uncoated fibers. In fact in this region for a constant displacement, the pull-out load for coated fibers was greater than pull-out load of uncoated fibers. Thus load transfer from matrix to coated fibers was more effective than that of uncoated fibers. Consequently it was concluded that coated fibers could increase the bridging effect for a crack in cementitious matrix more than uncoated fibers .Secondary frictional load for pulling out the coated fibers was also more than that of uncoated fibers. It was probably due to the roughness of phosphate coating surface. Consequently, the required energy for pulling out the fibers from cementitious matrix was greater for coated fibers due to higher strength of the interface bone and frictional bond in these fibers. Information about pull-out test is given in Table 5.

TABLE 5. The Results of pull-out tests

Fibers Type	P_{peak} (N)	D_{peak} (mm)	P_{peak}/D_{peak} (N/mm)	t_{max} (MPa)	Ic/I	$f_{pull-out}$ (N)	$r_{pull-out}$ (N.mm)
Uncoated	150.2	0.30	500.67	6.37	2.18	27.6	438.5
Zn Phosphate Coated	318.9	0.36	885.83	13.53	1.03	48.1	808.5
Ca-Zn Phosphate Coated	304	0.36	844.44	12.90	1.08	47.7	792.7

Pull out energy of smooth uncoated and coated fibers were determined based on the analytical model for load-displacement curve of steel fiber in cementitious matrix presented by Naaman et al. [20, 21]. Figure 6 illustrates a schematic representation of pull-out curve. Three different stages are defined: In the first stage where displacement which named; $\Delta \leq \Delta_{crit}$, the second stage where elastic bond condition prevailed at the interface, and the third stage where no de-bonding occurred; i.e., the fiber remains fully bonded to the surrounding matrix. As can be seen, in this case there was a linear relationship between the applied force p1 and the displacement of the fiber end Δ. The equation of first part can be expressed as:

$$p_1 = \frac{\lambda A_m E_m}{Q-2} \frac{1+e^{-\lambda l}}{1-e^{-\lambda l}} \Delta \qquad (2)$$

Where A_m= cross section area of the matrix, E_m= modulus elasticity of matrix, L= fiber length, Q and λ (which will be used in eq. 5) can be expressed as:

$$Q = \frac{A_m E_m + A_f E_f}{A_m E_m} \qquad (3)$$

$$\lambda = \sqrt{\left[1 + \frac{A_m E_m}{A_f E_f}\right] \frac{\Psi \kappa}{A_m E_m}} \qquad (4)$$
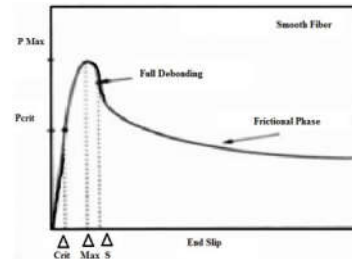
In which A_f and E_f are the cross sectional area and elastic module of the fiber, respectively; and κ is the interfacial bond modulus.

The other parameter, Δ_{crit}, is given by equation 5:

$$\Delta_{crit} = \frac{\tau_{max} \psi (Q-2)}{\lambda^2 A_m E_m}$$

$$\times \left[\frac{(1-e^{\lambda l})^2}{\left(1 - \frac{1}{Q}\right)(1 + e^{-2\lambda l}) + \left(\frac{1}{Q}\right) 2e^{-\lambda l}} \right] \qquad (5)$$

Where τ_{max} = bond strength of interface between fiber and matrix and Ψ = perimeter of reinforcement.

Figure 6. Typical pull-out load versus slip relationship of smooth fiber [21].

In the second stage when $\Delta_{crit} < \Delta < \Delta_o$, two interfacial zones adjacently coexisted, one was bonded and the other one was debonded. The length of the deboned zone is defined by u. Thus, the length of bonded zone is (L-u). Then p_2 can be found as:

$$p_2 = \tau_f \Psi u + \frac{\psi \tau_{max}}{\lambda}$$

$$\times \frac{1 - e^{-2\lambda(l-u)}}{\dfrac{2}{Q} e^{-\lambda(l-u)} + \left(1 - \dfrac{1}{Q}\right)\left[1 + e^{\lambda(l-u)}\right]} \qquad (6)$$

Where τ_f = the maximum frictional bond shear stress at interface between fiber and matrix, and the corresponding fiber end displacement Δ when $\Delta_{crit} < \Delta < \Delta_o$ is given by:

$$\Delta = \frac{\left\{ p_2(Q-1)u - \dfrac{\tau_f \psi u^2}{2}(Q-2)\right\}}{A_m E_m}$$

$$+ \frac{\left\{(p_2 - \tau_f \psi u)\left[\dfrac{1 - e^{-\lambda(l-u)}}{1 + e^{-\lambda(l-u)}}\right]\left(\dfrac{Q-2}{\lambda}\right)\right\}}{A_m E_m} \qquad (7)$$

$$- \frac{\{\tau_f \psi u l\}}{A_m E_m}$$

Where; Δ_o is given by:

$$\Delta_o = \frac{(Q-2)\psi \tau_f l^2}{2 A_m E_m} \qquad (8)$$

In the third stage, i.e., frictional phase when $\Delta > \Delta_o$, the pull-out load p_3 is given by:

$$p_3 = \psi \tau_d(\Delta)(l - \Delta + \Delta_o) \qquad (9)$$

Where:

$$\tau_d(\Delta) = \tau_f \frac{e^{-(\Delta - \Delta_o)^\eta} - \xi e^{-(l)^\eta}}{1 - \xi e^{-(l - \Delta + \Delta_o)^\eta}}$$

$$\times \frac{\left(1 - \exp\left\{\dfrac{-2\nu_f \mu(l - \Delta + \Delta_o)}{E_f r_f \left[\dfrac{(1+\nu_m)}{E_m} + \dfrac{(1-\nu_f)}{E_f}\right]}\right\}\right)}{\left(1 - \exp\left\{\dfrac{-2\nu_f \mu l}{E_f r_f \left[\dfrac{(1+\nu_m)}{E_m} + \dfrac{(1-\nu_f)}{E_f}\right]}\right\}\right)} \qquad (10)$$

Where ξ= damage coefficient, μ = friction coefficient of the fiber – matrix interface, ν_f and ν_m are Poisson's ratio of fiber matrix, δ_o = fiber-matrix misfit at onset of dynamic mechanism and η = factor reflective of steepness of descending branch of pull-out curve.

Now the theoretical pull-out energy ($W_{pull-out}$), can be determined by calculating the area under the theoretical pull-out curve. Integration versus the load-displacement, which is given in equations (2), (6) and (9), can be calculated such as follows:

$$W_{pull-out} = \int_0^{\Delta_{ctii}} p_1 d\Delta + \int_{\Delta_{crit}}^{\Delta_o} p_2 d\Delta + \int_{\Delta_o}^{l} p_3 d\Delta \qquad (11)$$

In Table 6, experimental results are compared with calculated results obtained from the mathematical model. As it is observed, there was a good agreement between experimental and calculated results.

TABLE 6. experimental and theoretical results of pull-out energy for smooth fibers

Type of fiber	Experimental ($W_{pull-out}$) (N.mm)	Theoretical ($W_{pull-out}$) (N.mm)
Uncoated fiber	438.5	473.7
Zn phosphate coated fiber	808.5	859.9
Zn-Ca phosphate coated fiber	792.7	852.1

The bond strength, τ, is often assumed in engineered evaluation. Based on the results of Naamen [20,21] and also the results presented in Table 6, The bond strength increasing the average bond strength led to a direct increase in the post-cracking strength of the composite and the other important properties as well as toughness and energy absorption capacity.

4. CONCLUSION

In this research, the effects of zinc phosphate and zinc-calcium phosphate coatings on the reinforcing mechanism of smooth steel fiber in cementitious matrix were studied. These coatings increased the strength of interface bond up to 100% and consequently caused cracking strength and fracture energy of cementitious composite to increase. In short fiber reinforced composition; increasing strength of interface bond with coating fibers led to an increase in cracking strength of composite. This is because of the enhancing the strength of interface bond by coating fibers and matrix which can transfer applied load to fibers quickly. When fiber length was lower than their critical length, enhancing the strength of interface bond by coating the fibers increased the fracture strength of cementitious composite due to difficulty of pulling out fibers from matrix.

5. ACKNOWLEDGEMENT

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