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Effect of Hooked-End Steel Fibres Geometry on Pull-Out Behaviour of Ultra-High Performance Concrete

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Abstract**—**In this study, a comprehensive approach has been adopted to examine in detail the effect of various hook geometries on bond-slip characteristics. Extensive single fibre pull-out tests on ultra-high performance matrix with three different W/B ratios and embedded lengths have been carried out. Test results showed that the mechanical deformation of fibre hook is the main mechanism governing the pull-out behaviour. Furthermore, the quantitative analyses have been completed to compare the hook design contribution of 3D, 4D and 5D fibres to assess overall pull-out behaviour. It was also revealed that there is a strong relationship between the magnitude of hook contribution and W/B ratio (i.e. matrix strength). Reducing the W/B ratio from 0.20 to 0.11 greatly optimizes the interfacial transition zone (ITZ) and enables better mobilization, straightening of the hook and results in bond-slip-hardening behaviour.

Keywords**—**bond mechanisms, fibre-matrix interface, hook geometry, pullout behaviour and water to binder ratio.

I. INTRODUCTION

BRITTLE materials such as concrete and mortar are well-known for their low ability in resisting tensile stresses and crack propagation [1]-[3]. Numerous studies have been carried out to overcome this deficiency [2]. Steel fibre reinforcement has been shown to improve impact resistance, absorbed energy, flexural and shear strength [4], [5]. The contribution of the fibre is primarily reflected after cracking stage and often improves the post-cracking behaviour [4], [6], [7]. The efficiency of fibres in transferring the stresses is greatly dependant on bond mechanisms between the fibre and matrix [8]-[10]. Therefore, the study of the bond mechanisms is a key factor in understanding the tensile behaviour of steel fibre-reinforced cementitious composites (SFRCCs) [11]-[13].

In SFRCCs, the pull-out mechanisms mainly comprise of physical and chemical adhesion, debonding and frictional resistance for straight steel fibres [13]-[15]. However, in the case of mechanically deformed fibres, an additional mechanism could be observed, which is mechanical anchorage [15], [16]. There are many types of deformed steel fibres that are used in concrete such as crimp, hooked end and twisted [11], [17], [18]. Nevertheless, hooked end fibres are more widely used in cementitious composites compared with other types of steel fibres [17], [19]. Hooked end fibres only use a small portion of its hook to resist a pull-out force. Studies have proved the high efficiency of these fibres to provide high mechanical anchorage [5], [15], [17], [20]. The latter mechanism is based on the principle of plastic deformation of the hooks and results in immense energy consumption to straighten the plastic hinges of the steel fibre hooks [2], [21]. Moreover, the mechanical interlock provided by fibre hooks not only increases resistance to pull-out but also has significant importance for the whole tensile behaviour of SFRCCs. Although, the pull-out behaviour of straight (without deformations) fibres has been intensively studied by several researchers [3], [14], [16], [22], the completed knowledge on pull-out behaviour of deformed fibres is scarce. Generally, the most effective ways to improve bond-slip characteristics are through enhancing the mechanical anchorage of fibres and the quality of matrix (strength) [12], [14]. The contribution of mechanical anchorage on bond-slip behaviour is more significant than de-bonding and frictional resistance mechanisms [11].

To investigate the influence of fibre geometry on pull-out behaviour of SFRCCs extensive single fibre pull-out tests have been done during the last three decades [3], [5], [16], [20], [23], [24]. However, all single fibre pull-out tests have been carried out on hooked end fibres were with two hinges in its hook. Lately, the hooked end fibres of improved geometrical and tensile properties, namely 4D and 5D fibres have been introduced. Therefore, mechanisms associated with pull-out behaviour of these (i.e. 4D and 5D) deformed fibres are not yet understood.

The main objectives of this study are to investigate the effect of new hook geometry of 4D and 5D hooked end fibres on bond-slip characteristics. Also, a comprehensive analysis is necessary to compare the hook contribution of classic shape of hooked end fibres (3D) with new ones 4D and 5D fibres. This study is also aimed to improve the fibre-matrix interface by densification of the ITZ i.e. using very low W/B ratios. However, there are many factors that could affect the pull-out behaviour such as length, diameter, and geometry of the fibre and embedded length; all these factors will be taken in account.

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II. EXPERIMENTAL PROGRAM

A. Materials and Specimens

The main aim of the experimental programme is to investigate the influence of fibre geometry, water/binder ratio and fibre embedded length on pull-out response. All fibres were embedded in three ultra-high performance cementitious mortars and only water to binder (W/B) ratio changed. The following constituent materials were used for the formulation of the ultra-high performance cementitious mortars: Portland cement CEM III 52.5 N, silica fume, ground quartz, fine sand (150-600 µm), superplasticizer, accelerator and water (Table I). Three types of Dramix hooked-end steel fibres (3D, 4D and 5D) with same length (60 mm), diameter (0.90 mm) and aspect ratio (l/d=65) but different in hook geometry were used throughout this study. For each type of fibres, the fibre was electronically scanned and the measurement of end-hook geometry was performed by using computer software (SUPRA 35 VP). The geometrical properties of each fibre type are depicted in Fig. 1 and detailed in Table II. To study the pull-out behaviour of straight fibres, the hooked ends of both 3D and 5D fibres have been cut off.

In each mortar cylinder (100 mm diameter and 50 mm height), one steel fibre was placed through a hole made in the bottom of the mould. Three different embedded lengths El (10, 20 and 30 mm) were used. During mortar fabrication, the components were firstly dry mixed for 1 minute for homogeneity and then water and superplasticizer were added to dry mixtures which were then mixed for 11 minutes. After the casting and vibration, the specimens were covered with a thin polyethylene film and left for 24 hours at room temperature. Then specimens were removed from their moulds and cured for further 28 days in the conditioning chamber (20 ± 2 °C, 96 ± 4%RH). For all series, the test was carried out at an age of 30 ± 2 days and the average of three specimens was considered.

TABLE I
MIXTURE PROPORTIONS BY WEIGHT OF THE UHPC

Type	UHPM1	UHPM2	UHPM3
Constituent		Kg/m^3	
Cement type III 52.5 N	710	710	710
Silica fume	231	231	231
Ground quartz	211	211	211
Fine sand	1020	1020	1020
Superplasticizer	30.7	30.7	30.7
Accelerator	30	30	30
Water	126.72	172.8	230.4
W/B	0.11	0.15	0.2

TABLE II
THE MEASURED GEOMETRIC PROPERTIES OF FIBRE HOOK

Fibre type	Hook length (mm)				Hook angles (°)		Hook height (mm)	
	L1	L2	L3	L4	α	β	H1	H2
3D	2.12	2.95	-	-	45.7	47.5	1.85	-
4D	2.98	2.62	3.05	-	53	33.8	4.37	2.20
5D	2.57	2.38	2.57	2.56	27.9	30.5	2.96	1.57

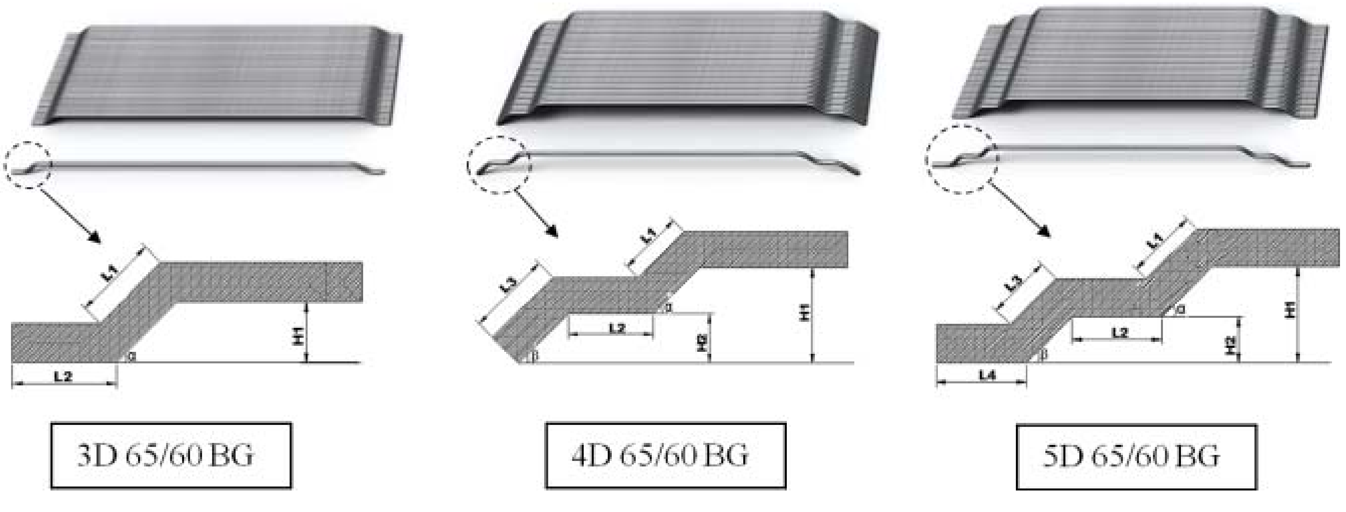


Fig. 1 Geometrical properties of 3D, 4D and 5D hooked end steel fibres

B. Test Setup

The pull-out tests were performed by using a specially designed grip mechanism attached on Instron 5584 machine (Fig. 2). The grip arrangement is made to simulate the actual situation of crack bridging by fibres. The body was lathed out of mild steel with a tapered end to allow 4 x M4 grub screws to be added, these holes were drilled and threads tapped in to except the grub screws. These were then equally tightened to the steel fibre for an even distribution of gripping pressure and to minimise deformation of the fibre ends and avoid breakage at the tip.

Two Instron 2601-093 LVDT Deflection sensors using +/- 15 mm travel with M3 threaded shafts were used, held in place inside two aluminium sleeves either side of the main grip body, these were run through the strain 1 and 2 channels on the Instron 5584 load frame. The LVDT's were then connected via a steel strut to sit either side of the fibre during testing. The LVDT's ran with ball bearing tips to allow for accurate readings from the deck face of the samples. These were balanced and zeroed before each test.

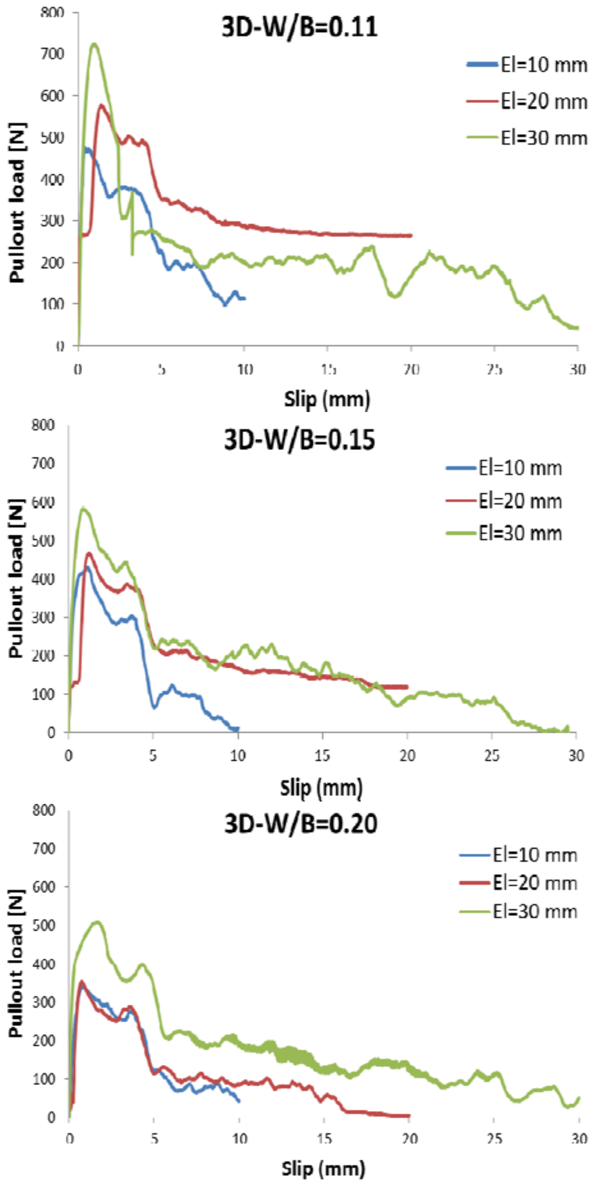
The sample was secured to the Instron T-slot base via strap clamps used with riser blocks and M16 studs. This allowed the sample to be held to the base. The sample sat on a brass 100 mm OD round disc to take up discrepancies in the sample base and allow for distortion. In all pull-out tests, the displacement rate of 10 µm/s was adopted.

Fig. 2 Single fibre pull-out test setup

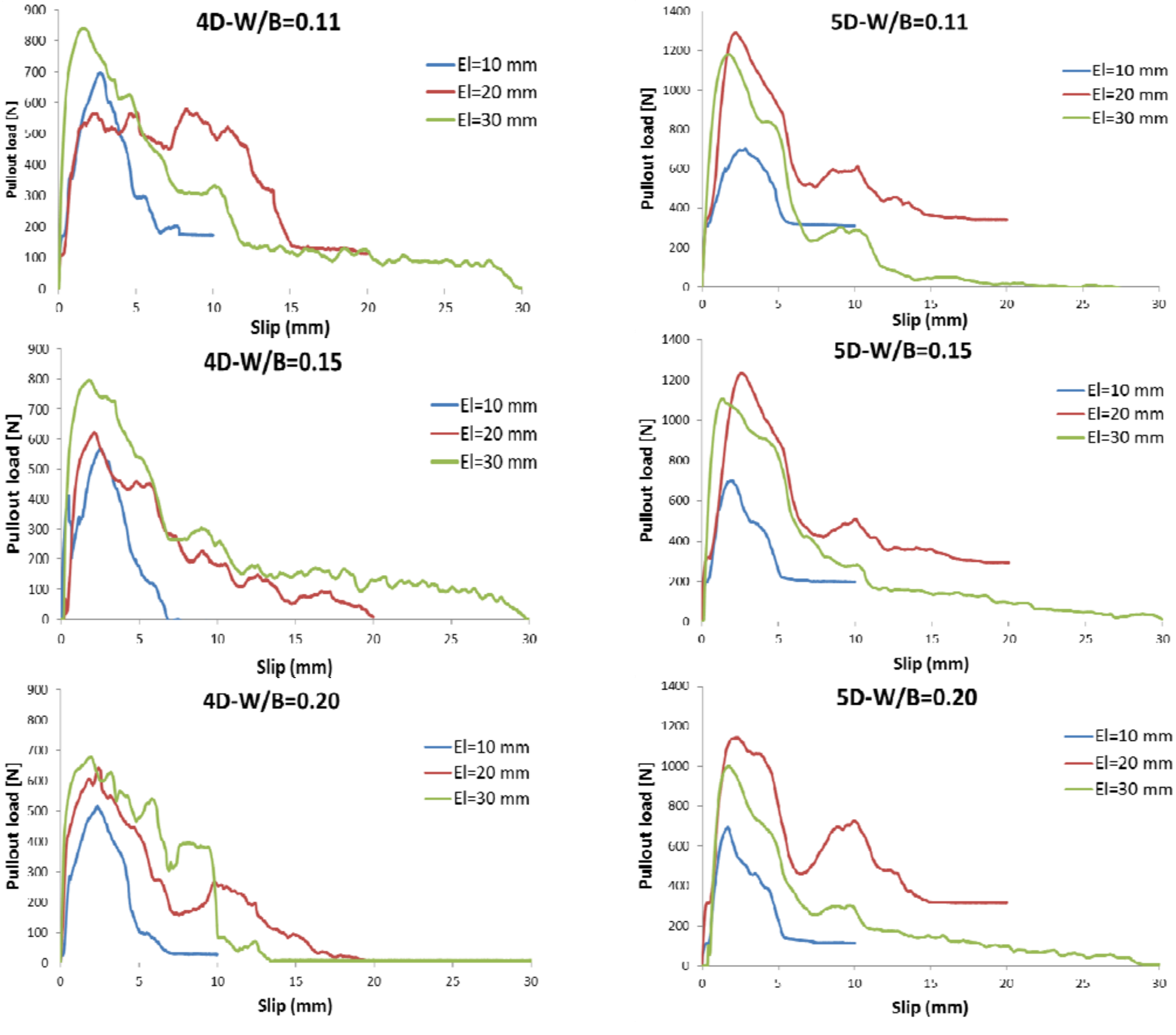
III. EXPERIMENTAL RESULTS

A. Effect of Fibre Embedment Length on Pull-Out Behaviour

The influence of embedded length on maximum pull-out load and general pull-out behaviour are presented in Fig. 3. It can be seen that the maximum pull-out load increases when the embedded length increases. For series with 3D, 4D and 5D steel fibres, the peak loads increased by 52.21%, 35.34%, 48.68%, 20.51%, 40.88%, 30.94%, 68.47%, 58.20% and 43.95% for w/b= 0.11, 0.15 and 0.2, respectively, when fibre embedded length increased from 10 to 30 mm. However, series with embedded length of 20 mm of 5D steel fibres were an exception to latter assertion. The reduction in peak loads were 9.22%, 11.45% and 14.51% for w/b=0.11, 0.15 and 0.2, respectively, when fibre embedded length increases from 20 to 30 mm. It is well established that the larger the embedded length, the higher are peak load and total pull-out work can be obtained. This can be attributed to a larger surface area of fibre in contact with surrounding matrix. However, the latter fact is more remarkable in case of straight fibres and not the case in hooked end fibres. The reason for this is the pull-out mechanism in case of hooked end fibres is considerably influenced by the plastic deformation of its hook than frictional resistance of its straight part. Although the increase of embedment length from 10 to 30 mm has great effect on pull-out behaviour of 3D fibres, there is a slight difference in pull-out behaviour when embedment length increased from 10 to 20 mm. Since the hook length of 3D fibres is roughly 5 mm, the embedment length of 10 mm seems to be long enough to achieve full deformation and straightening of the hook. The experimental results presented in this paper have verified that if the fibre embedment length is twice the hook length it can guarantee completely the mobilisation and straightening of the hook. Therefore, the fibre embedded length is not of great importance any longer. On the other hand, since the hook length of 4D and 5D fibres are approximately 8.66 and 10 mm (Table II), respectively, the full deformation of fibre hooks did not occur with embedded length 10 mm and only partial straightened hooks have been observed. This can be explained by the lower peak load that was obtained with 10 mm compared with 20 and 30 mm embedment lengths.



(a)



(b)

(c)

Fig. 3 Influence of embedment length on pull-out behaviour. (a) 3D, (b) 4D and (c) 5D hooked end fibres

B. Effect of W/B Ratio on Pull-Out Behaviour

It is generally well known that the decreasing W/B ratio considerably enhances the properties of interfacial bond between fibre and matrix. The use of both the low W/B ratio and silica fume results in an improvement in the density and micro-hardness of the fibre-matrix interfacial zone.

The influence of three W/B ratios (W/B= 0.11, 0.15 and 0.2) on pull-out behaviour of three types of hooked end steel fibres were investigated throughout this study. The pull-out load-slip curves of 3D, 4D and 5D fibres embedded in various W/B ratios are presented in Fig. 4. It is apparent that the peak load and total pull-out work increases with the deceasing W/B ratio for all fibre series. As can be seen from Fig. 4 that there is a remarkable difference in pull-out behaviour of 3D, 4D and 5D fibres, when W/B ratio decreases from 0.20 to 0.11, while a slight difference in pull-out behaviour of 4D and 5D fibres is obtained, when W/B ratio decreases from 0.15 to 0.11. The peak loads of 3D, 4D and 5D steel fibres embedded up to half fibre length increased by 41.81%, 24.07% and 18.21%, while, the corresponding increase in total pull-out work is 18.43%, 31.91% and 52.65%, respectively when W/B ratio decreased from 0.2 to 0.11. However, the peak loads only increased by 14%, 17.57% and 11%, while, the corresponding increases in total pull-out work are 1.86%, 43.80% and 14.93% for 3D, 4D and 5D, respectively when W/B decreased from 0.2 to 0.15.

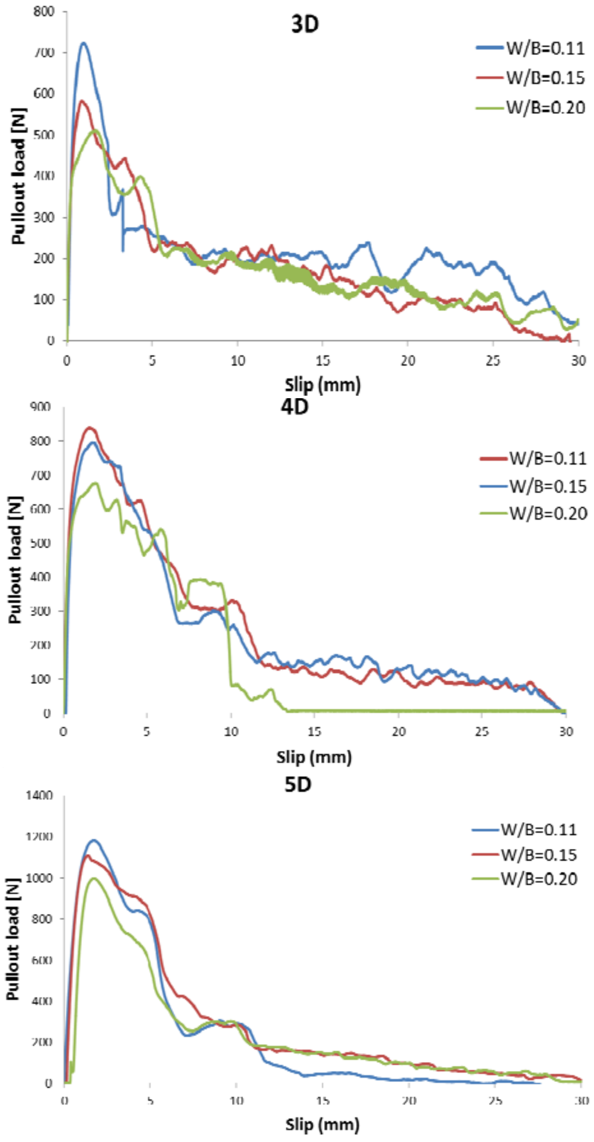


Fig. 4 Influence of W/B ratio on pullout load-slip curves

Fig. 5 shows SEM images of the steel fibre-matrix interface of three different mortars W/B=0.11, 0.15 and 0.20. It can be seen from Fig. 5 (a) that 0.11 W/B ratio mixture has lower levels of pores than 0.15 W/B ratio (Fig. 5 (b)). This indicates the congestion of hydration products and a higher cement-hydrate packing in the ITZ in mixture with 0.11 W/B. Thus, it improves the interfacial bond strength as a result of densification the microstructures in the ITZ and formed a thinner ITZ. On the other hand, mixture with 0.20 W/B ratio has a dramatically high level of porosity along the fibre-matrix interface as shown in Fig. 5 (c). It is noteworthy that the increased level of porosity in ITZ is mainly due to high water content and less dense packing of cement grains close to the fibre surface. This may help to explain the remarkably lower pull out load and total pull-out work of the matrix with 0.20 W/B compared with 0.11 W/B.

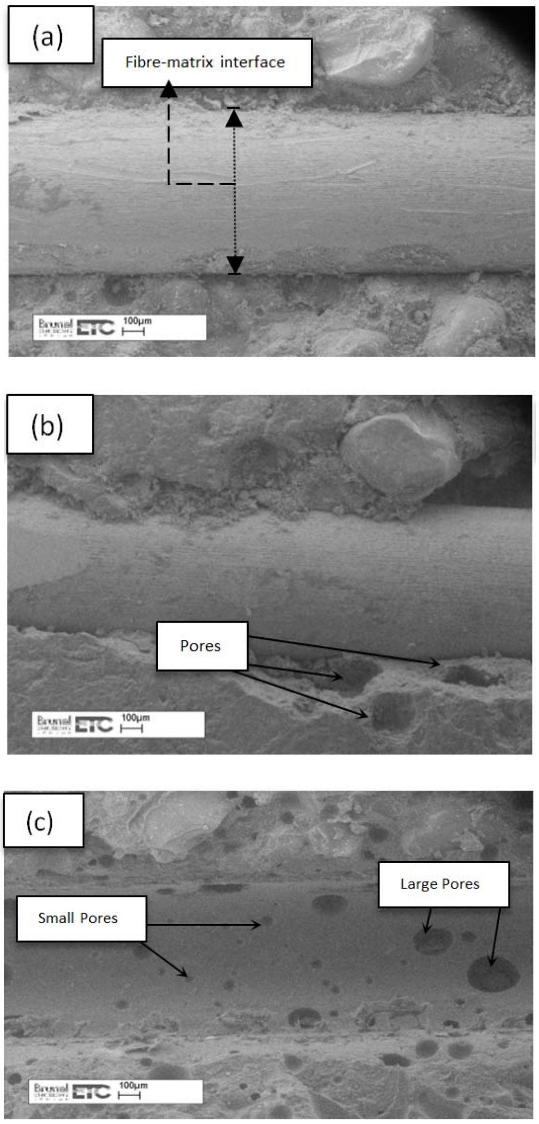


Fig. 5 SEM images of the fibre-matrix interface (a) UHPM1 (W/B=0.11), (b) UHPM2 (W/B=0.15) and UHPM3 (W/B=0.20)

IV. CONCLUSIONS

In this study, the bond mechanisms and overall pull-out behaviour of various hook end steel fibre reinforced concretes have been fully investigated. Based on the experimental results obtained by pull-out tests, the following conclusions can be drawn:

1) The decrease W/B ratio from 0.20 up to 0.11 considerably enhanced the bond strength between fibre-matrix.

However, the reduction in W/B ratio from 0.20 to 0.15 had a slight effect on pull-out behaviour.

2) For 3D and 4D hooked end steel fibres, the pull-out load and total pull-out work increase as embedment length increases. However, this is not case for 5D hooked end fibres, whereas mortars with 20 mm embedment length exhibited higher pull-out load and total pull-out work than 30 mm embedment length. Thus, the embedment length does not play a significant role on pull-out behaviour
3) The pull-out behaviour comparison of 3D, 4D and 5D fibres showed that the peak pull-out load and total pull-out work of 5D fibres is greatly higher than 3D and 4D fibres. Due to the high anchorage effect provided by the lengthy hook of 5DH fibres significantly enhances the pull-out behaviour, generating higher pull-out load and pull-out work as compared to 3D and 4D fibres.
4) Microstructural investigation on the ITZ revealed that the lower the porosity is, the higher matrix packing density around the fibre. Therefore, higher content of the hydration products along ITZ which is necessary to improve the microstructure of the interface between fibre and matrix, and hence the bond characteristics.

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