INTERFACE BETWEEN CEMENTITIOUS MATRIX AND FIBRES INFLUENCED BY THE MODIFICATION OF FIBRE SURFACE

Anna Antonova (1), Marika Eik (1), Ville Jokinen (2), Jouni Punkki (1) and Jari Puttonen (1)

(1) Department of Civil Engineering, Aalto University, Finland

(2) Department of Chemistry and Materials Science, Aalto University, Finland

Abstract

The performance of fibre reinforced cementitious composites depends on the interaction between the cementitious matrix and the fibres on the micro-scale. This interaction is affected by the material and surface properties of the fibre and the micro-scale characteristics of the cementitious matrix close to the fibre surface, creating the interfacial transition zone (ITZ). However, the discussions regarding the effect of the fibre surface on the formation of the ITZ and, as a result, the bond strength between the matrix and the fibres are limited. The present paper reports the progress of the ongoing research project, which concentrates on investigating the interface created by the steel fibres with different characteristics of the surface roughness and cementitious matrix. The results of this study can support the development of efficient fibre reinforced cementitious composites.

Keywords: fibre-matrix interface, roughness, wettability, fibre reinforced cementitious composites, pull-out

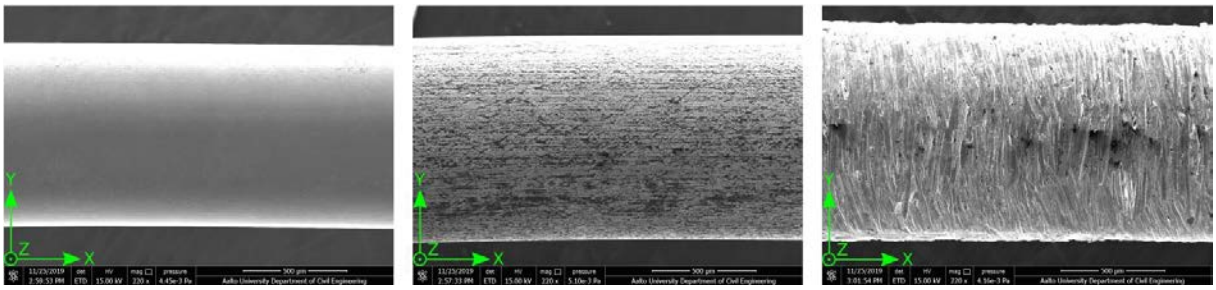
1. INTRODUCTION

The inclusion of fibres into the cementitious matrix can help to restrict the propagation of cracks and improve the ductile performance of the fibre reinforced cementitious (FRC) composites. However, the behaviour of FRC composites at the structural level depends on the stress transferring from the cement-based matrix to the fibres on the micro-scale. The stress is transferred from the matrix to the fibre by the interfacial contact. This contact is provided by the interfacial transition zone (ITZ), that is known to have porous microstructure with precipitation of calcium hydroxide (CH), whose binding property is lower than that of the calcium-silicate-hydrate (C-S-H) phase [1]. The increased porosity in the ITZ is governed by the poor packing of the cement clinker grains [2]. Since fibre is several orders of magnitude larger than the cement clinker grains, it acts as a wall, and the cement grains that are located at the surface of the fibre cannot efficiently fill the space available. Those empty spaces created between the cement grains also may contribute to increased porosity close to the fibre surface, as it was discussed in [3] by comparing the measured roughness of the fibre and the size of the particles that can fill the surface grooves. Authors in [4] discussed that the wetting of the fibre surface can affect the distribution of cement hydrates near the fibre. The relation between the wetting and the roughness of the fibre surface and the quality of contact between the fibre and water-based geopolymer matrix was also observed in [5]. At a more general level, the roughness of the surface is known to have an impact on the wetting properties of a material, as was reported in [6, 7]. The ongoing research work is aimed to investigate the influence of the steel fibre roughness on its wetting properties and their mutual effect on the interface characteristics between the steel fibre and the cementitious matrix, such as packing of cement-based matrix around the fibre and mechanical resistance of fibre to the pull-out from a matrix.

2. MATERIALS AND METHODS

2.1 Materials

Steel fibres with a diameter of 1 mm with different surface roughness were examined. The fibres were divided by types of the processing technique applied to receive the different roughness profiles: electro-polished; non-processed; coarsened with sandpaper (Fig. 1). The cement-paste was prepared from the ordinary Portland cement (OPC) CEM I 52,5 N.



(a) Polished (b) Non-processed (c) Sanded

Figure 1: SEM images of the fibres with different roughness of the surface.

2.2 Methods

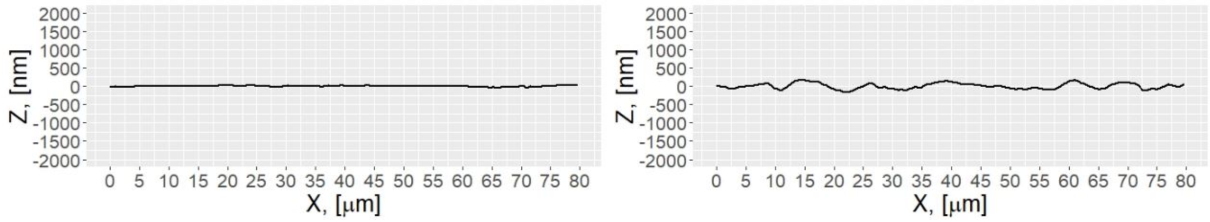
The atomic force microscope (AFM) and stylus profilometer were used to quantify the three different surface profiles of the steel fibre. Contact angle goniometry was implied to examine the wetting properties of the steel fibres with different surface roughness by studying advancing (water spreading along the dry surface) and receding (adhesion of the water to the surface) water contact angles of the surface. The cementitious matrix in the vicinity of the fibre was examined with the scanning electron microscope (SEM) by analysing backscattered electron (BSE) images. The performance of the bond between the steel fibres with different surface roughness and the cement-based matrix will be studied with the pull-out test.

3. PRELIMINARY RESULTS AND DISCUSSION

3.1 Roughness profile of the steel fibres

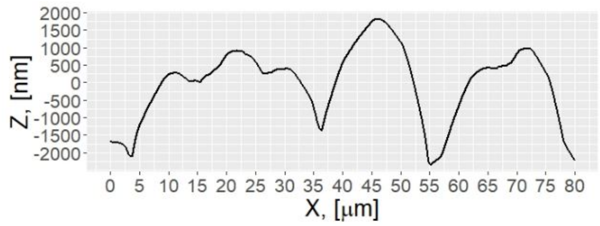
AFM was used to directly measure the roughness of fibres with the polished and non-processed surfaces. The fibres with the sanded surface were measured with stylus profilometer since the size of this roughness exceeded the measuring limits of the AFM. The measurements were performed in the longitudinal direction of the fibres.

Figure 2 illustrates the surface profiles of the fibres with different types of roughness. The apparent grooves on the surfaces of the non- processed and sanded may contribute to the



mechanical interlocking between the fibre and the cement-based matrix. The mechanical interlocking between the cement hydrates and the aggregates with a rough surface was noticed previously in [8].

(a) Polished (b) Non-processed



(c) Sanded

Figure 2: The examples of measured surface profiles of the steel fibres with different types of roughness.

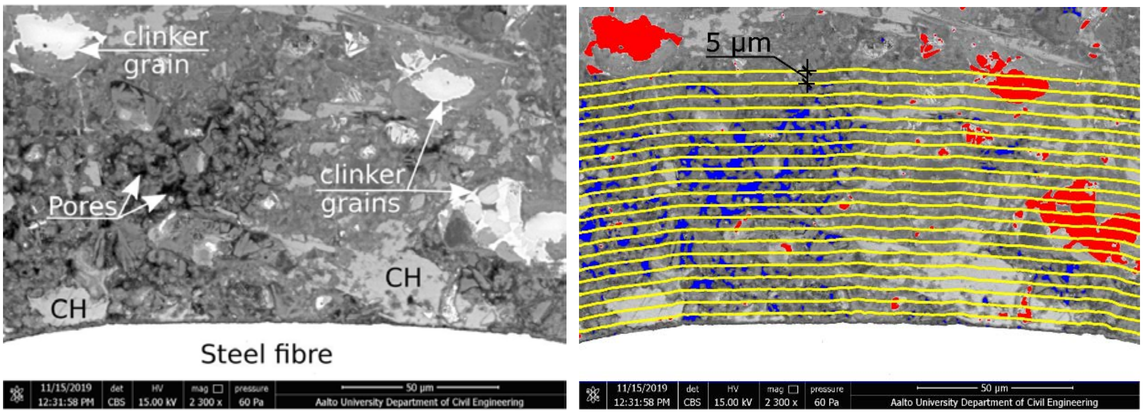
The surface irregularities observed on non-processed and sanded fibres may also affect the spreading of the water, that can be captured by the grooves of the surface. The abrupt spreading of the water along the rough surface was explained before in [9] as the “slip-stick” behaviour of the water droplet on the rough surfaces. The peaks of the surface profile work as barriers, which block further movements of the water and capture water in surface grooves. This phenomenon may affect the wetting behaviour of fibres leading to the formation of the uniform water film along the fibre or, in contrary, micro-bleeding. The spreading and sticking of the water at the surface of the steel fibre is crucial for the formation of the hydrates, i.e. packing of the cement-based matrix in the close vicinity to the fibre.

3.2 Packing of the cementitious matrix around the steel fibres

Sufficient packaging of the cementitious matrix around the fibre, especially decreased porosity, promotes lower permeability, thus decreasing the possible corrosion of the steel fibres. In addition, the denser cement-based matrix in the vicinity of the fibre is contributing to better bond between mentioned constituents, therefore increasing the resistance to the cracking of the FRC composite and reducing the subsequent destruction of the material.

In the scope of this study, the packing of the cementitious matrix near the steel fibre was investigated with SEM and backscattered electron (BSE) detector. The pores and unhydrated (UH) cement grains were segmented from the BSE images (Fig. 3(a)) with the automated k-means clustering algorithm, as it is demonstrated in Figure 3(b).

The distributions of pores and UH cement grains were examined within a distance of 100 µm from the fibre surface with the step of 5 µm (Fig. 3(b)).



(a) (b)

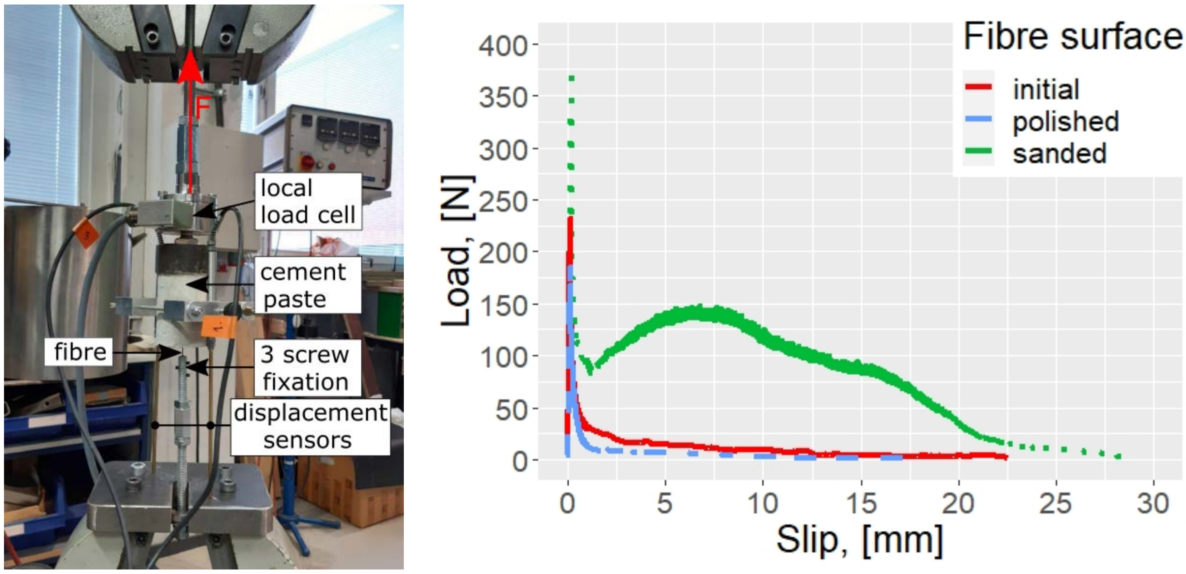
Figure 3: (a) Example of SEM image. (b) Example of the segmented SEM image. The distributions of pores (blue) and unhydrated clinker grains (red) will be analysed with the step of 5 µm stripe-wise, which are marked with yellow lines.

3.3 Single fibre pull-out test

The quality of the packing of the cementitious matrix around the fibre, i.e. bond, can be also defined with the performance of the pull-out test.

The steel fibre with a total length of 50 mm and the embedded lengths of 30 mm was cast into the cement-paste cylinder with a diameter of 45 mm. The free end of the fibre was fixed from one side and the cement cylinder was fixed from the other side in the loading setup (Fig. 4 (a)). The setup of the pull-out test was designed to eliminate the influence of possible compressive stress, that may occur from the fixation of fibre or cement cylinders. The load was applied with the rate of 0.05 mm/min. Figure 4 (b) illustrates the results of the preliminary pull-out tests of the fi bres with three different fibre roughness.

According to the Figure 4 (b) the peak load was increasing with the increase of roughness. This could be influenced by the differences in the microstructure of the ITZ around fibres with different surface roughness, that could be governed by the variations in fibre wetting and cement grains packing near the fibre. In addition, the occurrence of the hardening behaviour was noticed with the sanded fibres after the adhesion breakage. This behaviour may be attributed to the additional mechanical anchorage provided by the roughness of the fibre surface and non-uniform ITZ structure, which result in the interlocking between the cementitious matrix and the steel fibre. This response is typical for the general contact of rough surfaces, that was discussed previously in [10]. The possible occurrence of the slip hardening behaviour during the slippage of fibre from the cementitious matrix was explained in [11] by the nature of the interaction and the damage developed along the interface during the slip.



(a) (b)

Figure 4: (a) Setup for single fibre pull-out test. (b) Example of the load-slip curve obtained with single fibre pull-out test of the fibres with different fibre surface treatment.

4. CONCLUDING REMARKS

The combination of several measuring techniques are used in the present study to examine the relation between roughness, packing of the cement-based matrix in the vicinity of the fibre and mechanical performance of the contact between the cement-paste and fibre. This research has the potential to increase understanding of the interaction between the cementitious matrix and steel fibres considering the filling effect and interlocking between the fibre grooves and the cement hydrates and water spreading affected by the roughness of the fibre on the micro-scale.

ACKNOWLEDGEMENTS

The research leading to these results received funding from the Doctoral program of the School of Engineering, Aalto University.

REFERENCES

[1] Lee, S.F., Jacobsen, S. ‘Study of interfacial microstructure, fracture energy, compressive energy and debonding load of steel fiber-reinforced mortar’. *Mat. and Str.* **44** (2011) 1451 – 1465.

[2] Scrivener, K. L., Crumbie, A. K. and Laugesen, P. ‘The Interfacial Transition Zone (ITZ) Between Cement Paste and Aggregate in Concrete’. *Interface Sci.* **12** (2004) 411 – 421.

[3] Eik, M., Antonova, A. and Puttonen, J. ‘Roughness of steel fibre and composition of cement paste close to fibre surface’. *Journal of Adv. Concr. Tech.* **17** (2019) 628 – 638.

[4] Xu, L., Deng, F. and Chi, Y. ‘Nano-mechanical behavior of the interfacial transition zone between steel-polypropylene fiber and cement paste.’ *Constr. and Build. Mat.* **145** (2017) 619 – 638.

[5] Ranjbar, N., Talebian, S., Mehrali, M., Kuenzel, C., Metselaar, H. S. C. and Jumaat, M. Z. 'Mechanisms of interfacial bond in steel and polypropylene fiber reinforced geopolymer composites'. *Comp. Sci. and Tech.* **122** (2016) 73 – 81.
[6] Wenzel, R. N. 'Resistance of solid surfaces to wetting by water'. *Industrial and Eng. Chem.* **28** (1936) 988 – 994.
[7] Kubiaka, K.J., Wilsona, M.C.T., Mathia, T.G. and Carval Ph. 'Wettability versus roughness of engineering surfaces'. *Wear.* **271** (2011) 523 – 528.
[8] Qudoos, A., Rehman, A. U., Kim, H. G. and Ryou, J. S. 'Influence of the surface roughness of crushed natural aggregates on the microhardness of the interfacial transition zone of concrete with mineral admixtures and polymer latex'. *Constr. and Build. Mat.* **168** (2018) 946 – 957.
[9] Shanahan, M. E. R. 'Simple theory of "stick-slip" wetting hysteresis'. *Langmuir* **11** (1995)1041-1043.
[10] Jiménez, A.-E. and Bermúdez, M.-D. 'Friction and wear'. In: Davim, J. P. (eds.), Tribology for Engineers. Woodhead Publishing, 2011, 33-63.
[11] Bentur, A. and Mindess, S. 'Fibre reinforced cementitious composites'. Crc Press, 2006, 31 – 97.