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Effect of the fibre geometry on pull-out behaviour of HVFA mortar containing nanosilica

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Abstract

It is essential to understand the single fibre pull-out response in order to understand and predict the behavior of fibre reinforced composites. Hook geometry can largely affect the post-crack behaviour of fibres in structural elements. There is limited data available on newly developed multi hooked end steel fibers. This paper presents results of single fibre pull-out tests of three types of hooked end steel fibres embedded in high volume fly ash (HVFA) mortar. Steel fibres were defined as double, triple or quadruple hooked based on their geometry. The results of this study indicates that the pull-out load of the steel fibres was increased with the increase of the number of bends at the ends. It was also observed that the extra hooks resulted in some plastic deformation of the fibres. The average pull-out load of the quadruple hooked fibre was 1.4 times higher than that of the average pull-out load of the double hooked fibre. Pull out strength was increased with the increase of the matrix strength. The compressive strength of the mortar was increased by 18% with the addition of 2% nanosilica (NS) and 10% microsilica (MS). Inclusion of these fine particles improved the bond between fibres and the mortar which consequently increased the pull-out load. The double hooked end fibre exhibited the smallest pull-out load among the three types of fibre studied. It was also observed that the pull-out load of all types of fibres increased with the reduction of fly ash (FA) content. Furthermore, results also demonstrate that the addition of MS and NS increased the pull-out load of steel fibres in HVFA mortar up to 31%.

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Keywords: Hooked-end steel fibre, PVA fibre, High volume fly ash mortar, Pull-out test

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1. Introduction

Despite all the benefits of cement based mortar and concrete, they are identified as brittle construction materials with a low tensile strength which makes them prone to cracking. For decades, the addition of fibres to these materials have been a common practice to improve the mechanical behaviour, and delay propagation of cracks while saving the costs of excessive reinforcement. An additional mechanical component is obtained when straight fibres are deformed, which produces anchorage effect. In case of smooth fibres the only mechanism preventing slippage are adherence and friction. However, in case of deformed fibre particular geometry such as hooked end or twists will provide additional bonding force. Mechanical anchorage is the key parameter affecting toughness and energy absorption capacity and is caused mainly by deformations or hooks in fibres

It is important to study the bond between fibre-matrix interface characteristics in order to understand the behaviour of any composite material produced with fibres. The fibre-matrix interface bond has been studied in recent years [1]. Numerical models have been developed based on geometry and strength of fibres with focus on fibre inclination [2-4]. Some of the parameters affecting the bond are known as length of the fibres (L), diameter (d), embedement length (L_b), Aspect ratio (L/d), fibre orientation angle (θ) and the tensile strength of fibres [5]. Analytical models have been developed to predict the pull-out load by other researchers [6-8]. Alwan et al. [9] investigated various parameters such as fibre diameter, length and aspect ratio.

The fiber–matrix interface bond is usually determined by a single fiber pull-out test. Pull-out behaviour depends on both the matrix and the fibre characteristics. An ideal pull-out test has two main components:sliding and mechanical anchorage. The embedment length of smooth and hooked-end fibres have been studied by researchers [10-12]. Tuyan and Yazici [10] showed that the peak pull-out load of hooked steel fibres was significantly higher than smooth steel fibres. By implementing microstructral study, it has been observed that the transition zone in mature traditional cementitous composite is quite porous which is filled with CH gel where it is also in direct contact with fibres [13]. The density of the interfacial transition zone can be increased by addition of supplementary cementitious materials (SCM) [14-20]. Shannag et al. [11] studied the embedment length of fibres, it has been observed that embedment length affects both the peak pull-out load and pull-out work. Silva et al. [21] reported that fibre morphology plays an important role in the bond strength of the fibre-matrix. Lee et al. [22] observed that highest peak load for fibre during the pull-out test occurs with angle of 30° and 45°.

A series of experimental pull-out tests of different fibres from various types of matrix have been investigated in this paper. Limited studies are available on the effects of fibre geometry, matrix type and combined actions of the above parameters. The effect of end condition of steel fibres on the fibre-matrix bond charastristics is investigated here. Based on the results, the pull-out behaviour has been analysed and mechanisms affecting the pull-out load and post peak behaviour are explained.

2. Illustrations

2.1. Materials and specimen preparation

Ordinary Portland cement (OPC), Class F fly ash, microsilica (MS) and nanosilica (NS) with the properties given in Table 1 were used in all the mortar mixtures. The properties of the fibres used in this study are given in Table 2. The fibres were of a smooth surface with the ends bent in three different configurations, as shown in Fig. 1.

The mixtures were mixed in a Hobart mixer. A constant water/ binder ratio of 0.4 and sand/binder ratio of 2 was used to prepare all the mortars. In this study, seven types of mortars were prepared and cast in plastic moulds. The first series was control mortar that consisted of OPC only as the binder. After casting, the specimens were kept for 24h in 20 ± 2 °C and then were demolded and cured for a testing period of 7 and 28 days.

The second, third and fourth series were HVFA mortars containing 40%, 50% and 60% (by wt) fly ash as partial replacement of the OPC, respectively. The fifth, sixth and seventh series contained 2% NS, 10% MS and combined 2% NS + 10% MS, respectively, with fly ash. The specimens were prepared in a plastic mould with a size of 12 × 24 × 42 mm. Cube specimens of 50 mm size were cast for compressive strength tests at 28 days.

Table 1. Chemical composition and physical properties of cementitious materials

Chemical analysis	Cement (wt%)	Fly ash (wt%)	Microsilica (wt%)	Nanosilica (wt%)
SiO_2	21.1	63.13	89.6	99
Al_2O_3	5.24	24.88	-	-
Fe_2O_3	3.1	3.07	-	-
CaO	64.39	2.58	-	-
MgO	1.1	0.61	-	-
K_2O	0.57	2.01	0.225	-
Na_2O	0.23	0.71	0.11	-
SO3	2.52	0.18	-	-
LOI	1.22	1.45	3.8	-
Particle size	-	73% < 45 μm	95% < 1 μm	25 nm
Specific gravity	3.17	2.65	0.625	2.2-2.6
BET Surface area (m^2/g)	-	1.53	15-30	160

Table 2. Properties of fibres

Type	Geometry	Length (mm)	Diameter (mm)	Aspect ratio	Modulus (GPa)	Tensile strength (MPa)
Steel	Hooked end	60	0.90	65	210	1345

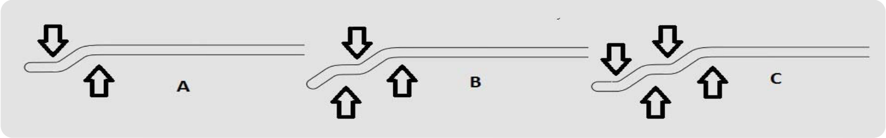

Fig. 1. Configuration of fibres used in this study: (A) doubled bend; (B) triple bend; (C) quadruple bend. (bends numbering is based on number of bends shown by the arrows)

2.2. Test procedure

In order to determine the fibre-matrix characteristics, a single fibre pull-out test was carried out which is a common method for pull-out test used by other researchers [20]. A stiff steel frame was used during the pull-out test. The fibre was embedded half way through the matrix ($L_b=0.5\times l_f$) during casting. The fibre orientation is in the same direction as that of the pull-out force. The specimen was mounted in a steel supporting system with a hole located on the top, through which the fibre was clamped to the upper jaw of a universal testing machine, while a long screw bolt which is connected to the bottom of the tube was clamped by the lower jaw of the machine. The test set up is shown in Fig 2. By using this setup, it was assured that the specimens were only under pull-out load and no other lateral confining pressure existed. The upper jaw was connected to a load cell with a capacity of 5 kN and a loading rate of 1 mm/min was used in the test. The pull-out load vs displacement data were recorded for each specimen. The maximum pull-out load was determined from the load displacement curve.

Fig. 2. Apparatus of pull-out test

3. Results and discussion

The 28-day compressive strengths of the mortars containing fly ash, microsilica and nanosilica with no fibres are presented in Fig. 3. As expected, compressive strength of mortars decreased with the increase of fly ash replacing cement. It can be seen that 2% NS, 10% MS or 2% NS and 10% MS increased compressive strength as compared to the mortar containing 40% fly ash. The compressive strength of the mortar containing 10% MS and 2% NS was closest to that of the control mortar mix.

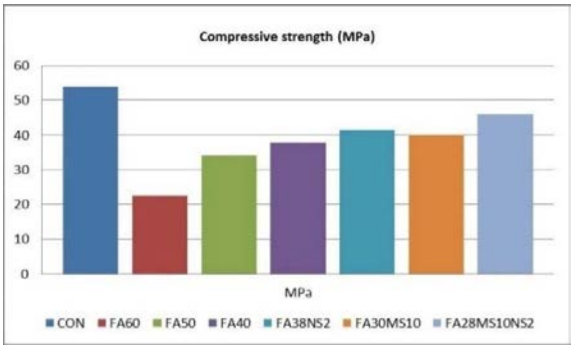

Fig. 3. Compressive strength of mortars at 28 days

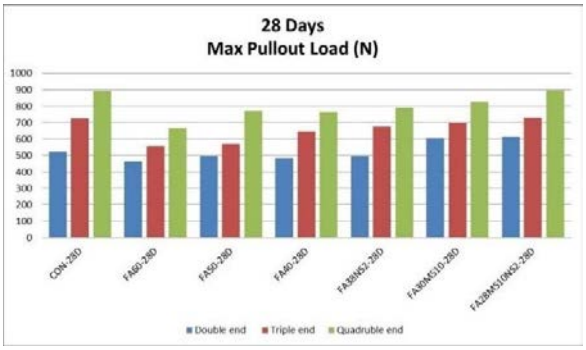

Fig. 4. Peak pull-out load at 28 days curing

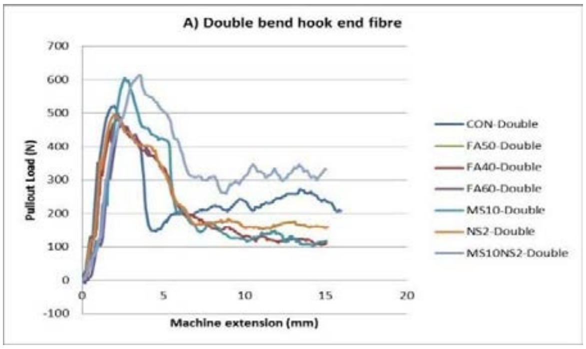

Fig. 5. Pull-out vs displacement of the double-bend fibres

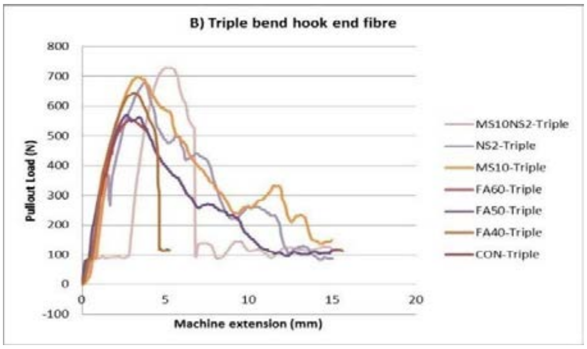

Fig. 6. Pull-out load vs displacement of the triple-bend fibres

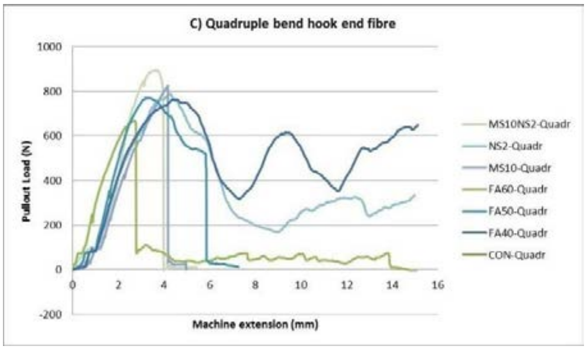

Fig. 7. Pull-out vs displacement of the quadruple-bend fibres

3.1. Effect of fibre geometry on the pull-out behaviour

The maximum values of the pull-out load of the fibres in different matrices are shown in Fig.4. It can be seen that the maximum pull-out load of the fibre in each type of matrix was increased with the increase in the number of bends in the fibre. The pull out load was decreased by the replacement of cement by fly ash. However, it can be seen that the pull-out load gradually increased by the addition of microsilica and nanosilica. The decrease of the pull-out load is attributed to the decrease of the compressive strength by fly ash. The maximum pull-out load of the fibres in the matrix containing 28% fly ash, 10% MS and 2% NS were almost same as those of the fibres in the control matrix. The trends of the maximum pull-out load of a particular type of fibre in different matrices is seen to be similar to that of the compressive strength of the mortars shown in Fig. 3.

The effects of different fly ash contents, 2% NS, 10% MS and combinations of both (2NS%+10MS%) on the bond behavior of three types of hook-end steel fibres in HVFA mortar are presented in Figs. 5, 6 and 7. By investigating the failure modes of fibres in this study, it was observed that the fibres were pulled out with some plastic deformation. It can be observed from results that pull-out load displacement curves present characteristics mainly based on fibre geometry and matrix properties. A variability of experimental results were observed by considering a single matrix on various fibre types. This is to be attributed to fibre geometry. Quadruple fibre has shown superior peak loads in all mixes as compared to the triple bend and double bend fibres. This can be due to the effectiveness of hook geometry and better mechanical interlock of bends.

Zile et al. [23] identified the overall pull-out load (P) of steel fibres into two main resisting elements; the first component is the load associated with geometric deformation under plastic bending force (Ppl) and the second is the load corresponding to the frictional force (Pfric), as described by Eq. 1

$$P = P_{pl} + P_{fric} \tag{1}$$

P_{pl} is a result of bending or unbedding of fibers. A similar amount of load is required to bend a straight fibre during the production of a hooked fibre, and is known as plastic bending force. This load will be released when fibres are under debonding process and while the geometric deformation happens during the pull-out. The cementitious matrix is assumed as a curve duct where fibres are positioned inside it. Frictional force (P_{fric}) is another resisting element which is a result of the friction between steel fibre and the matrix duct. The frictional force is affected by the parameters such as friction shearing stress, embedded length and the fibre slip.

By observing Fig. 5, it can be said that, addition of combined MS+NS resulted in highest peak load and the best post peak behaviour in case of double bend fibres. A very similar effect was observed in Fig. 6 in case of triple bend fibres and in Fig. 7 for quadruple bend fibres.

By comparing Figs. 5, 6 and 7, the effect of different fibre geometry can be observed. The repetitive bending and unbending required to smoothen the quadruple fibres has increased the plastic deformation. Furthermore, extra bending of this fibre in comparison to the triple bend fibre has increased the frictional force by increasing the anchorage which have been in a direct contact with the matrix during the bending. Better post-peak behaviour was observed due to the greater mechanical interlock of bends with quadruple and triple bend fibres.

The principal failure mode observed in case of double, triple and quadruble end steel fibres was plastic deformation followed by pull-out. The reason for fluctualtion after peak load can be due to fractures of matrix in micro-level while fibres go through an elasto-plastic phase. As it can be observed in Fig 5, 6 and 7 the slope of the load vs displacement graph of these type of fibres has been close to linear to the point of peak load. The first stage of pull-out of the fibres occured when the maximum load was reached. The second stage of pull-out begun after peak load, when the fibre went through the curved matrix and debonding resulted. The debonding happened either in a hardening behaviour such as the double bend fibre in the matrix of FA28MS10NS2 or with a drastic drop in the load such as the triple bend fibre in in the matrix of FA28MS10NS2

4. Conclusions

In this study, a sustainable mortar containing a high volume of fly ash as a partial replacement of cement was used to characterize the bond slip behaviour of three types of hooked end steel fibres. A displacement controlled pull-out test was conducted. The results are discussed based on compressive strength of the matrix and the pull-out load vs displacement graphs. The main findings of this study can be summarized as follows:

- The addition of 2% NS and 10% MS increased the compressive strength of flu ash mortar by 18%. By implementing a relatively low w/c ratio besides the addition of these SCMs, the amorphous content of the matrix has been increased. Due to the addition of SCM materials, the formation of additional calcium silicate hydrate (C-S-H) gel improved the bonding. All these resulted in the production of a sustainable matrix with a dense microstructure which improved the frictional force (P_{fric}). The stiffness of the matrix played an important role both in failure modes and in post peak behavior of the fibre pull-out.

- The fibre geometry has affected both peak load and post peak behavior. The average pull-out load of the quadruple hooked fibre was 1.4 times higher than that of the average pull-out load of double hooked fibre. An elasto-plastic semi-hardening behaviour has been observed in most mixes which is result of debonding and sliding in the fibre-matrix interface. The pull-out peak load and the debonding toughness increased with increase in number of bends, this corresponds to increase in plastic bending force (P_{pl}) and increased mechanical interlock caused by the bends at the ends.

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