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Preface

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On enhancing the mechanical behavior of ultra-high performance concrete through multi-scale fiber reinforcement

ABSTRACT

Steel fibers are typically used in ultra-high performance concretes (UHPC) to impart flexural ductility and increase fracture toughness. However, the mechanical properties of the steel fibers are underutilized in UHPC, as evidenced by the fact that most of the steel fibers pull out of a UHPC matrix largely undamaged during tensile or flexural tests. This research aims to improve the bond between steel fibers and a UHPC matrix by using *steel wool*. The underlying mechanism for fiber-matrix bond improvement is the reinforcement of the matrix tunnel, surrounding the steel fibers, by steel wool. Single fiber pullout tests were performed to quantify the effect of steel wool content in UHPC on the fiber-matrix bond. Microscopic observations of pulled-out fibers were used to investigate the fiber-matrix interface. Compared to the control UHPC mixture with no steel wool, significant improvement in the flexural behavior was observed in the UHPC mixtures with steel wool. Thus, the addition of steel wool in steel fiber-reinforced UHPC provides multi-scale reinforcement that leads to significant improvement in fiber-matrix bond and mechanical properties of UHPC.

1. Introduction

Over the past three decades, significant amount of research has been performed to improve the mechanical performance of the ultra-high performance concrete (UHPC) class of materials. From classical beam mechanics, we know that increasing the area under the tensile stress-strain curve of a material improves the flexural capacity and ductility of a beam made of that material [1]. A larger area under the tensile stress-strain curve is typically achieved in UHPC through the addition of fibers (typically steel) that stabilize the cracks in UHPC under tension. Therefore, a majority of recent research on UHPC materials has focused on various methods to increase the crack-bridging capacity of the fibers in order to improve the tensile and flexural performance of UHPC [2–6].

The fiber-matrix bond properties play a key role in determining the crack-bridging behavior of the fibers in UHPC and other fiber-reinforced concretes [7]. Although polymer fibers with high aspect ratios have been successfully used in limited studies on UHPC [3,8,9], steel fibers are typically used in the majority of UHPCs due to their ease of processing, lower cost, and lower water demand compared to the polymer fibers. The UHPCs in this study also utilize steel fibers, and therefore, we have limited our discussion on the fiber-matrix bond to steel fibers only. A

major limitation of straight, smooth steel fibers is their weak bond with the cementitious matrix of UHPC [10,11]. This is supported by the fact that most steel fibers in UHPC pull out of the matrix unbroken during a tension or a flexure test, as the maximum stress developed in the fibers is significantly smaller than their capacity [12,13]. Furthermore, micro-scale studies on steel fiber pullout have shown slip-softening behavior caused by the breakage of the matrix tunnel surrounding the steel fiber [14]. As a result, several approaches for improving the steel fiber-matrix bond have been investigated in recent years, which can be broadly classified as fiber-based approaches and matrix-based approaches.

Fiber-based approaches for improving the steel fiber-matrix bond in UHPC include modifications to the fiber's geometry by developing hooks, twists, and crimps (or undulations) along the fiber length to increase the bond. These modifications are intended to increase the frictional bond and mechanical anchorage of steel fibers [15]. Hooked steel fibers have been used in Cor-Tuf – a UHPC developed at the Engineer Research and Development Center of the U.S. Army Corps of Engineers [16–18]. Micro-scale investigations reveal a significant increase in the fiber-matrix bond due to the mechanical anchorage provided by the hooks [19,20]. Similarly, the use of twisted steel fibers in UHPC results

in a post-cracking tensile strength that is up to three times greater than that observed with smooth steel fibers [11,21,22]. Pullout loads also increase due to crimping of fibers [23]; however, such fibers do not produce significant gains in the composite properties of UHPC [24].

Matrix-based approaches for improving the steel fiber-matrix bond in UHPC have focused on increasing the density, strength, and roughness of the matrix surrounding the steel fiber or the fiber-matrix interface. For instance, Wille and Naaman [25] observed that the bond strength of brass-coated straight steel fibers can be significantly increased through enhanced particle packing, improved fine particle dispersion, and the use of nanoscale particles. These matrix enhancements also led to visible scratching of the fiber's surface and a slip-hardening behavior instead of the typically observed slip-softening behavior with steel fibers [25,26]. Wu et al. and Demirhan et al. [27,28] observed improvement in the matrix microstructure due to the addition of nanoparticles, which led to higher pullout loads on steel fibers.

While the above matrix modifications involve particle inclusions in the matrix, secondary fibers or fibrous inclusions, which are significantly smaller than the primary fibers, can also be used in the matrix to enhance its bond with the primary fiber as discussed below. The smaller scale secondary fibers reinforce the matrix surrounding the primary fibers, which delays the progression and coalescence of micro-cracks in the matrix as shown schematically in Fig. 1. As the primary fiber pulls out of the matrix under tension, the surrounding matrix reinforced by the secondary fiber provides larger frictional bond and may even result in slip-hardening instead of slip-softening pullout behavior.

There have been very few studies on the use of multi-scale fiber reinforcement in UHPC, but a similar approach has been implemented in other cementitious composites. For instance, hybrid fiber-reinforced, normal strength concrete containing both small (micro) and large (macro) steel fibers has been observed to exhibit greater fracture toughness and flexural/tensile strength than mono fiber-reinforced concrete [29–35]. Similarly, the addition of carbon nanofibers at 0.3% volume fraction has been observed to enhance the steel fiber-matrix bond, which results in significant increases in the tensile and flexural strengths of a UHPC [36]. Parant [37] used steel wool as micro-fibers along with steel fibers as macro-fibers in a UHPC and observed an increase in the flexural capacity along with improved post-peak performance as compared to the composites with only steel fibers. These improvements in the mechanical performance of other cementitious composites have motivated us to perform a thorough investigation on the use of multi-scale reinforcement for improving the mechanical properties of a UHPC.

The objectives of this research are (1) to investigate the effects of *steel wool* on the composite rheological and mechanical properties of a steel fiber-reinforced UHPC and (2) to explain these effects on the composite properties by investigating the influence of steel wool on the bond between the steel fibers and UHPC matrix. An experimental approach is used to achieve these objectives. At the macro-scale, rheological properties, including flow and viscosity, and mechanical properties – including compressive strength, flexural strength, and fracture toughness – were determined experimentally for mixtures with varying amounts of steel wool and a fixed volume fraction of hooked steel fibers.

Fig. 1. Bond improvement through multi-scale fiber reinforcement.

At the micro-scale, single fiber pullout experiments were performed on a variety of steel fibers embedded in UHPC matrices with varying amounts of steel wool. The details of these experiments – including mixture proportions, specimen preparation, and testing procedures – are given in Section 3, followed by the results and discussion in Section 4. The following section provides an overview of steel wool and its properties.

2. Steel wool

Steel wool (or chopped steel fiber), typically made of low-carbon steel, is commonly used in the form of rolls or pads for applications in brake pad linings (as thermal shield), automobile exhaust pipes (as acoustic shield), metal separation, water and air filtration, cleaning, etc. The cost of steel wool is about 30–50% of the cost of steel fibers, and it can be produced from recycled metal scrap. A sample of steel wool used in this study is shown in Fig. 2. The individual particles of steel wool are shaped like fibers in terms of high aspect ratio; however, they are flat instead of cylindrical. Therefore, *thickness* (larger of the two thicknesses) is used instead of diameter to characterize their cross-section. Due to the nature of the manufacturing process, the lengths and thicknesses of steel wool particles vary widely. We performed particle size analysis of a steel wool sample using an optical microscope, and the size distributions are shown in Fig. 3. It shows that the length of the steel wool particles varies between 0.3 and 4.8 mm (<1% of particles are longer than 4.8 mm), with median length of 1.22 mm. The thickness of the steel wool particles varies between 10 and 200 μm (<1% of particles have thickness greater than 200 μm), with median thickness of 63 μm .

Steel wool's application in construction materials has been investigated by several researchers. Garcia et al. [38–40] used steel wool to enhance the conductive properties of dense asphalt concrete for deicing pavements using electrical induction. One of the early applications of steel wool in cementitious materials was slurry-infiltrated mat concrete (SIMCON) [41,42]. These studies showed that, with 2% volume fraction of steel wool in a cement-based mortar, the flexural strength increased by more than two times and the fracture toughness increased by seven times compared to the mortar without the steel wool mat. Durability studies [43,44] showed that the presence of steel wool in high-strength cementitious composites and conventional concrete limits crack openings and improves the self-healing capacity. However, to the best of our knowledge, the influence of steel wool on the bond between the steel fibers and a UHPC matrix and its effects on the mechanical and rheological properties of steel fiber-reinforced UHPC have not been investigated so far.

3. Details of experiments

3.1. Materials and mix proportions

The ingredient materials of the UHPC matrix used in this research are Type I cement (ASTM C150 [45]), microsilica (also called silica fume), slag (full name is ground granulated blast furnace slag), manufactured sand, polycarboxylate ether (PCE)-based high-range water-reducing

Fig. 2. Steel wool particles.

Fig. 3. Particle size distribution of steel wool fibers.

admixture (HRWRA), and tap water. Due to its ultra-fine particle size and high amorphous silica content, microsilica is used as a supplementary cementitious material (SCM) in almost all the UHPC mixtures in the literature. Undensified microsilica [46] used in this research has a silica content greater than 95.5% by weight and free carbon less than 1% by weight. Grade 100 slag conforming to ASTM C989 [47] is used as another SCM in this UHPC matrix due to its favorable effects on mixture rheology and mechanical properties. Blaine fineness of this slag is about 4600 cm²/g, and the amount retained on the ASTM sieve #325 (45 μm) is 0.7%. Washed manufactured sand with median and nominal maximum particle sizes of 0.4 mm and 3.5 mm, respectively, was used in this study. Specific gravities of cement, microsilica, slag, sand, and HRWRA were 3.15, 2.20, 2.95, 2.56, and 1.2, respectively. The particle size distributions of all the solid ingredients of the UHPC matrix are presented in Fig. 4.

For the macro-scale research on the influence of steel wool content on the composite properties, five UHPC mixtures with varying steel wool content were prepared in this study. The mix proportions, relative to the weight of cement, of these five mixtures are given in Table 1. The name of each mixture is formatted as SW-X, where 'X' is the volume fraction of steel wool in the mixture. In all the mixtures, the matrix composition and the steel fiber content were kept constant. Steel fibers with hooked ends [48] were used in these composite mixtures at a volume fraction of 2%, and their dimensions and mechanical properties are given in Table 2. In addition to the hooked steel fibers, straight and twisted steel fibers were also investigated in the single fiber pullout tests described below, but only hooked steel fibers were used in the composite mixtures.

For micro-scale research investigating the influence of steel wool content on the bond between steel fibers and the UHPC matrix, three

Fig. 4. Particle size distributions of solid ingredients of UHPC matrix.

different types of steel fibers were selected: (a) hooked steel fibers [48], (b) straight (smooth brass-coated) steel fibers [49], and (c) twisted steel fibers [50]. Samples of these fibers are shown in Fig. 5. The dimensions and mechanical properties of all the three fibers are presented in Table 2. While only the frictional bond governs the pullout process in the straight fibers, additional mechanical anchorage and frictional bond are generated in the hooked and twisted steel fibers. The purpose of investigating these three types of steel fibers was to compare the effect of steel wool on the fiber-matrix bond with other strategies (i.e., provision of hooks or twists in the fibers).

3.2. Mixing procedure

The mixing timeline is shown in Fig. 6. All the mixtures were prepared by using a planetary floor mixer of 28.4 L capacity. First, the dry ingredients of UHPC listed in Table 1, excluding steel wool and fibers, were mixed at a paddle speed of 60 rpm for 3 min. Water and HRWRA were added and mixed for another 3 min at paddle speed of 60 rpm. The paddle speed was then increased to 120 rpm for 2 additional minutes. Steel wool was then added and mixed with the rest of the ingredients at paddle speed of 60 rpm for 3 min. The steel wool was considered a part of the UHPC "matrix" in this study as it was expected to affect the matrix rheological properties (especially viscosity), which in turn, affected the fiber distribution. With the help of an assistant, the casting of the matrix and single fiber pullout specimens (Section 3.4) and the measurement of rheological properties (Section 3.3) were performed simultaneously. The mixing was resumed after approximately 5 min and the hooked steel fibers were added gradually and mixed at a paddle speed of 60 rpm for 3 min. Thus, the overall mixing time for the matrix was approximately 11 min, and that for the composite was approximately 19 min.

3.3. Procedures for characterizing fresh properties

The flow diameter, a measure of workability, of each matrix (including steel wool) was determined according to the flow test procedure given in ASTM C1437 [51] (without drops) using the apparatus described in ASTM C230 [52]. The diameter of the base of the conical mold used for this test was 100 mm, and therefore, the flow diameter (in mm) is equal to the magnitude of the percent flow.

A rotational rheometer [53] specifically designed for mortars and cement pastes was used to determine the rheological properties, especially viscosity, of the matrix (including steel wool). For this purpose, a sample of approximately 370 ml of the fresh matrix was placed in a cylindrical container. Then, a mortar probe was rotated inside the container at varying rotational speeds (ω), and the corresponding torque

Table 1

Mix proportions (relative to the weight of cement).

Mixture No.	Cement	Micro-silica	Slag	Sand	w/cm ^a	HRWRA	Steel Wool	Hooked Fibers
SW-0	1	0.3	0.6	1.72	0.21	0.029	0	0.28
SW-0.5	1	0.3	0.6	1.72	0.21	0.029	0.07	0.28
SW-1.0	1	0.3	0.6	1.72	0.21	0.029	0.14	0.28
SW-1.5	1	0.3	0.6	1.72	0.21	0.029	0.21	0.28
SW-2.0	1	0.3	0.6	1.72	0.21	0.029	0.28	0.28

^a w/cm – ratio of weight of water to weight of cementitious material.**Table 2**

Dimensions and mechanical properties of steel fibers (provided by the manufacturer).

Fiber Type	Diameter (d _f) mm	Length (L _f) mm	Nominal Strength MPa	Young's Modulus (E _f) GPa	Specific Gravity
Hooked [48]	0.55	30	1345	210	7.8
Straight [49]	0.20	13	2750	200	7.8
Twisted [50]	0.50	13	1700	210	7.8

(T) applied on the probe was recorded. While T and ω can be converted into shear stress (τ) and shear strain rate ($\dot{\gamma}$), we did not do so as the applicability of the conversion factors specified by the rheometer manufacturer (for moderate strength mortars) could not be verified for the UHPC class of materials. Furthermore, only relative values (rather than absolute values) of fresh properties were of interest in this study. Therefore, an alternative form of the Bingham plastic model [54], as defined in Equation (1), was used in this research. Here, yield torque (T_y) is a measure of yield stress, and slope (S) of the T- ω plot is a measure of plastic viscosity. In this study, ω was linearly increased from 0 to 125 rpm in 2 min and then linearly reduced to 0 rpm over the next 2 min. The same cycle was repeated over the next 4 min. The first cycle of this rheometry protocol can be relatively unstable and is typically not used in

calculations. The rheological parameters, T_y and S, were determined from the best-fit line for the T- ω plot of the second cycle of this experiment.

$$T = T_y + S\omega \quad (1)$$

3.4. Specimens and curing procedure

The test matrix in Table 3 shows the number and type of *macro-scale* specimens cast for each mixture listed in Table 1. Here, “matrix” includes steel wool but not steel fibers. For each mixture, (1) three matrix cubes and three composite cubes of size 51 mm × 51 mm × 51 mm were cast to measure the compressive strength, (2) three matrix beams and three composite beams of length 304.8 mm, height 76.2 mm, and width 38.1 mm were cast for determining the modulus of rupture (MOR) using four-point flexure setup, and (3) four matrix beams of the same dimensions as those used for MOR were cast for measuring the matrix fracture toughness using ASTM E399 procedure [55].

Twenty sets (five different matrices and four types of fibers) of single fiber pullout specimens were prepared by embedding individual fibers in the matrix of each of the five mixtures in Table 1. The following four types of fibers were used in the single fiber pullout specimens: (1) hooked steel fibers with hooks intact, (2) hooked steel fibers with hooks cut-off, (3) straight steel fibers, and (4) twisted steel fibers. Eight specimens with the same fiber-matrix combination were cast in each set of specimens; however, as discussed in the results, not all the specimens

Fig. 5. Fiber samples of (a) hooked fibers, (b) straight fibers, and (c) twisted fibers. **Fig. 6.** Mixing timeline.

Table 3

Macro-scale test matrix for each UHPC mixture.

Material	Uniaxial compression	Four-point flexure	Fracture toughness
Matrix (includes steel wool)	3 cubes (51 mm) ³	3 beams (304.8 × 76.2 × 38.1 mm ³)	4 notched beams (304.8 × 76.2 × 38.1 mm ³)
Composite (matrix + steel fibers)	3 cubes (51 mm) ³	3 beams (304.8 × 76.2 × 38.1 mm ³)	Not applicable

could be tested due to premature pullout or breakage of the fiber prior to testing during specimen handling.

The purpose of casting single fiber pullout specimens with hooks cut-off is to isolate the contribution of the frictional bond and the mechanical anchorage provided by the hooked ends. The end of one of the steel fibers with its hook cut-off is shown in Fig. 7(a). A slight button-shaped deformation is visible at the fiber end as a result of cutting. Such deformations might provide additional anchorage and defeat the purpose of cutting the hooks. Therefore, the end deformations were removed by sanding as shown in Fig. 7(b). All the steel fibers were cleaned with denatured alcohol to remove the water-soluble glue (present only in hooked steel fibers) and other impurities on the surface before the casting of the single fiber pullout specimens.

The dimensions of a single fiber pullout specimen and the mold are presented in Fig. 8. The geometry of the specimen was similar to that used in Alwan et al. [20]. The cross section of the specimen was 12.5 mm (thickness) × 25 mm (width) at the plane where the fiber exits the matrix. For casting the specimen, a fiber with a certain embedment length (L_e) was placed at the center of the mold as shown in Fig. 8 and clamped down by the fiber clamping plate. The UHPC matrix was then poured into the mold around the fiber. In this arrangement, either two separate fibers or a long single fiber could be clamped at the center to produce two single fiber pullout specimens on either side. The embedment lengths (L_e) for hooked fiber (with hook or hook cut-off), twisted fiber, and straight fiber were approximately 12.5 mm, 6 mm, and 6 mm, respectively.

All the specimens (macro-scale and single fiber pullout specimens) were subjected to the same curing procedure. Right after casting, they were covered by wet paper towels and sealed with a plastic sheet to maintain a moist environment until demolding at 24 h. After demolding, the specimens were subjected to curing at high temperature. The specimens were cured in water at 90 °C for 4 days, then cured in air at 90 °C for 2 days. The specimens were tested at the age of 7 days since casting. The high temperature accelerates the hydration reactions and helps us to achieve the long-term compressive strength of the UHPC in only 7 days, which would otherwise require 56 days of curing at ambient temperature.

3.5. Procedures for characterizing mechanical properties

Uniaxial compression tests on the cube specimens were performed according to ASTM C109 [56] at a load rate of approximately 1350 N/sec. Prior to the compression tests, the load-bearing surfaces of the 51 mm cubes were smoothed by using a belt sander and checked to ensure that they were flat and parallel to each other. Additionally, lubricating oil was applied to reduce friction between the loading platens of the machine and specimen surface. The flexural behavior of the beams was measured by using a four-point flexure test setup similar to that given in ASTM C1609 [57]. The lower and upper spans of each beam were approximately 294 mm and 98 mm, respectively. The flexure

tests were conducted at a constant compressive displacement rate of 0.5 mm/min.

The matrix fracture toughness was determined by testing the notched beam specimens according to the provisions in ASTM E399 [55]. Although this standard is specified for determining fracture toughness of metals, it can be used for the highly brittle mortar materials investigated in this study, where the fracture process zone is small so that the Linear Elastic Fracture Mechanics assumptions are valid [58,59]. A sharp notch of approximately 30 mm in length (equal to about 40% of the beam depth) was made at the mid-span of the beam specimens. The notched beams were tested by using a three-point flexure setup as shown in Fig. 9. A constant compressive displacement rate of 1 μm/s was applied at mid-point of the beam for this experiment. The fracture toughness was evaluated according to ASTM E399 [55] based on the peak load and the exact depth of the notch measured for each specimen.

A single fiber pullout specimen and the test setup are shown in Fig. 10. These tests were conducted at two tensile displacement rates of 5 μm/s for the first 300 μm displacement and 10 μm/s thereafter (to limit experiment duration) by using a displacement controlled closed loop test system. A precision load cell with range of ±491 N was added in series with test setup to measure the pullout load. The displacement of the fiber relative to the matrix face was measured by using two potentiometers with a range of ±6.25 mm, mounted on either side of the specimen as shown in Fig. 10.

4. Results and discussion

4.1. Rheological properties

The variation of the observed flow diameter with the volume fraction of steel wool in the UHPC matrix is presented below in Fig. 11. The horizontal dashed line shows the base diameter of the conical mold used for the flow test. It can be observed that the flow diameter decreases steadily as the volume fraction of steel wool increases from 0 to 2%. As described in Section 2, steel wool particles have a high aspect ratio and surface area, which adsorbs some mix water and reduces lubrication in the matrix. Additionally, the fibrous nature of steel wool particles creates interlocking within the UHPC matrix. Both of these mechanisms explain the observed loss of flowability with increase in steel wool content in the UHPC matrix.

The flow curves (torque versus rotational velocity or $T-\omega$ plots) of the five UHPC matrices investigated in this study are given in Fig. 12. The equation of the best-fit straight line is also shown in each plot. Yield torque, T_y (measure of yield stress), and slope, S (measure of plastic viscosity), are deduced by comparing these equations with Equation (1) in Section 3.3. T_y and S for the base UHPC matrix with 0% steel wool volume, named T_{y0} and S_0 , are 3.9 N-mm and 0.33 N-mm/rpm, respectively. In Fig. 13, T_y/T_{y0} and S/S_0 are plotted against the volume fraction of steel wool in the UHPC matrix. The normalized yield torque (T_y/T_{y0}) increases with increase in steel wool content, which is consistent with

Fig. 7. Steel fiber end with hook cut-off.

Fig. 8. Single fiber pullout mold and cast specimen.

Fig. 9. Fracture toughness specimen and three-point flexure setup.

the corresponding decrease in flow mentioned above, as less flowable mixtures require greater initial torque for rotating the probe in the rheometer.

In Fig. 13, we observe that the normalized plastic viscosity (S/S_0) increases with increase in the steel wool content of the UHPC matrix. The SW-0 matrix possessed the least viscosity among the five mixtures. The plastic viscosity of the SW-1.5 matrix was about 1.7 times that of the SW-0 matrix. It is well known that the matrix viscosity strongly influences the fiber dispersion [60,61]. As a result, the distribution of steel fibers in the SW-1.5 composite beam specimen was slightly more homogeneous than that in the SW-0 composite beam specimen. In Fig. 14, we observe fewer fibers at the top and slight segregation of steel fibers toward the bottom of one of the SW-0 composite beam specimens. The distribution of fibers appears to be more homogeneous in the SW-1.5 specimen; however, it is difficult to distinguish between the steel fibers and steel wool. In order to reduce the influence of segregation on the MOR (and to have smooth surfaces for load application), all the beam specimens were rotated by 90° for the flexure tests.

4.2. Mechanical properties

4.2.1. Compressive strength

The average compressive strengths (after 7 days of accelerated curing described in Section 3.4) of the five UHPC mixtures investigated in this study are plotted against their respective volume fractions of steel wool in Fig. 15. As discussed in Section 3.4, the compressive strength was measured for the UHPC matrix (containing steel wool but not the hooked steel fibers) as well as the UHPC composite (containing steel wool and hooked steel fibers). Regardless of the steel wool content, the composites exhibited about 2–8% higher compressive strength than the corresponding matrices. This is because the fibers delay the initiation

and propagation of cracks, provide confinement against the transverse expansion of the specimen, and bridge the tensile splitting cracks. Other studies on UHPC have reported similar differences in matrix and composite compressive strengths [22,62,63].

The compressive strengths of both matrix and composite seem to increase with the steel wool content up to volume fraction of 1.5%. The compressive strengths of SW-1.5 matrix (147 MPa) and composite (159 MPa) are 19% and 22% greater than those of SW-0 matrix (124 MPa) and composite (130 MPa), respectively. The fibrous particles of steel wool bridge and stabilize the micro-cracks, which explains these increases. As the steel wool content is further increased to 2% by volume, the compressive strength slightly decreases. Compared to the SW-1.5 matrix, we observed a steep increase in viscosity and decrease in flowability for the SW-2.0 matrix (Fig. 13), which cause greater air entrapment, leading to reduction in the compressive strength. Thus, a steel wool volume fraction of 1.5% is optimal for achieving maximum compressive strength of this UHPC.

4.2.2. Modulus of rupture (MOR)

The MOR, or flexural strength, of the beam specimens obtained using four-point flexure tests are plotted against the steel wool volume fraction in Fig. 16(a). At all the steel wool contents, the UHPC composites exhibited about three times higher MOR than the corresponding matrices due to effective bridging of the flexural cracks by the hooked steel fibers. Even without steel wool, this UHPC (SW-0) exhibited a deflection hardening behavior with hooked steel fibers used at 2% volume fraction, as observed in Fig. 16(b). Similar to the compressive strength, the MOR of the UHPC matrix and composite increased with the steel wool content up to volume fraction of 1.5%. The MORs of the SW-1.5 matrix (7.3 MPa) and composite (23.7 MPa) are 66% and 62% greater than that of SW-0 matrix (4.4 MPa) and composite (14.6 MPa),

Fig. 10. Single fiber pullout experiment.

respectively. The MOR slightly decreased at steel wool volume fraction of 2%, despite the increase in the fiber-matrix frictional bond with increase in steel wool volume fraction from 1.5% to 2% as discussed in Section 4.3.1 below. This may have been caused by increased air voids due to the significantly greater viscosity and poor workability of the SW-2.0 matrix as discussed above. Thus, the steel wool volume fraction of 1.5% is optimal for achieving the maximum MOR of this UHPC.

The relative changes (relative to SW-0) in the mechanical properties of UHPC with increase in steel wool content are presented in Fig. 17. It can be observed that the relative changes in the MORs of the matrix and the composite are 3–4 times higher than the corresponding relative changes in the compressive strength at all volume fractions of steel wool. This indicates significant improvement in the tensile properties of UHPC due to the addition of steel wool. It is interesting to observe in Fig. 17 that the relative change in the MOR is approximately the same for the matrix and the composite at a given steel wool volume fraction. This observation points toward a harmonious interaction between steel fibers and steel wool. If the steel wool contributed only to bridging the matrix micro-cracks, the *relative* change in the composite MOR due to addition of steel wool would have been smaller than that in the matrix MOR. Hence, while the increase in the MOR of the UHPC matrix with the increase in steel wool content is attributable to the bridging of matrix micro-cracks by steel wool, the increase in the MOR of the UHPC composite is caused by bridging of the matrix micro-cracks as well as improved fiber-matrix bond with the addition of steel wool, which is

Fig. 11. Effect of steel wool content on workability of a UHPC matrix.

verified by the single fiber pullout test results discussed below.

4.2.3. Matrix fracture toughness

The fracture toughness results of UHPC matrices, containing varying steel wool volume fractions (but no steel fibers), are presented in Fig. 18. The matrix fracture toughness increases with steel wool content. The average fracture toughness of the SW-2.0 matrix ($0.8 \text{ MPa}\sqrt{\text{m}}$) is 1.8 times that of the SW-0 matrix ($0.45 \text{ MPa}\sqrt{\text{m}}$). The increase in fracture toughness is caused by the bridging of the matrix micro-cracks by steel wool. This is consistent with the observations in other studies. For instance, Banthia and Sheng [64] observed that the presence of micro-fibers (similar to steel wool) in cement-based composites leads to high fracture resistance. Fig. 19 shows a qualitative comparison between the tortuosity of the crack path in notched beams made of the SW-0 matrix and the SW-1.5 matrix. The crack propagation path in the beam of the SW-0 matrix is approximately a straight line joining the tip of the notch to the point of load application. However, due to crack-bridging by the steel wool particles, the crack path slightly deviates and propagates along the path of least resistance in some of the specimens made of the SW-1.5 matrix, as observed in Fig. 19.

4.3. Fiber-matrix bond

Before the presentation of the single fiber pullout test results, it is important to recognize the known differences in the bond mechanisms of the three steel fibers (straight, hooked, and twisted) investigated in this study. The bond mechanism for each type of fiber is schematically presented in Fig. 20. Frictional bond exists in the pullout of all the three types of fibers. In addition to the frictional bond, the pullout of an embedded hooked steel fiber is resisted by the formation of two plastic hinges (PH1 and PH2), as shown in Fig. 20 (b) [20]. As the embedded end of the fiber passes through these plastic hinges, the pullout force reduces due to deactivation of these two hinges one by one. The pullout of a twisted fiber is resisted by the frictional bond and the energy required for untwisting the fiber [65]. With this understanding of the bond mechanisms, the single fiber pullout test results and the influence of steel wool on the fiber-matrix bond are discussed below for each type of fiber.

Fig. 12. Flow curves for UHPC matrices with varying steel wool volume fraction.

Fig. 13. Effect of steel wool content on plastic viscosity and yield torque of a UHPC matrix.

4.3.1. Hooked fibers

As mentioned in Section 3.4, two types of specimens were prepared to characterize the hooked steel fiber pullout behavior. The first type of specimens contained hooked steel fibers with *hooks removed* (cut off) to determine the influence of steel wool only on the frictional bond of these fibers with the UHPC matrix. These fibers are henceforth called *hook-removed steel fibers* to distinguish them from the straight steel fibers discussed below. The second type of specimens contained hooked steel fibers with *intact hooks* to determine the influence of steel wool on the

Fig. 14. Effect of steel wool content on steel fiber distribution in UHPC beam specimens.

plastic hinge capacities and overall pullout behavior of the hooked steel fibers.

The results of the pullout of the hook-removed steel fibers from UHPC matrices, containing varying amount of steel wool, are presented in Fig. 21. In these plots, the y-axis is the pullout load and the x-axis is

Fig. 15. Effect of steel wool content on the compressive strength of UHPC matrix and composite.

(a) MOR of matrix and composite beam specimens

(b) Flexural stress-displacement curves of representative composite specimens

Fig. 16. Effect of steel wool content on the flexural behavior.

the slip, which is the displacement of a fiber relative to the matrix face. The embedded lengths of all the hook-removed steel fibers were in the range of 12.5 ± 0.5 mm. An average pullout curve is shown in each plot, which is obtained by taking the average of the pullout loads of all the individual curves in each plot. All the average pullout curves in Fig. 21 exhibit two stages: debonding and pullout, which have been well established in the existing literature. The pullout load on the fiber initially increases with slip (or relative displacement) as a debond zone propagates from the matrix face towards the embedded end of the fiber. After complete debonding of the fiber, the entire fiber gradually pulls out of the matrix resisted only by the frictional bond between the fiber and the matrix. There is no sudden drop in the pullout load after complete debonding (after peak load) in majority of the specimens, which

Fig. 17. Relative changes in the mechanical properties due to steel wool.

Fig. 18. Effect of steel wool content on matrix fracture toughness.

indicates the absence of a chemical bond. The fiber pullout load almost linearly reduces to zero as the slip approaches the embedment length (≈ 12.5 mm).

The variation of τ_0 with the volume fraction of steel is presented in Fig. 22. The fiber-matrix frictional bond (τ_0) is computed by using Equation (2) below, where P_{peak} is the peak pullout load at the end of debonding, d_f is the fiber diameter, and L_e is the initial embedment length of the fiber. Overall, τ_0 steadily increases with increase in the steel wool content. The maximum τ_0 of 9.4 MPa is observed for the fibers embedded in the SW-2.0 matrix containing 2% steel wool by volume. In comparison, τ_0 of 3.0 MPa is observed for the fibers embedded in the base UHPC matrix SW-0 with no steel wool. For reference, τ_0 is 3.7 MPa [19] between the same steel fiber and the matrix of a widely studied UHPC, Cor-Tuf, which has a compressive strength of about 200 MPa. Such significant improvement in the frictional bond observed in this study is explained by the micro-scale matrix reinforcement provided by the steel wool around the steel fiber, as discussed in the introduction.

$$\tau_0 = \frac{P_{peak}}{\pi d_f L_e} \quad (2)$$

The results of the pullout of hooked steel fibers from UHPC matrices containing varying amount of steel wool are presented in Fig. 23. The pullout curves of individual specimens and the average of these curves are shown in each plot of Fig. 23. Similar to the hook-removed steel fibers, the pullout load on hooked steel fibers increases with slip as a debond zone propagates toward the embedded end of the fiber. When the debond zone reaches the hook region, even a small amount of additional slippage requires overcoming the anchorage provided by the hooks. Additional force (or work) must be applied to plastically deform

Fig. 19. Qualitative comparison of crack path tortuosity in fracture toughness specimens.

Fig. 20. Pullout mechanism of various steel fibers: (a) straight fibers, (b) hooked fibers, and (c) twisted fibers.

the steel fiber as it passes through the bent region [20]. The pullout load reaches a peak value when the debond zone reaches the embedded end of the hooked fiber. Thus, the peak pullout load of a hooked steel fiber is the sum of the peak pullout load of a hook-removed steel fiber (provided by the frictional bond) with the same embedment length and the hook's pullout capacity (due to mechanical anchorage) [19]. After complete debonding, the entire hooked fiber begins to pull out of the matrix. The hook remains engaged until the fiber is entirely out of the bent region. A step-down in the pullout load is observable in each pullout curve in Fig. 23, which signifies the end of the contribution from the hook. Thereafter, the pullout load decays linearly with a constant slope (similar to the hook-removed fiber), as it is governed only by the frictional bond and the length of the fiber remaining inside the matrix, similar to the hook-removed steel fibers.

The pullout curves of the SW-2.0 specimens (with matrix containing 2% volume fraction of steel wool) are not presented in Fig. 23 because the fibers of these specimens broke during the pullout tests. The breaking load for a hooked steel fiber, based on the mechanical data

provided by the manufacturer, is 320 N. As observed in Fig. 23, the average peak pullout loads of hooked fibers embedded in the SW-1.5 matrix ($L_e \approx 12.5$ mm) reaches close to 320 N. The peak pullout load of a hooked fiber similarly embedded in the SW-2.0 matrix is expected to be greater than that in the SW-1.5 matrix due to the higher frictional bond observed for the hook-removed fibers above.

In Fig. 24, the peak pullout loads of hooked steel fibers, P_{peak} , are plotted against the steel wool volume fractions in the UHPC matrix. Each bar in Fig. 24 is divided into the load contribution from the frictional bond and the mechanical anchorage of the hook. For a given steel wool volume fraction, the mechanical anchorage contribution is obtained by subtracting the average P_{peak} of hook-removed steel fibers (deduced from Fig. 21) from the average P_{peak} of the hooked steel fibers of the same embedment length. It can be observed that the increase in steel wool content not only increases the frictional bond contribution, but also leads to increased mechanical anchorage of the hooks, thereby utilizing the fiber's strength more effectively. This may be explained by the reinforcement of the matrix surrounding the hook by the steel wool, which prevents microspalling and increases the mechanical anchorage. Similar mechanisms have been observed by other researchers when multi-scale reinforcement is used [14,29,62]. The average mechanical anchorage contribution to the peak pullout load reduces slightly (within the limits of experimental error) as the steel wool volume fraction is increased from 1% to 1.5%. Overall, the pullout load capacity of the hooked steel fiber increases significantly with increase in steel wool content due to the increase in frictional bond as well as mechanical anchorage.

The pullout behavior of a hooked fiber can be defined mathematically by using the analytical model by Ranade [19], which is based on the original model developed by Alwan et al. [20]. In this model, the pullout load contributions from frictional bond and mechanical anchorage are distinctly calculated for the five stages of pullout [19]. Table 4 presents a summary of all the micro-scale fiber-matrix interaction parameters, determined by best-fitting the mathematical model to the average observed fiber pullout curves of both the hooked and the hook-removed steel fibers for UHPC matrices with various steel wool contents. The physical significance and the meaning of these parameters are given in detail in Ranade [19].

As an example, the modeled pullout behaviors of the hook-removed and the hooked fibers embedded in the SW-1.0 matrix are compared with the experimentally observed average pullout curves in Fig. 25. In this figure, the modeled contribution of the hook's mechanical anchorage as a function of slip is shown using the curve named 'Model mech anchorage'. It can be observed that the analytical model captures the experimentally observed pullout curves satisfactorily for the fibers pulled out from the SW-1.0 matrix. Similarly, the modeled curves can be plotted for the pullout behavior of fibers embedded in the other matrices containing different volumes of steel wool by using the parameters given in Table 4.

The values in Table 4 are further used to generate empirical equations showing the variation of parameters τ_0 , P_1 , and P_2 with steel wool volume fraction as shown in Fig. 26. While the parameters β_1 , c_1 , and c_2

Fig. 21. Pullout behavior of the hook-removed steel fibers.
(The legend for plot (a) is applicable for other plots as well.).

Fig. 22. Effect of steel wool content of the frictional bond of hook-removed fibers.

do not change significantly with the steel wool volume fraction, an average value of 0.005 can be assumed for the parameter β_2 . The empirical equations in Fig. 26, along with the other parameters, can be used in the analytical model to predict the fiber pullout behavior at a given volume fraction of steel wool for this particular UHPC. Combined with a scale-linking model, this can be used in a design tool for determining the appropriate volume fraction of steel wool to achieve the target properties with the given matrix containing 2% by volume of

hooked steel fibers.

4.3.2. Straight and twisted fibers

The results of the pullout of the straight and the twisted steel fibers from UHPC matrices containing varying amount of steel wool are presented in Fig. 27 and Fig. 28, respectively. Since these fibers are only 13 mm long, the embedment lengths were in the range of 6 ± 1.5 mm for the straight fiber and 4.5 ± 1.5 mm for the twisted fiber. Due to the smaller length of these fibers (13 mm) compared to the hooked steel fiber (30 mm), the embedment length at the time of casting could not be controlled more precisely. The actual embedment lengths were determined after the pullout tests, and those values were used to calculate the frictional bond. The specimens with straight fibers embedded in the SW-2.0 matrix could not be tested. Due to the small length of the straight fiber, the gripping length (for pulling the fiber) is also small, and the necessary gripping force needed to pull the fiber could not be applied without breaking the fiber (due to pinching of the fiber at the grip).

Similar to the hooked fibers, the average pullout load capacity of the straight fibers increased with increase in steel wool content. The frictional bond, computed from the pullout capacity, of the straight fibers increased from 4.6 MPa for the UHPC matrix without steel wool to 11.4 MPa for the UHPC matrix containing 1.5% volume fraction of steel wool. Similarly, the pullout load of the twisted fibers also increased with increase in steel wool content. However, the specimens with steel wool content greater than 0.5% by volume could not be tested, as the fibers broke in the grip region (outside of the matrix). The average load capacity of the twisted fibers is 335 N per the manufacturer's specifications, which was reached by some of the specimens with 0.5% volume

Fig. 23. Results of pullout test on hooked fibers.
(The legend for plot (a) is applicable for other plots as well.).

Fig. 24. Effect of steel wool on total pullout loads and hook capacities.

Fig. 25. Comparison of experimental results and analytical model for pullout of hooked and hook-removed steel fibers from the SW-1.0 matrix.

Table 4
Fiber/matrix interaction properties of hooked steel fibers in various UHPC matrices.

UHPC matrix	Frictional bond (τ_0) (MPa)	Slip softening parameters		Hook pullout capacities (N)		Hinge softening parameters	
		β_1	β_2	P_2	P_1	c_1	c_2
SW-0	3.0	-0.07	0.006	52	19	-1.3	0.8
SW-0.5	4.3	-0.07	0.006	94	70	-1.3	0.8
SW-1.0	5.3	-0.07	0.004	148	80	-1.3	0.8
SW-1.5	7.9	-0.07	0.004	142	100	-1.3	0.8

fraction of steel wool, as observed in Fig. 28. As discussed before, the pullout force in twisted fibers is resisted by the combined effect of frictional bond and untwisting of the fiber, and it is difficult to isolate the contribution of the frictional bond to the pullout force. Other researchers [7] have used equivalent frictional bond based on pullout work (area under the pullout load-slip curve); however, we have not

Fig. 26. Empirical equations for fiber-matrix interfacial bond parameters.

Fig. 27. Pullout behavior of the straight steel fibers.
(The legend for plot (a) is applicable for other plots as well.).

Fig. 28. Pullout behavior of the twisted steel fibers.

used that approach in this study as the pullout curves for steel volume fractions greater than 0.5% could not be determined. Overall, increasing the steel wool content improved the frictional bond of the UHPC matrix with straight and twisted steel fibers.

4.3.3. Frictional bond comparison between straight and hooked fibers

The fiber-matrix frictional bonds for straight and hooked fibers are compared in Fig. 29. The frictional bond of the straight fibers with the UHPC matrix at a given steel wool content is greater than that of the hooked fibers (determined from hook-removed fibers). This can be attributed to the brass coating on the straight fibers, which is abraded by the surrounding UHPC matrix during pullout. The damaged coating jams the matrix tunnel and increases the frictional bond [65]. To verify this mechanism, surface observations of the brass-coated straight fibers and hooked fibers before and after pullout were performed by using a scanning electron microscope combined with energy dispersive spectroscopy (SEM/EDS). These observations are presented in Figs. 30 and 31. From Fig. 30, it can be observed that the extent of scratching of the brass-coated straight fibers progressively increases with the increase in steel wool content. Elemental identification, performed in the areas highlighted by red boxes in Fig. 30, shows that copper (Cu) and zinc (Zn) (constituents of the brass coating) reduce with the increase in steel wool volume. On the other hand, in Fig. 31, there is no significant additional scratching on the surface of the hooked fiber due to the pullout and the

Fig. 29. Effect of steel wool content on the fiber-matrix frictional bond.

elemental composition of the surface does not change significantly before and after pullout from the SW-1.5 matrix. This observation supports the higher frictional bond observed with the brass-coated straight steel fibers compared to the hooked steel fibers (without brass coating).

Fig. 30. SEM/EDS observations of brass-coated straight fibers (a) before pullout, (b) after pullout from the SW-0 matrix, and (c) after pullout from the SW-1.5 matrix.

Fig. 31. SEM/EDS observations of hooked fibers (a) before pullout, (b) after pullout from the SW-1.5 matrix.

5. Conclusions

The effects of adding steel wool on the mechanical and rheological properties of a steel fiber-reinforced UHPC were investigated experimentally in this study. For this purpose, five different volume fractions of steel wool, ranging from 0% to 2%, were added in a base UHPC mixture to prepare five distinct mixtures. At the macro-scale, the most significant effect of steel wool addition was the substantial increase in the modulus of rupture (MOR). Single fiber pullout tests were conducted to understand the micro-scale effects of steel wool and explain the macro-scale improvement of MOR. The following conclusions can be drawn from this study:

5.1. Macro-scale conclusions

1. Increase in the steel wool volume fraction from 0% to 1.5% of the UHPC matrix leads to about 65% increase in plastic viscosity, which enhances the dispersion of steel fibers and reduces their segregation. For the same change in the steel wool volume fraction from 0% to 1.5%, the flow diameter (measure of workability) of the UHPC matrix reduces from 330 mm to 248 mm with the HRWRA content held constant. While the plastic viscosity continues to increase further for steel wool volume fraction of 2%, such high viscosity combined with poor workability is detrimental to the mechanical properties of the UHPC.
2. The compressive strength of the UHPC increases with increase in steel wool content. Addition of 1.5% steel wool by volume in the UHPC containing 2% hooked steel fibers by volume leads to approximately 22% increase in its compressive strength. A similar relative change is observed in the compressive strength of the UHPC matrix without the steel fibers, which shows that the positive effect of steel wool on the UHPC's compressive strength is independent of the fibers. The fibrous particles of steel wool bridge and stabilize the matrix micro-cracks, which explains these increases in compressive strength.
3. Similar to compressive strength, the MOR of the UHPC increases with steel wool content but at a significantly faster rate. The MOR of the UHPC with or without steel fibers increases by approximately 65%. This indicates significant improvement in the tensile properties of the UHPC due to the inclusion of steel wool. While the increase in MOR of the UHPC matrix with the increase in steel wool content is attributable to the bridging of matrix micro-cracks by steel wool, the increase in the MOR of the UHPC composite is caused by the bridging of matrix micro-cracks as well as by the improved fiber-matrix bond with the addition of steel wool.
4. The fracture toughness of the UHPC matrix increases with steel wool content. The average fracture toughness of the UHPC matrix with 2% steel wool by volume is 1.8 times that of the same UHPC matrix without steel wool. There is a visible increase in the tortuosity of the crack path with the addition of steel wool in the UHPC matrix.

5.2. Micro-scale conclusions

5. Both the average frictional bond and the mechanical anchorage of hooked steel fibers embedded in the UHPC matrix were observed to increase significantly with increase in the steel wool content. The contributions of both the frictional bond and the mechanical anchorage to the peak pullout load of hooked fibers increased by approximately 170% when 1.5% steel wool by volume is added to the UHPC matrix. Steel wool is expected to bridge the micro-cracks in the matrix surrounding the hooked steel fibers, which leads to such significant improvement in the fiber-matrix interaction. Such significant increase in the fiber-matrix bond explains the corresponding improvement in the MOR of the UHPC.
6. Similar to the hooked steel fibers, the frictional bond of straight and twisted steel fibers with the UHPC matrix also increased significantly

with increase in steel wool content. Owing to the interaction of brass coating with the cementitious matrix, the frictional bond of the straight fibers was almost twice that of the hooked steel fibers with the cementitious matrix of the UHPC.

The fibers are the most expensive components of a UHPC. As the cost of steel wool is only 30–50% the cost of the steel fibers, this research can be used in the future to determine an optimum combination of steel wool and steel fibers that can make steel fiber-reinforced UHPC a more practical material by lowering its cost.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.cemconcomp.2019.103422>.

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14. ABSTRACT Steel fibers are typically used in ultra-high performance concretes (UHPC) to impart flexural ductility and increase fracture toughness. However, the mechanical properties of the steel fibers are underutilized in UHPC, as evidenced by the fact that most of the steel fibers pull out of a UHPC matrix largely undamaged during tensile or flexural tests. This research aims to improve the bond between steel fibers and a UHPC matrix by using steel wool. The underlying mechanism for fiber-matrix bond improvement is the reinforcement of the matrix tunnel, surrounding the steel fibers, by steel wool. Single fiber pullout tests were performed to quantify the effect of steel wool content in UHPC on the fiber-matrix bond. Microscopic observations of pulled-out fibers were used to investigate the fiber-matrix interface. Compared to the control UHPC mixture with no steel wool, significant improvement in the flexural behavior was observed in the UHPC mixtures with steel wool. Thus, the addition of steel wool in steel fiber-reinforced UHPC provides multi-scale reinforcement that leads to significant improvement in fiber-matrix bond and mechanical properties of UHPC.					
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