**NOTATIONS**

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| --- | --- |
| *a* | Shear span, mm; |
| *b* | Width of rectangular beam section, mm; |
| *d* | Effective depth, mm; |
| *db* | Steel bar diameter, mm; |
| *df* | Fibre diameter (wire diameter), mm; |
| *Es* | Young’s modulus of steel, GPa; |
| *fck* (or *f´c*) | Characteristic cylinder strength of concrete, MPa; |
| *fm* | Target mean cylinder strength of concrete, MPa; |
| *fu* | Ultimate stress of steel, MPa; |
| *fy* | Yield stress of steel, MPa; |
| *h* | Height of rectangular beam section, mm; |
| *lf* | Fibre length, mm; |
| *L* | Length of rectangular beam section, mm; |
| *Lc* | Clear span of beam, mm; |
| *Mu* | Ultimate moment-carrying capacity, kN.m; |
| *vfc* | Shear strength of SFRC beam without stirrups, MPa; |
| *vfc, exp* | Experimental shear strength of SFRC beam without stirrups, MPa, |
| *vfc, pre* | Predicted shear strength of SFRC beam without stirrups, MPa; |
| *Vf* | Fibre volume content; |
| *µ* | Average compressive strength of eight concrete specimens, MPa; |
| *ρ* | Longitudinal tension reinforcement ratio; |
| *σ* | Standard deviation; |

**1. INTRODUCTION**

Fibre Reinforced Concrete (FRC) is a cement-based composite material reinforced with discrete (usually randomly distributed) fibres as multi-directional and closely spaced reinforcement. After concrete cracks initiate, the contribution of the fibres start as crack growth arrestors transferring tensile stresses across the cracked sections which consequently leads to the enhancement of the post-cracking properties of concrete [1]. The bridging effect of steel fibres can generally prevent tensile cracking localisation and produce multiple cracks in Steel Fibre Reinforced Concrete (SFRC) members. Therefore, after the first cracking initiates (either diagonal shear or vertical flexural), the bridging role of steel fibres starts resulting in the improvement of stiffness and ductility of the members.

In the early days of SFRC, the fibres were mostly undeformed (straight). The crack bridging performance of such fibres directly depends on the physical and chemical adhesions between the fibres and the surrounding matrix (physicochemical bond) which are predominantly determined by the properties of the fibre-matrix interface and matrix packing density [2,3]. Findings of numerous studies indicate that mechanical anchorage in the deformed fibres effectively improves pullout resistance [3]. The mechanical bond properties are determined by the physical geometry of the fibre and the transverse tensile stress resistance of the matrix. The mechanical anchorage could be provided by deformation at the fibre ends, such as with flat-end and hooked-end fibres (which locally increases the mechanical bond), or deformation along the fibre length, such as in crimped or twisted fibres (which provides a mechanical bond along the fibres) [2,3]. Typical steel fibres are shown in **Fig. 1**.

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| **TYPES OF STEEL FIBRE** | **Straight Fibres**  **Physicochemical**  Adhesion  Friction |  | Surface Treatment (oil) |
|  |
| Smooth (round, flat, or of any section) |
|  |
| Etched, roughened surface |
|  |
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|  |
| **Deformed Fibres**  **Physicochemical and Mechanical**  Adhesion  Friction  Additional Friction | At the fibre end | Round with end paddles |
|  |
| Round with double anchorages |
|  |
| Round with end buttons |
|  |
| Round with hooked ends |
|  |
|  |  |
|  |
| Along the fibre | Crimped |
|  |
| Indented surface |
|  |
| Twisted |
|  |
| Spiral (not commercially available) |
|  |  |  |  |
| **Fig. 1.** Various types of steel fibre grouped according to their bond characteristics. | | | |

The existing steel fibres on the market (e.g. hooked-end fibre) possess slip-softening behaviour (i.e. after the peak load at the early stage of the pullout process, as the slip increases, the pullout load decreases) causing a continuous decay in the overall internal force transferred by the fibres across the cracked sections. It implies that the overall contribution of the fibres to the load-bearing capacity of SFRC members where wide cracks are expected is marginal [2-6]. It is mentioned that the twisted fibres demand restrictive requirements on the concrete composition in order to show slip-hardening response [3].

Extensive research has been conducted to investigate the contribution of steel fibres to the behaviour of SFRC beams [7-14]. Findings of the investigations support the employment of steel fibres as an alternative to the conventional shear reinforcement. However, the contribution of fibres to the flexural capacity of SFRC beams is marginal. As the deflection of SFRC members increase, the width of the flexural cracks (within the tension zones along the members) increase, especially after longitudinal tension reinforcement yields [10,11]. The continuous pullout process of the fibres (possessing slip-softening behaviour) as a result of crack opening leads to the progressive decay of residual tensile strength of the fibrous concrete section [12,13].

The idea of spiral fibres as reinforcement for concrete was first proposed by Xu et al. [15,16] followed by further investigations by Hao et al. [17,18]. The experimental tests on cubic and cylindrical concrete specimens reinforced with various spiral fibres under dynamic loads indicated that depending on the geometrical properties of the spiral, such a fibre could be a better option compared with the existing fibres on the market e.g. hooked-end fibre. The spiral fibres employed throughout the entire investigation were limited to 18 arbitrary configurations. Even though the fibres showed relatively favourable post-peak pullout response (slip-hardening), however for structural applications (with the presence of conventional reinforcement), the fibres could not effectively contribute to the load-bearing capacity of SFRC members as expected, mainly attributed to the poor efficiency of the fibres [6-20]. Hence, Hajsadeghi and Chin [20] conducted extensive parametric studies on the geometrical and material properties of spirally deformed steel fibres via fibre pullout Finite Element (FE) modelling and testing in order to engineer an efficient high-performing spiral fibre denoted as SD-9-1.45-0.4-40 [6,19,20].

This paper investigates the structural contribution of the engineered spirally deformed steel fibre to the load-bearing capacity of SFRC beams via an experimental testing programme. Findings of the research reveal that the spiral fibre effectively enhances the load-bearing capacity of SFRC beams and could be employed as partial/full replacement for conventional reinforcement.

**2. STRUCTURAL TESTING PROGRAMME**

The specimens consist of two categories of SFRC beams with the spirally deformed steel fibres, i.e. shear-critical and flexure-critical, which are designed such that the contribution of the fibre to the shear and flexural load-bearing capacity of the beams can be assessed individually. The dimensions of the beams, respectively width (*b*), height (*h*), and length (*L*), are 130 mm, 165 mm, and 1200 mm. The clear span (*Lc*) and effective depth of section (*d*) of all the beams are 1100 mm and 140 mm, respectively. Various experiment parameters including fibre volume content (*Vf*), concrete strength (*fck*), longitudinal tension reinforcement ratio (*ρ*), and shear span to effective depth (*a*/*d*) are considered in the programme. Moreover, Non-fibrous Reinforced Concrete (RC) beams, as well as a number of SFRC beams with commercially available steel fibres (hooked-end and crimped) are also tested for comparison purposes.

The beams are statically loaded in a displacement-controlled manner with the loading rate of 0.6 mm/min using a closed-loop control Universal Testing Machine (UTM) with the capacity of 300 kN [21,22].

**2.1. MATERIAL PROPERTIES**

**2.1.1. CONCRETE AND FIBRES**

Two different concrete mix designs with 42.5 type Portland cement [23] are used for both plain and fibrous concrete. The 28-day target cylinder strengths of concrete (*fm*) are 35 MPa and 45 MPa where Building Research Establishment [24] is selected for the mix designs. To increase the workability of fibrous concrete and also considering the consistency issue, superplasticizer with the amount of 1 per cent of the cement content is added to both types of the mixture, i.e. fibrous and non-fibrous. The dry composition per cubic metre of the mixes is presented in **Table 1**. To decrease the risk of balling of fibres and also further enhance the workability of concrete, a type of coarse aggregate which is 95 per cent finer than 10 mm is used. The fine and coarse aggregates conform to the requirements given in BS EN 12620 [25].

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| **Table 1**  Concrete mix design. | | | | | | |
| Target strength  (MPa) | Cement 1  (kg) | Water  (kg) | Superplasticizer 2  (kg) | | Fine aggregate 3  (kg) | Coarse aggregate 3  (kg) |
| *fm*=35 | 350.0 | 188.3 | 3.50 | | 880 | 988 |
| *fm*=45 | 423.1 | 188.3 | 4.25 | | 802 | 993 |
| 1 42.5 type Portland cement [23]  2 Sika ViscoCrete® 1200 series | | | | 3 Saturated Surface-Dry (SSD) condition  - | | |

The engineered spirally deformed steel fibre labelled as SD-9-1.45-0.4-40 has 9 turns (coils), the outer diameter of 1.45 mm, and wire diameter of 0.4 mm and it is 40 mm in length, as shown in **Fig. 2** [20]. The fibre material tensile strength is 1500 MPa. To compare the performance of the spiral fibre with that of the existing fibres available on the market, two types of fibres, i.e. hooked-end and crimped, as presented in **Fig. 2** are incorporated into this study where the ultimate tensile strength (*fu*) of the fibres are 1000 MPa and 1500 MPa, respectively.

In order to verify the suitability of the size of the standard cylinder (diameter of 150 mm and height of 300 mm) for obtaining realistic compression tests results from the fibrous cementitious matrices, trial experiments are conducted to determine the Representative Volume Element (RVE). Three different sizes of cylinder specimens (diameters of 150 mm, 200 mm, and 250 mm with heights two times of the corresponding diameters) are considered for the tests to provide suitable variations of the samples’ volumes for the comparison of the compression tests results.

|  |
| --- |
| 1.45  *lf* = 40 |
| **(a)** Spirally deformed fibre (SD-9-1.45-0.4-40), *df* = 0.40 mm |
| 4  6.7  32.4  6.7  2.1  *lf* = 50 |
| **(b)** Hooked-end fibre, *df* = 0.9 mm |
| 1.4  R 5  *lf* = 50 |
| **(c)** Crimped fibre, *df* = 0.9 mm |
| **Fig. 2.** Steel fibres (dimensions are in mm). |

For each concrete strength (**Table 1**) and cylinder size, eight specimens were cast and tested where the fibre content of concrete (*Vf*) is fixed at 0.5%. The results are presented in **Table 2** in which the concrete strengths are reported as *fck*=*μ*±2*σ* MPa where *μ* is the average strength and *σ* is the standard deviation. As evident from the table, in general, the compressive strength of fibrous concrete specimens and the corresponding standard deviations slightly decrease as the size of the cylinder specimens increases (for the same target concrete strength and fibre type). Considering the marginal variations of the average strengths and the corresponding standard deviations, it is deemed that the compression test results on standard cylinder specimens can properly reflect the mechanical properties of fibrous matrices.

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| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Table 2**  Size effect of cylinder concrete specimens on the compressive strength. | | | | | | | | | | |
| Dimensions | | 150 mm × 300 mm | | | 200 mm × 400 mm | | | 250 mm × 500 mm | | |
| Fibre type | | SD 1 | H 2 | C 3 | SD | H | C | SD | H | C |
| Target strength  (MPa) | *fm*=35 | 36.7±0.8 | 35.7±0.5 | 35.1±1.0 | 36.2±0.6 | 35.2±0.3 | 34.9±0.8 | 35.8±0.5 | 35.0±0.4 | 34.8±0.7 |
| *fm*=45 | 47.3±0.6 | 46.3±0.7 | 46.4±0.9 | 46.8±0.5 | 46.4±0.6 | 46.1±0.6 | 46.5±0.5 | 45.9±0.4 | 46.0±0.3 |
| 1 SD: Spirally deformed, 2 H: Hooked-end, 3 C: Crimped | | | | | | | | | | |

**2.1.2. CONVENTIONAL REINFORCEMENT**

Steel reinforcing bars with three different diameters (6 mm, 8 mm, and 10 mm) are used as the conventional steel reinforcement for the beam specimens. Tensile coupon tests as per ASTM E8/E8M - 13a [26] are performed on three samples for each category of steel bars where the material characteristics, i.e. Young’s modulus and yield and ultimate stresses, are calculated from the average stress-strain curves.

The average stress-strain relationships of the reinforcement are provided in **Fig. 3**. The material properties of steel bars are summarised in **Table 3**.

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|  |
| **Fig. 3.** Average coupon testing results of steel reinforcement bars. |

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| --- | --- | --- | --- |
| **Table 3**  Coupon test results of reinforcing bars. | | | |
| **Bar No.**  Diameter, *db* (mm) | Modulus of elasticity  *Es* (GPa) | Yield stress  *fy* (MPa) | Ultimate stress  *fu* (MPa) |
| 6 | 220 | 500 | 650 |
| 8 | 210 | 520 | 670 |
| 10 | 215 | 490 | 620 |

**3. CONTRIBUTION OF SPIRAL FIBRE TO SHEAR RESISTANCE**

To evaluate the effectiveness of the spiral fibre on the shear-bearing capacity of concrete beams, a testing programme was conducted on a number of shear-critical beam specimens where the influential factors including fibre volume content (*Vf*), concrete strength (*fck*), longitudinal tension reinforcement ratio (*ρ*), and shear span to effective depth (*a*/*d*) are considered as the experiment parameters [12-14]. All the specimens did not have shear links and the shear action is intended to be carried by the overall contribution of concrete, longitudinal reinforcement, and the fibres. The number and specifications of the specimens are summarised in **Table 4**.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Table 4**  Number and specifications of the shear-critical beams. | | | | | | |
| Fibre | *fm*  (MPa) | *ρ*  (%) | | *Vf*  (%) | *a*/*d*  (-) | No. of specimens |
| Spirally deformed | 35, 45 | 0.55 a, 0.86 b | | 0 c, 0.2, 0.35, 0.5, 0.65 d | 1.5, 3 | 36 |
| a 2 H 8 as longitudinal tension reinforcement  b 2 H 10 as longitudinal tension reinforcement | | | c Non-fibrous RC beams as the reference  d *fm*=35 MPa | | | |

The beams were labelled such that their specifications can be identified by the corresponding labels. For instance, SC-0.55-1.5-S-0.2-35 indicates that the beam was shear-critical, having a reinforcement ratio of 0.55%, which is tested with a shear span to the effective depth of 1.5. The remaining parts of the label indicate the matrix characteristics (concrete reinforced with the spirally deformed fibre, where the fibre content and target compressive strength of concrete are respectively 0.2% and 35 MPa). Also, SC-0.55-1.5-P-45 represents a shear-critical beam with a reinforcement ratio of 0.55% and plain concrete (non-fibrous) having a target compressive strength of 45 MPa.

The testing setup and the cross-section layouts of the beam specimens are shown in **Figs. 4(a)** and **4(b)**. The mid-span deflection is measured using a high-precision pair of LVDTs, mounted underneath the beams’ sides and the average result is considered as the mid-span deflection. The intended shear span is adjusted using moveable roller supports of the loading beam (see **Fig. 4(a)**). The closed-loop control UTM with a beam specimen is shown in **Fig. 4(c)**.

|  |  |  |
| --- | --- | --- |
| Loading beam  Anchorage reinforcement  Tension reinforcement  LVDT  260 mm / 680 mm  Roller support  Moveable rollers  1100 mm  1200 mm | | |
| **(a)** Test setup | | |
| 2 H 8 | 2 H 10 |
| SC-0.55 | SC-0.86 |
| **(b)** Reinforcement layouts | | |
|  | | |
| **(c)** Universal Testing Machine (300 kN) with the beam testing setup | | |
| **Fig. 4.** Shear-critical beams testing. | | |

The load-deflection response of the beams, non-fibrous and fibrous with the spiral fibre, is provided in **Figs. 5(a)** to **(h)** such that the contribution of the fibre and the effect of its dosage can be assessed clearly. Each part of the figure shows the responses of a reference beam (non-fibrous) and a set of fibrous beams having different fibre contents where all the beams have the same reinforcement ratio, shear span to effective depth, and compressive strength of concrete. The responses are smoothed in order to remove the graph’s noise.

As can be seen, the fibre effectively contributes to the enhancement of the ultimate load-bearing capacity and post-cracking characteristics of the beams which directly correlates with the fibre volume content. The shear capacity can be only determined for the beams that fail in shear which is equal to the half of the ultimate load-bearing capacity (for beams with flexural failure, half of the ultimate load-bearing capacity times shear span represents the flexural capacity). Contrary to the existing steel fibres on the market which generally improve the shear capacity of reinforced concrete members, not the flexural capacity, the high-performing spiral fibre remains intact even where the wide cracks exist resulting in the improvement of both shear and flexural capacities [6,12,18]. The inclusion of the spiral fibre in beams with no shear links (where the shear action is carried by the overall contribution of concrete, longitudinal reinforcement, and the fibres) enhances the stiffness of the members and leads to two distinguishable scenarios, as follows:

1- The reference beam (non-fibrous beam) fails in shear before it reaches its flexural capacity. The presence of the spiral steel fibre improves both shear and flexural capacities of beams enabling them to sustain greater loads. As the applied load on the beam increases, both shear and moment in the sections increase until one of them reaches its corresponding capacity (in the critical section) and consequently the beam fails (in shear or flexure). For instance, as seen in **Fig. 5(a)**, the fibrous beam SC-0.55-1.5-S-0.65-35 has a higher flexural capacity compared with its non-fibrous counterpart failed in shear (SC-0.55-1.5-P-35); however, it also fails in shear but at a higher load. Besides, as seen in **Fig. 5(c)**, the reference beam (SC-0.55-3-P-35) experiences shear mode of failure but its fibrous counterpart (SC-0.55-3-S-0.65-35) fails in flexure.

2- The reference beam (non-fibrous beam) fails in flexure before it reaches its shear capacity (mainly due to the low longitudinal reinforcement ratio). The inclusion of the spiral fibre improves both shear and flexural capacities and changes the mode of failure from flexure to shear (as seen in **Fig. 5(b)**).

Moreover, the fibres greatly improve the tension stiffening and residual strength of the matrix and consequently enhance the post-peak response of the beams. As seen in the figures, the reference beams with shear failure, suffer from sudden load drop following the peak load while in their fibrous counterparts, the load degrades at lower rates leading to a gradual and ductile failure.

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|  |
| **(a)** *fm*=35 MPa |
|  |
| **(b)** *fm*=45 MPa |
| **Fig. 5.** Response of shear-critical beams, *ρ*=0.55% and *a*/*d*=1.5. |

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| --- |
|  |
| **(c)** *fm*=35 MPa |
|  |
| **(d)** *fm*=45 MPa |
| **Fig. 5 (Continued).** Response of shear-critical beams, *ρ*=0.55% and *a*/*d*=3. |

|  |
| --- |
|  |
| **(e)** *fm*=35 MPa |
|  |
| **(f)** *fm*=45 MPa |
| **Fig. 5 (Continued).** Response of shear-critical beams, *ρ*=0.86% and *a*/*d*=1.5. |

|  |
| --- |
|  |
| **(g)** *fm*=35 MPa |
|  |
| **(h)** *fm*=45 MPa |
| **Fig. 5 (Continued).** Response of shear-critical beams, *ρ*=0.86% and *a*/*d*=3. |

The capacity of the beams and the corresponding failure modes are summarised in **Table 5** where the labels of specimens with flexural failure are bold.

The failure patterns for selected beams (*Vf*=0%, 0.5%, and 0.65%) are shown in **Figs. 6** and **7**. In general, the presence of high-performing spiral fibres change the cracking pattern from a single wide diagonal crack to closely spaced multiple diagonal cracks (as the bridging stress exceeds the concrete cracking stress) resulting in the enhancement of post-cracking characteristics (as seen in **Fig. 5**).

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Table 5**  Results of beams with no shear links. | | | | | | | | |
| Beam ID | *a*/*d* | *fck* | *Vf* | *ρ* | Failure mode | *vfc, exp* 1 (MPa) | *vfc, pre* 2  (MPa) | *vfc, pre* 3  (MPa) |
| SC-0.55-1.5-P-35 | 1.5 | 35.9 | 0 | 0.55 | Shear | 2.20 | - | 2.15 |
| SC-0.86-1.5-P-35 | 1.5 | 35.9 | 0 | 0.86 | Shear | 2.27 | - | 2.28 |
| SC-0.55-1.5-S-0.2-35 | 1.5 | 35.3 | 0.2 | 0.55 | Shear | 2.48 | 1.41 | 2.49 |
| SC-0.86-1.5-S-0.2-35 | 1.5 | 35.3 | 0.2 | 0.86 | Shear | 2.58 | 1.48 | 2.62 |
| SC-0.55-1.5-S-0.35-35 | 1.5 | 35.4 | 0.35 | 0.55 | Shear | 2.70 | 1.63 | 2.73 |
| SC-0.86-1.5-S-0.35-35 | 1.5 | 35.4 | 0.35 | 0.86 | Shear | 2.83 | 1.71 | 2.86 |
| SC-0.55-1.5-S-0.5-35 | 1.5 | 36.7 | 0.5 | 0.55 | Shear | 2.99 | 1.83 | 3.01 |
| SC-0.86-1.5-S-0.5-35 | 1.5 | 36.7 | 0.5 | 0.86 | Shear | 3.13 | 1.92 | 3.14 |
| SC-0.55-1.5-S-0.65-35 | 1.5 | 34.2 | 0.65 | 0.55 | Shear | 3.09 | 1.86 | 3.12 |
| SC-0.86-1.5-S-0.65-35 | 1.5 | 34.2 | 0.65 | 0.86 | Shear | 3.27 | 1.96 | 3.26 |
| **SC-0.55-1.5-P-45** | 1.5 | 46.0 | 0 | 0.55 | Flexure | - | - | 2.55 |
| SC-0.86-1.5-P-45 | 1.5 | 46.0 | 0 | 0.86 | Shear | 2.65 | - | 2.68 |
| **SC-0.55-1.5-S-0.2-45** | 1.5 | 46.5 | 0.2 | 0.55 | Flexure | - | 1.7 | 2.94 |
| SC-0.86-1.5-S-0.2-45 | 1.5 | 46.5 | 0.2 | 0.86 | Shear | 3.10 | 1.79 | 3.07 |
| SC-0.55-1.5-S-0.35-45 | 1.5 | 46.0 | 0.35 | 0.55 | Shear | 3.27 | 1.95 | 3.16 |
| SC-0.86-1.5-S-0.35-45 | 1.5 | 46.0 | 0.35 | 0.86 | Shear | 3.40 | 2.05 | 3.29 |
| SC-0.55-1.5-S-0.5-45 | 1.5 | 47.3 | 0.5 | 0.55 | Shear | 3.63 | 2.18 | 3.43 |
| SC-0.86-1.5-S-0.5-45 | 1.5 | 47.3 | 0.5 | 0.86 | Shear | 3.77 | 2.29 | 3.56 |
| SC-0.55-3-P-35 | 3 | 35.9 | 0 | 0.55 | Shear | 1.12 | - | 0.98 |
| SC-0.86-3-P-35 | 3 | 35.9 | 0 | 0.86 | Shear | 1.21 | - | 1.12 |
| SC-0.55-3-S-0.2-35 | 3 | 35.3 | 0.2 | 0.55 | Shear | 1.34 | 1.41 | 1.33 |
| SC-0.86-3-S-0.2-35 | 3 | 35.3 | 0.2 | 0.86 | Shear | 1.48 | 1.48 | 1.46 |
| SC-0.55-3-S-0.35-35 | 3 | 35.4 | 0.35 | 0.55 | Flexure-Shear | 1.53 | 1.63 | 1.57 |
| SC-0.86-3-S-0.35-35 | 3 | 35.4 | 0.35 | 0.86 | Shear | 1.71 | 1.71 | 1.7 |
| **SC-0.55-3-S-0.5-35** | 3 | 36.7 | 0.5 | 0.55 | Shear-Flexure | - | 1.83 | 1.85 |
| SC-0.86-3-S-0.5-35 | 3 | 36.7 | 0.5 | 0.86 | Shear | 2.00 | 1.92 | 1.98 |
| **SC-0.55-3-S-0.65-35** | 3 | 34.2 | 0.65 | 0.55 | Shear-Flexure | - | 1.86 | 1.96 |
| SC-0.86-3-S-0.65-35 | 3 | 34.2 | 0.65 | 0.86 | Shear | 2.10 | 1.96 | 2.09 |
| SC-0.55-3-P-45 | 3 | 46.0 | 0 | 0.55 | Flexure-Shear | 1.16 | - | 1.39 |
| SC-0.86-3-P-45 | 3 | 46.0 | 0 | 0.86 | Shear | 1.37 | - | 1.52 |
| **SC-0.55-3-S-0.2-45** | 3 | 46.5 | 0.2 | 0.55 | Flexure | - | 1.7 | 1.77 |
| SC-0.86-3-S-0.2-45 | 3 | 46.5 | 0.2 | 0.86 | Shear | 1.79 | 1.79 | 1.91 |
| **SC-0.55-3-S-0.35-45** | 3 | 46.0 | 0.35 | 0.55 | Flexure | - | 1.95 | 1.99 |
| SC-0.86-3-S-0.35-45 | 3 | 46.0 | 0.35 | 0.86 | Shear | 2.05 | 2.05 | 2.12 |
| **SC-0.55-3-S-0.5-45** | 3 | 47.3 | 0.5 | 0.55 | Flexure | - | 2.18 | 2.27 |
| SC-0.86-3-S-0.5-45 | 3 | 47.3 | 0.5 | 0.86 | Shear | 2.40 | 2.29 | 2.4 |
| 1 Experimental shear strength  2 Predicted shear strength using **Eq. (1)**  3 Predicted shear strength using **Eq. (2)** | | | | | | | | |

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| --- | --- |
|  |  |
| SC-0.55-1.5-P-35 | SC-0.86-1.5-P-35 |
|  |  |
| SC-0.55-1.5-P-45 | SC-0.86-1.5-P-45 |
|  |  |
| SC-0.55-3-P-35 | SC-0.86-3-P-35 |
|  |  |
| SC-0.55-3-P-45 | SC-0.86-3-P-45 |
| **Fig. 6.** Failure of non-fibrous RC beams without stirrups. | |

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| SC-0.55-1.5-S-0.5-35 | SC-0.86-1.5-S-0.5-35 |
|  |  |
| SC-0.55-1.5-S-0.65-35 | SC-0.86-1.5-S-0.65-35 |
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| SC-0.55-3-S-0.5-35 | SC-0.86-3-S-0.5-35 |
|  |  |
| SC-0.55-3-S-0.65-35 | SC-0.86-3-S-0.65-35 |
| **Fig. 7.** Failure of SFRC beams (with the spiral fibres) without stirrups. | |

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| SC-0.55-1.5-S-0.5-45 | SC-0.86-1.5-S-0.5-45 |
|  |  |
| SC-0.55-3-S-0.5-45 | SC-0.86-3-S-0.5-45 |
| **Fig. 7 (Continued).** Failure of SFRC beams (with the spiral fibres) without stirrups. | |

**Fig. 8** shows the scatter plots of the shear strength of the beams with shear and flexure-shear failures versus the experiment parameters including *a*/*d*, *fck*, *ρ*, and *Vf*.

The contribution of each parameter to the shear strength of the beams is discussed as follows:

1- Shear span to effective depth (*a*/*d*) is one of the most influential parameters on the shear strength of SFRC beams (*vfc*) as seen in **Fig. 8**. As *a*/*d* increases, *vfc* decreases drastically which is confirmed by the literature [14]. In an overall analysis, the results indicate that *vfc* of the SFRC beams decreases by 45% (from 2.96 MPa to 1.64 MPa) as *a*/*d* increases from 1.5 to 3. It is attributed to the arch action which is the transfer process of the compressive force through the path created along the loading points and the supports of the beams. As the shear span decreases, the arch action improves the shear strength.

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| **Fig. 8.** Contribution of the experiment parameters on the shear strength of SFRC beams. | |

2- Concrete effectively contributes to the shear capacity of SFRC beams, as the concrete compressive strength increases, shear strength increases [14]. From the test results, by increasing the target mean cylinder strength of concrete (*fm*) from 35 MPa to 45 MPa, *vfc* increases from 2.22 MPa to 2.6 MPa, on average.

3- The longitudinal tension reinforcement contributes to enhancing the shear strength of SFRC beams. As the tension reinforcement ratio (*ρ*) increases from 0.55% to 0.86%, *vfc* increases from 2.32 MPa to 2.40 MPa.

4- The fibres (as the crack growth arrestors) transfer tensile stresses across the cracked sections and improve the shear capacity of the beams. The addition of 0.5% the spiral fibres result in the shear strength increase from 1.71 MPa to 2.99 MPa, on average. As shown in **Table 5**, the addition of the spiral fibres enhance the load-bearing capacity (shear and flexural) of the beams and might change the failure mode from shear to flexure.

**3.1. EMPIRICAL SHEAR DESIGN EQUATION**

To identify the effect of the four experiment parameters (factors or independent variables), as well as their interactions on the shear strength of the beams (dependent variable), 24 Factorial Design is employed where each factor linearly varies between two values provided in **Table 6**, i.e. the lower and upper boundaries known as levels [14]. A 5% risk is considered as the *P*-value in the factorial design to reject the null hypothesis. The four experiment parameters, as well as all the possible combinations, comprise of two parameters (two-way interactions), three parameters (three-way interactions), and all the parameters (four-way interactions) are assessed in the study [27].

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| **Table 6**  Levels of factors for 24 factorial designs. | | |
| Experiment parameters (factors) | Lower boundary | Upper boundary |
| Shear span to effective depth (*a*/*d*) | 1.5 | 3 |
| Concrete compressive strength (*fck*)\* | 35 | 45 |
| Tension reinforcement ratio (*ρ*) | 0.55 | 0.86 |
| Fibre volume content (*Vf*) | 0.2 | 0.5 - 0.65 |
| \* Concrete strengths are rounded to the nearest target strength (35 MPa or 45 MPa) | | |

The results indicate that all the experiment parameters (*a*/*d*, *fck*, *ρ*, and *Vf*) greatly affect the shear strength where the shear span to effective depth has the highest effect with *P*-value and per cent contribution of 0 and 60, respectively. Besides, it is found that among all the possible combinations of the parameters (two-, three-, and four-way interactions), only *a*/*d* and *Vf* are highly interacting with each other having *P*-value and per cent contribution of 0.002 and 5.5, respectively (all the other interactions have *P*-values considerably greater than 0.05). Therefore, in addition to the main parameters affecting the shear strength (*vfc*), the interaction of *a*/*d* and *Vf* (the term *a*/*d* × *Vf*) needs to be considered in developing shear design equations to improve accuracy.

The Genetic Algorithm (GA) [28] as a robust optimisation tool is used in order to propose empirical shear design equations for SFRC beams with the spirally deformed steel fibre. The GA is employed on the obtained experimental database (capacity of beams with shear failure) as seen in **Table 5** to determine the coefficients and exponents of the considered general forms for the shear strength equations (**Eqs. (1)** and **(2)**). The first form of the equation (product form), i.e. **Eq. (1)**, is intended just for fibrous RC beams (*Vf*≠0) while the second one (multinomial form) is for both non-fibrous and fibrous RC beams. The coefficients and exponents of the equations are constrained to vary between -10 and 10. It is evident that consideration of the term (*a*/*d* × *Vf*) in the product form of the equation (**Eq. (1)**) is not necessary.





To initiate the iterative optimisation process using the GA, 1000 sets of the coefficients and exponents are randomly generated known as the initial populations where each set (combination) is a member of the population.

The mean absolute error (MAE) as the fitness function is employed to measure and score how close the predicted shear strengths (*vfc, pre*) are to the corresponding experimental strengths (*vfc, exp*). From the current population, 60% of the members which possess a lower MAE are chosen as elite and passed to the next population. Using crossover (combining pairs of members in the current population) and mutation (randomly changing the variables of individual members) techniques, the rest of the next generation (40%) is produced [28]. The iterative process (scoring members and producing new populations) is stopped manually when the target MAE is achieved. To this end, a GA code was written in MATLAB version 8.5.1 [27].

The proposed empirical shear design equations are **Eqs. (3)** and **(4)** which respectively result in MAEs of 6% and 5%.





The predicted shear strengths using **Eqs. (3)** and **(4)** are provided in **Table 5**. From the equations, *a*/*d* and *vfc, pre* have a negative correlation while as *fck*, *ρ*, and *Vf* increase, *vfc, pre* increases (positive correlation) which confirm findings of previous research [14].

**4. CONTRIBUTION OF SPIRAL FIBRE TO FLEXURAL RESISTANCE**

To examine the contribution of the spiral fibre to the overall flexural performance of SFRC members, a set of beams were designed, cast, and tested where two different target concrete strengths (*fm*) and longitudinal tension reinforcement ratios (*ρ*) are incorporated into the testing programme. The number and specifications of the specimens are summarised in **Table 7**. The specimens are labelled as the shear-critical beams, except for the first part of the labels which is FC (indicative of flexure-critical behaviour) and the third part (*a*/*d*) which is omitted. The testing setup and the reinforcement arrangements of the beam specimens are shown in **Fig. 9**. Adequate shear reinforcement is provided for all the beams to ensure the failure mode of flexure (see **Fig. 9**). The shear span (*a*) is set to be 300 mm.

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| **Table 7**  Number and specifications of the flexure-critical beams with the spiral fibre. | | | | |
| Fibre | *fm*  (MPa) | *ρ*  (%) | *Vf*  (%) | No. of specimens |
| Spirally deformed | 35, 45 | 0.31 a, 0.55 b | 0.5 | 8 |
| a 2 H 6 as longitudinal reinforcement  b 2 H 8 as longitudinal reinforcement | | | | |

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| --- | --- | --- | --- |
| 500 mm  Roller support  Loading beam  Anchorage reinforcement  Tension reinforcement  12 H 6 @ 100 mm  Moveable rollers  LVDT  1100 mm  1200 mm | | | |
| **(a)** Test setup | | | |
| 2 H 6 | 2 H 8 | |
| FC-0.31 | | FC-0.55 | |
| **(b)** Reinforcement layouts | | | |
| **Fig. 9.** Flexure-critical beams testing. | | | |

The load-deflection responses of the beams are shown in **Fig. 10**. The flexural capacity (*Mu*) of the non-fibrous beams reinforced with 0.31% and 0.55% longitudinal tension reinforcement are 4.67 kN.m and 7.48 kN.m (for *fm*=35 MPa) and 4.95 kN.m and 7.80 kN.m (for *fm*=45 MPa). The beams capacities are increased with the addition of 0.5% of the spiral steel fibre to 9.37 kN.m and 12.29 kN.m (for *fm*=35 MPa) and 10.24 kN.m and 13.33 kN.m (for *fm*=45 MPa). Besides, the addition of 0.5% of the spiral fibre improves the load-bearing capacity of the beams reinforced with 0.31% and 0.55% longitudinal reinforcement by 103% and 68%, on average.

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| **(a)** Non-fibrous concrete |
|  |
| **(b)** Fibrous concrete with the spirally deformed steel fibres |
| **Fig. 10.** Response of flexure-critical beams. |

As the depth of neutral axis at the critical section decreases, the tension zone height (depth of critical flexural crack) increases resulting in an increase in the number of fibres bridging the crack. On the other hand, from the section analysis, it is evident that at the plateau stage of the response of the beams, the depth of neutral axis has respectively a direct and an inverse correlation with reinforcement ratio and concrete strength. Therefore, the effectiveness of the fibres is more pronounced with the lower reinforcement ratio and higher concrete strength (*ρ*=0.31% and *fm*=45 MPa).

The failure patterns for selected beams (*fm*=45 MPa and *Vf*=0% and 0.5%) are shown in **Fig. 11**.

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|  |  |
| FC-0.31-P-45 | FC-0.55-P-45 |
|  |  |
| FC-0.31-S-0.5-45 | FC-0.55-S-0.5-45 |
| **Fig. 11.** Failure of flexure-critical beams. | |

**5. COMPARISON OF FIBRES’ PERFORMANCE**

In this section, the structural performance of the spirally deformed steel fibre and those available on the market (see **Fig. 2**) are compared. To this end, a set of shear-critical and flexure-critical beams with fibrous concrete containing hooked-end and crimped fibres are tested. The number and specifications of the beams are listed in **Table 8**.

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| **Table 8**  Number and specifications of the beams with commercially available fibres. | | | | | | |
| Beam type | Fibre | *fm*  (MPa) | *ρ*  (%) | *Vf*  (%) | *a*/*d*  (-) | No. of specimens |
| Shear-critical | Hooked-end  Crimped | 35 | 0.55, 0.86 | 0.5 | 1.5, 3 | 8 |
| Flexure-critical | Hooked-end  Crimped | 35 | 0.31, 0.55 | 0.5 | 2.14 | 4 |

The load-deflection response of the shear-critical beams is shown in **Fig. 12** where the response of the beams with the spiral fibre and non-fibrous beams is included for comparison purposes.

As expected, the addition of hooked-end and crimped fibres increases the shear capacity of the beams and also in some cases it can change the failure mode from shear to flexure. There is a negligible difference in the fibres’ performance (hooked-end and crimped fibres); however, the results indicate that hooked-end fibre possesses slightly higher performance. It could be attributable to the higher fibre count of hooked-end fibre versus crimped fibre due to their geometries.

The results of the shear-critical beams and shear capacity improvement relative to the capacity of the corresponding non-fibrous RC are summarised in **Table 9**. From the table, as the longitudinal reinforcement ratio increases, the fibres (hooked-end, crimped, and spiral) more effectively contribute to the load-bearing capacity of the beams (relative to their corresponding non-fibrous counterpart); however, the effect of fibre type decreases. As the reinforcement ratio increases, the critical shear crack width at the ultimate state decreases (due to the larger dowel action) which enhances the effectiveness of the fibres especially those having softening response. The failure patterns for selected beams are shown in **Fig. 13**.

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| **(a)** *a*/*d*=1.5 |
|  |
| **(b)** *a*/*d*=3 |
| **Fig. 12.** Response of shear-critical RC beams with various steel fibres. |

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| --- | --- | --- | --- |
| **Table 9**  Results summary of the shear-critical beams with various steel fibres. | | | |
| Beam ID | Failure mode | Capacity (kN) | Improvement (%) |
| SC-0.55-1.5-P-35 | Shear | 80.1 | - |
| SC-0.55-1.5-H-0.5-35 | Shear | 100.3 | 25 |
| SC-0.55-1.5-C-0.5-35 | Shear | 98.7 | 23 |
| SC-0.55-1.5-S-0.5-35 | Shear | 108.8 | 36 |
| SC-0.86-1.5-P-35 | Shear | 82.6 | - |
| SC-0.86-1.5-H-0.5-35 | Shear | 110.3 | 33 |
| SC-0.86-1.5-C-0.5-35 | Shear | 108.8 | 32 |
| SC-0.86-1.5-S-0.5-35 | Shear | 113.9 | 38 |
| SC-0.55-3-P-35 | Shear | 40.8 | - |
| SC-0.55-3-H-0.5-35 | **Flexure** | 49.5 | - |
| SC-0.55-3-C-0.5-35 | **Flexure** | 47.5 | - |
| SC-0.55-3-S-0.5-35 | **Flexure** | 58.8 | - |
| SC-0.86-3-P-35 | Shear | 44.0 | - |
| SC-0.86-3-H-0.5-35 | Shear | 71.3 | 62 |
| SC-0.86-3-C-0.5-35 | Shear | 69.9 | 59 |
| SC-0.86-3-S-0.5-35 | Shear | 72.8 | 65 |

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| --- | --- |
|  |  |
| SC-0.55-3-H-0.5-35 | SC-0.86-1.5-H-0.5-35 |
|  |  |
| SC-0.55-1.5-C-0.5-35 | SC-0.86-3-C-0.5-35 |
| **Fig. 13.** Failure of shear-critical RC beams with commercially available steel fibres. | |

The load-deflection curves of the flexure-critical beams with hooked-end and crimped steel fibres are shown in **Fig. 14**. The responses of the corresponding beams with the spiral steel fibre (beams having identical specifications except for the fibre type) and non-fibrous beams are included for comparison purposes.

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| **(a)** *ρ*=0.31% |
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| **(b)** *ρ*=0.55% |
| **Fig. 14.** Response of flexure-critical RC beams with various steel fibres. |

The flexural capacity of the SFRC beams and capacity improvement relative to the capacity of the corresponding non-fibrous RC beams are summarised in **Table 10**. As seen from the results, the addition of fibres enhances the capacity of the beams. Furthermore, there is no considerable difference between hooked-end and crimped fibres; however, the capacity enhancement is further pronounced for the spiral fibre due to the high-performing behaviour especially with the lower reinforcement ratio (*ρ*=0.31%).

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| **Table 10**  Results summary of the flexure-critical beams with various steel fibres. | | |
| Beam ID | Capacity (kN) | Improvement (%) |
| FC-0.31-P-35 | 31.1 | - |
| FC-0.31-H-0.5-35 | 41.3 | 33 |
| FC-0.31-C-0.5-35 | 38.9 | 25 |
| FC-0.31-S-0.5-35 | 62.5 | 100 |
| FC-0.55-P-35 | 49.8 | - |
| FC-0.55-H-0.5-35 | 65.0 | 31 |
| FC-0.55-C-0.5-35 | 62.3 | 25 |
| FC-0.55-S-0.5-35 | 81.9 | 65 |

The failure patterns of flexure-critical RC beams with commercially available fibres are shown in **Fig. 15**.

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| --- | --- |
|  |  |
| FC-0.31-H-0.5-35 | FC-0.55-H-0.5-35 |
|  |  |
| FC-0.31-C-0.5-35 | FC-0.55-C-0.5-35 |
| **Fig. 15.** Failure of flexure-critical RC beams with commercially available steel fibres. | |

**6. CONCLUSIONS**

A structural testing programme is performed to examine the contribution of the engineered spirally deformed steel fibre (SD-9-1.45-0.4-40) to the shear and flexural response of RC beams where based on the experimental database, shear design equations for RC beams with the spiral fibre are proposed. In the testing programme, a set of beams with hooked-end and crimped steel fibres (as the most widely used fibres on the market) is included for the comparison purposes.

Findings of the research reveal that the spiral fibre effectively enhances the load-bearing capacities of SFRC members (shear and flexural capacities) as hooked-end and crimped fibres. However, its contribution to flexural capacity at the ultimate state (where large deformations and wide cracks are expected) is more noticeable as compared with hooked-end and crimped fibres, owing to its slip-hardening characteristics.

Overall, the engineered fibre simultaneously and effectively enhances the shear and flexural capacities of the members; hence it can eliminate/reduce the demand for conventional reinforcement.

**REFERENCE**

[1] Brandt AM. Fibre Reinforced Cement-Based (FRC) Composites after over 40 Years of Development in Building and Civil Engineering. Compos Struct 2008; 86:3-9.

[2] Banthia N, Trottier JF. Concrete Reinforced with Deformed Steel Fibers, Part I: Bond-Slip Mechanisms. ACI Mater J 1994; 91-M43(5):435-446.

[3] Wille K, Naaman AE. Pullout Behavior of High-Strength Steel Fibers Embedded in Ultra High Performance Concrete. ACI Mater J 2012; 109-M46:479-488.

[4] Richardson AE, Coventry K, Landless S. Synthetic and steel fibres in concrete with regard to equal toughness. Struct Surv 2010; 28(5):355-369.

[5] Noghabai K. Beams of fibrous concrete in shear and bending: experiment and model. J Struct Eng-ASCE 2000; 126(2):243-251.

[6] Hajsadeghi M. Engineered Structural Fibres as Replacement for Traditional Reinforcements for Concrete (Ph.D. Dissertation). The University of Liverpool, School of Engineering; 2018.

[7] Mansur MA, Ong KCG, Paramasivam P. Shear Strength of Fibrous Concrete Beams without Stirrups. J Struct Eng-ASCE 1986; 112(9):2066-2079.

[8] Sharma AK. Shear Strength of Steel Fiber Reinforced Concrete Beams. J Am Concrete I (Journal Proceedings) 1986; 83(4):624-628.

[9] Ashour SA, Hasanain GS, Wafa FF. Shear Behavior of High-Strength Fiber-Reinforced Concrete Beams. ACI Struct J 1992; 89(2):176-184.

[10] Khuntia M, Stojadinovic B, Goel S. Shear Strength of Normal and High-Strength Fiber-Reinforced Concrete Beams without Stirrups. ACI Struct J 1999; 96(2):282-290.

[11] Kwak Y, Eberhard MO, Kim W, Kim J. Shear Strength of Steel Fiber-Reinforced Concrete Beams without Stirrups. ACI Struct J 2002; 99(4):530-538.

[12] Dupont D, Vandewalle L. Shear Capacity of Concrete Beams Containing Longitudinal Reinforcement and Steel Fibers. ACI Special Publication 2003; 216:79-94.

[13] Aoude H, Belghiti M, Cook WD, Mitchell D. Response of Steel Fiber-Reinforced Concrete Beams with and without Stirrups. ACI Struct J 2012; 109(3):359-368.

[14] Shahnewaz MD, Shahria Alam M. Improved Shear Equations for Steel Fiber-Reinforced Concrete Deep and Slender Beams. ACI Struct J 2014; 111-S71:851-871.

[15] Xu Z, Hao H, Li HN. Dynamic tensile behaviour of fibre reinforced concrete with spiral fibres. Mater Design 2012; 42:72-88.

[16] Xu Z, Hao H, Li HN. Experimental study of dynamic compressive properties of fibre reinforced concrete material with different fibres. Mater Design 2012; 33:42-55.

[17] Hao Y, Hao H. Dynamic compressive behaviour of spiral steel fibre reinforced concrete in split Hopkinson pressure bar tests. Constr Build Mater 2013; 48:521-532.

[18] Hao Y, Hao H. Pull-out Behaviour of Spiral-Shaped Steel Fibres from Normal-Strength Concrete Matrix. Constr Build Mater 2017; 139:34-44.

[19] Hajsadeghi M, Chin CS, Jones S. Development of a Generic Three-Dimensional Finite Element Fibre Pullout Model. Constr Build Mater 2018; 185:354-368.

[20] Hajsadeghi M, Chin CS. Geometrical and Material Optimisation of Deformed Steel Fibres: Spirally Deformed Fibres. Eng Struct 2019; 199:1-13.

[21] Adhikary SD, Li B, Fujikake K. Effects of High Loading Rate on Reinforced Concrete Beams (with Appendix). ACI Struct J 2014; 111(3):651-660.

[22] Kim W, Kim J, Kwak YK. Evaluation of Flexural Strength Prediction of Reinforced Concrete Beams with Steel Fibres. J. Struct. Integrity Maint 2016; 1(4):156-166.

[23] GB 175: Common Portland cement (2007). Chinese Standard Publication.

[24] Building Research Establishment: Design of normal concrete mixes (2nd Edition) (1997). BRE Press Publications.

[25] BS EN 12620: Aggregates for concrete (2013). British Standards (BS) Publication.

[26] ASTM E8/E8M - 13a: Standard Test Methods for Tension Testing of Metallic Materials (2013). West Conshohocken, PA, American Society for Testing and Materials (ASTM) International.

[27] MATLAB version 8.5.1. Natick, Massachusetts, the MathWorks Inc., 2015.

[28] Goldberg DE, Genetic Algorithms in Search, Optimization, and Machine Learning (1st Edition). Addison-Wesley Professional, USA, 1989.