BEHAVIOUR OF HYBRID STEEL FIBRE REINFORCED SELF COMPACTING CONCRETE USING INNOVATIVE HOOKED-END STEEL FIBRES UNDER TENSILE STRESS

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ABSTRACT.

The use of steel fibre hybridisation with different aspect ratios have been seen to enhance the pre and post cracking response of concrete, however the invention of new innovative macro hooked ends steel fibres with multiple hooks and increase in its linear length have been recently investigated. The results show that the new innovative macro hooked ends steel fibre with multiple hooks performed better than single hooked ends steel fibre with respect to material properties when used in self-compacting concrete. Therefore, the need to further investigate the performance of this new innovative macro (MAC) hooked ends steel fibre when combined with straight micro (MIC) steel fibre of the same aspect ratio in self-compacting concrete would be useful in the study of the stress-strain curve relationship of this composite material.

A laboratory investigation on two different conditions of steel fibre hybridisation using straight MIC steel fibre (Length 13mm and diameter 0.2mm) with two different types of hooked ends MAC steel fibres, Single (S1) and Double (M2) hook(s) at 0.75% and 1% fibre content respectively. These are optimised values from previous experiments (laboratory tests conducted using different macro steel fibres at 0.25%, 0.5%, 0.75% and 1% fibre content). The Uniaxial direct tension test method is used. The results show that steel fibre hybridisation decreased workability due to the influence of the micro steel fibre content irrespective of the hooked ends steel fibre type. The use of Single hook (S1) macro hooked end steel fibre in steel fibre hybridisation further improved the material properties (compressive strength, tensile strength and fracture energy) when compared to the use of only macro hooked end steel fibre. However a decrease in the fracture energy is observed when Double hooks M2 macro hooked end steel fibre is used. Although positive results are seen with respect to other properties.

Keywords: Single and double hooked ends steel fibres, Micro-steel fibre, Fracture energy, Tensile Strength, Compressive strength, Uniaxial tension test, Stress-strain relationship.

INTRODUCTION

The general behaviour of steel fibre reinforced concrete (SFRC) under loads produces a much higher post cracking residual strength than plain concrete due to the fibres bridging the cracks. This behaviour depends on the geometric characteristics and material properties of the fibre; and the properties of the concrete (Akcay and Tasdemir 2012; Baros et al 2013; Dupont 2003; Lofgren 2005; Sorelli 2006). The bridging efficiency of individual fibre largely depends on the fibre-matrix bond characteristics which contributes to the improvement in the mechanical properties of SFRC (Breitenbucher et al 2014). However, the use of short and long discrete steel fibres to control crack propagation (micro and macro cracks respectively) affects the mechanical behaviour of SFRC (Hannant 1978) and also increases the concrete tensile strength after macro-cracks are formed while they are pulled out. Markovic (2006) emphasised on a high ‘synergy’ when both short and long fibres are present, where short fibres are helping the long fibres to generate as high tensile stresses as possible thereby enabling a better tensile (softening) behaviour compared to concrete with one single type of fibre only. The influence of long steel fibres is significant in the post peak response part of the cracking process and increases both the fracture energy and ultimate tensile strength of the concrete (Akcay et al 2012). See Figure 1 for micro and macro fibres bridging micro and macro cracks respectively and Fig 2 illustrating the effect of steel fibre on the pre and post cracking behaviour of SFRC.

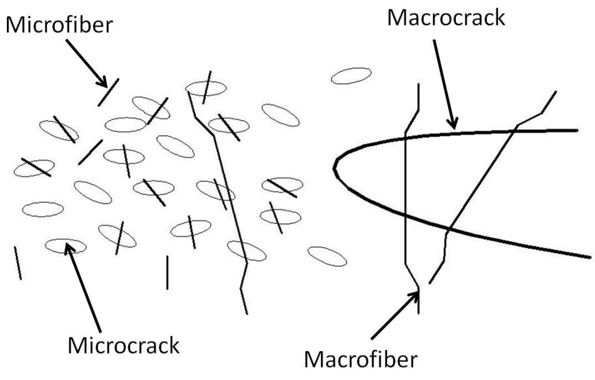


Figure 1: Micro and macro fibres bridging micro and macro cracks (Mo and Roberts, 2013)

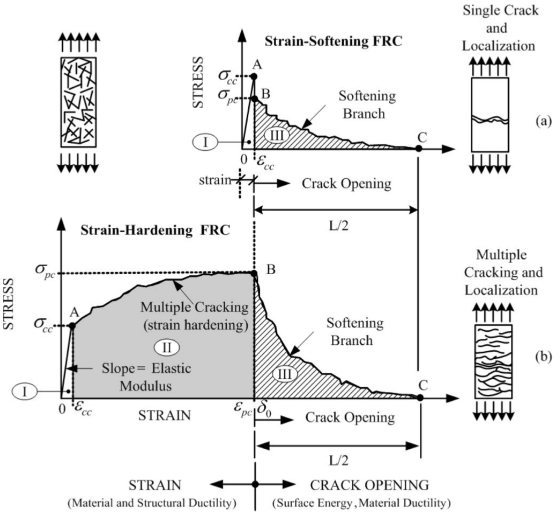


Figure 2: Effect of steel fibre on the pre and post cracking behaviour of SFRC (Naaman and Reinhardt, 1996)

Notwithstanding the improvement in the performance of SFRC with the inclusion of micro steel fibres which affects the fibre matrix bond characteristics, the influence of macro steel fibre geometry (straight, hooked, twisted, crimped etc.) presents different bond characteristics when used in concrete, hence alters the behaviour in both the pre and post cracking zone (Lok and Pei 1998).

The enhanced concrete performance in tension when single hooked end steel fibre is used compared to straight steel fibre geometrical characteristics cannot be over-emphasised as a result of the additional frictional force generated due to straightening of the hooks leading to higher frictional pull-out force (Breitenbucher et al 2014) in addition to the improvement in the matrix adhesion (Benaicha et al 2013). Its use and benefits in a composite concrete matrix in tension has been emphasised by (Markovic 2006); (Akcay et al 2012) with further enhancement of the mechanical properties. Most of these previous study (Markovic 2006); (Vandewalle 2007); (Jeenu et al 2007); (Akcay et al 2012); (Pajak and Ponikiewski 2013); (Dimas et al 2014), etc. undertaken on steel fibre hybridisation have focused on the use of macro hooked ends steel fibres with one hook and the aspect ratio different from that of the micro straight steel fibre, or both macro and micro steel fibres with aspect ratio lower than 40 which have produced enhancement in the mechanical properties. However, there is the need to investigate the effect of geometric characteristics of new innovative macro hooked end steel fibres with multiple hooks, increased linear length and increased tensile strength on the bridging efficiency, pull-out response and material properties scatter for structural applications. Hence this research investigation dwells on two conditions; a study of the effect of two different macro hooked end steel fibres (S1 and M2) with the same aspect ratio when used in a composite steel fibre self-compacting concrete matrix under uniaxial tension load.

EXPERIMENTS

This work follows on from the experimental investigation conducted by Okeh et al (2016) on the effect of new innovative hooked end steel fibres at 0%, 0.25%, 0.50%, 0.75% and 1.0% steel fibre content and for different hooked end shape and geometry. The results in the study show that M2 at 1.0% gave optimised performance in relation to mechanical properties under tensile load application. Hence the focus of this experimental programme is to further investigate if enhancement in the material properties can be obtained with M2 macro steel hooked end fibre in a composite steel fibre self-compacting concrete matrix with the same aspect ratio. Furthermore, S1 steel fibre type at 0.75% fibre content based on previous works such as Jeenu et al (2007) and Okeh et al (2016) will also be studied under the same condition. A number of parameters affecting the behaviour is investigated, such as proportion of macro to micro steel fibre content (100%:0%, 75%:25%, 50%:50%, 25%:75% and 0%:100% respectively) in relation to the type of macro hooked end steel fibres S1 and M2 at steel fibre content of 0.75% and 1% respectively. See Table 1 below. The effect of these parameters/variables on the material properties on these two conditions are carefully examined under the application of a tensile load.

Steel Fibre Content Ratio (MACRO:MICRO)%	S1 Type Fibre (0.75% total fibre volume)	M2 Type Fibre (1% total fibre volume)
100:0	S1A	M2A
75:25	S1B	M2B
50:50	S1C	M2C
25:75	S1D	M2D
0:100	S1E	M2E

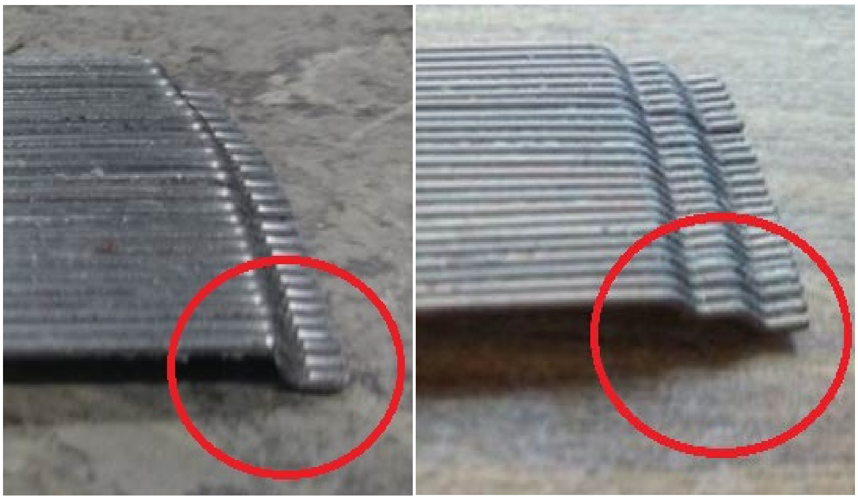
Table 1: Specimen Identification in relation to Steel fibre type and hybridisation ratio

Experimental programme

Material characteristics and specimen preparation

Figures 3, 4 and Table 2 give geometric and mechanical properties of the individual macro hooked end steel fibres and micro steel fibre used for the experiments. The admixture specified for the mix design is Fosroc Auracast .200 high range water reducing superplasticiser. Portland Cement CEM I 52.5R was used and the mix incorporated high cement content similar to (Okamura and Ouchi 2003) and (Pajak and Ponikiewski 2013) for self-compacting concrete (SCC). See Table 3 for material quantities. The fine aggregate composed of sea-won flint with no fraction of clay or fine silts and coarse aggregate composed of sea-won flint gravel, with maximum size of 6mm and 10mm respectively. The mix proportion content of the coarse and fine aggregates were fixed to achieve self-compatibility by altering only the superplasticiser and water-cement ratio dosage. The water/cement ratio of the concrete was 0.27 with 0.69% cement mass of superplasticiser admixture in order to obtain comparable rheological and mechanical parameters to that of (Okamura and Ouchi 2003) and (Pajak and Ponikiewski 2013).

Since the focus of this research is to investigate the effect of various hooked ends steel fibres within a composite self-compacting concrete matrix, no content of fly ash or silica fume was added to the mix design as emphasised by (Pajak and Ponikiewski 2013) to improve the strength of the concrete.



Type 1 (S1) Type 2 (M2)

Figure 3: Shape of hooked-end macro steel fibres (Manufactured by Bekaert 2012)

Figure 4: Micro steel fibre (Manufactured by Bekaert 2012)

Fibre Shape	Type	Length (mm)	Diameter (mm)	Aspect ratio	Effective Hooked-end Region Length (mm)	Depth of Hooked End Region (mm)	Tensile Strength (N/mm^2)	No of Fibres/kg	Young Modulus (N/mm^2)
Single Hooked end	**S1**	**60**	**0.90**	**65**	**5.66**	**3**	**1,160 (+/-7.5%)**	**3,183**	**210,000**
Double Hooked end	**M2**	**60**	**0.90**	**65**	**11.66**	**4**	**2,300 (+/-7.5%)**	**3,183**	**210,000**
Straight Micro-Fibre	**MIC**	**13**	**0.2**	**65**	**-**	**-**	**3,140**	**15,000**	**210,000**

Table 2: Geometry and properties of hooked end macro steel fibres (S1&M2) and micro steel fibre

Material	Quantity (Kg/ m^3)
Cement	**735**
Sand	**738**
Gravel	**761**
Water	**201**
Superplasticiser	**5**

Table 3: Self-compacting concrete mix design

Mixing procedure, manufacture and testing of specimens

All mixing operation during experimental work was carried out using a drum tilting mixer. The mixing procedure and time, started with 30 seconds wet mixing of coarse aggregate using 70% of measured water. Fine aggregate was added and allowed to mix for a further 1 minute. Cement was then added and mixing carried on for a further 2.5 minutes after which the remaining 30% of water containing superplasticiser was slowly added. Mixing continued for a further 4.5 minutes to allow the effect of the superplasticiser to kick-in followed by the addition of steel fibres (macro and/or micro) within 30 seconds after which a further 4 minutes mixing was allowed to ensure uniform dispersion of the steel fibres and to avoid a "balling effect" (Soutsos et al 2012). Total mixing time was 13 minutes. This procedure was adopted throughout the experimental programme.

The fluidity of the self-compacting concrete was measured with the use of a slump flow test in accordance with BS EN 12350-8:2010 testing procedures to determine the workability of all the mix.

30 dog bone shape specimens measuring 100mm x 100mm x 500mm in concrete plastic moulds with timber infills; and 30 number of 100mm^3 specimens in disposable polystyrene moulds were manufactured. A total of 3 specimens per each proportion of macro to micro steel fibre ratio was used in order to reduce experimental cost and labour to obtain average values. These values were used to describe the pre and post cracking behaviour of the innovative macro hooked end steel fibres (S1 and M2) in steel fibre hybridisation under a tension test method. It is proposed that the experimental data obtained will enable further parametric study by way of inverse analysis with the use of finite element numerical method in future study. The dog bone shape specimens manufactured were used for the uniaxial direct tension test (See Fig 5 below for test set up) while the cubes were used for density and compressive strength test. Specimens were demoulded after 24 hours and placed in a curing tank at

20◦C ± 2 for 28 days. The uniaxial direct tension test was carried out using a scissors grip tension test set up on a LOS Servo-hydraulic 1000 KN test machine that complies with CEN-EN-12390-4 National Research Council (CNR-DT 204/2006). The test was carried out under closed loop displacement control operation with a displacement rate of 0.5mm/minute using a linear variable displacement transducer (LVDT) to obtain displacement measurements for pre and post cracking stages.

Figure 5: Uniaxial direct tensile test set up with dog bone shape specimen

RESULTS AND DISCUSSION

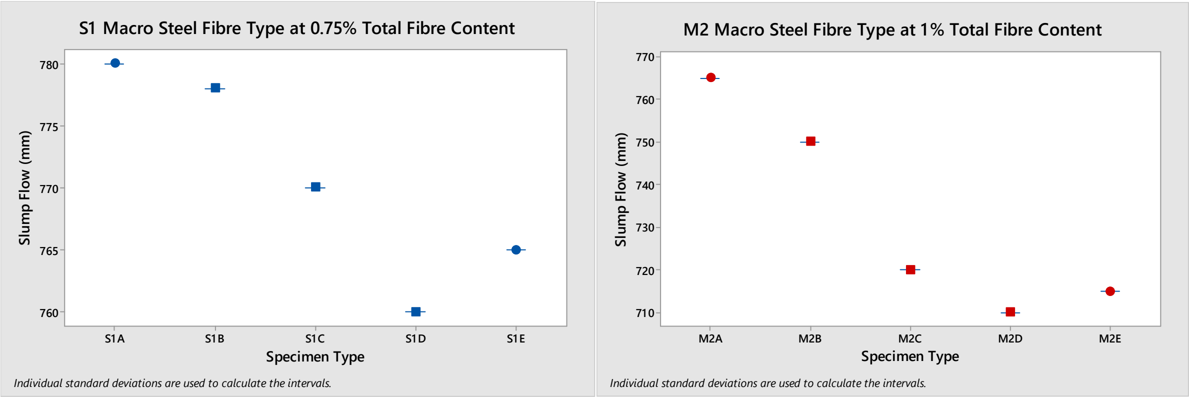
Test results were evaluated from the findings recorded on fresh and hardened properties as presented in this section. Discussions focus on workability, density, compressive strength, Stress-Strain relationship, tensile strength and fracture energy.

Workability

The measured values presented in Figure 6(a-b) for both conditions shows slump flow of steel fibre hybridisation using S1 type macro fibre at 0.75% total fibre content. These values are within the range of 760mm to 780mm in line with EFNARC 2005 recommendations (SP3) for vertical application in areas with high congestion of steel reinforcements. For example, in beam column joint which is to be the focus of future study. In the case of steel fibre hybridisation using M2 type macro steel fibre at 1% total fibre content, the slump flow falls within the range of 710mm to 750mm in line with EFNARC 2005 recommendations (SP2) for normal application in walls and columns but can still be used in vertical application in areas with high congestion of steel reinforcements where surface finish is not important but more control given to segregation resistance. The research findings and suggestions for applications mentioned above have followed EFNARC 2005 recommendations, however EFNARC 2005 recommendations are based on a plain concrete mix rather than a concrete mix that contains steel fibres. It is therefore recommended that further experimental evidence is needed to ascertain its passability criteria using an L-Box test before suggested applications above are considered.

Furthermore, Figure 6(a-b) results indicate that in both conditions, the use of micro steel fibre only in self-compacting concrete reduces the slump flow when compared to the use of only macro steel fibre thereby producing a less workable concrete. The decrease in the workability can be attributed to a change in the interfacial structure of the matrix (cement paste) around the aggregates in the wet state by the large amount of micro steel fibres and its high aspect ratio. This change is as a result of the large total surface area of the micro steel fibre resulting in increased adhesion and bonding between particles which limits the spread.

With respect to workability, the use of micro steel fibre in self-compacting concrete is seen to influence the result in steel fibre hybridisation with macro and micro steel fibres with the same aspect ratio. The results in Figure 6(a-b) also shows a decrease in the spread up to a maximum of 7% and 3% with steel fibre hybridisation when compared to the use of macro steel fibres M2 and S1 respectively indicating decrease in workability.

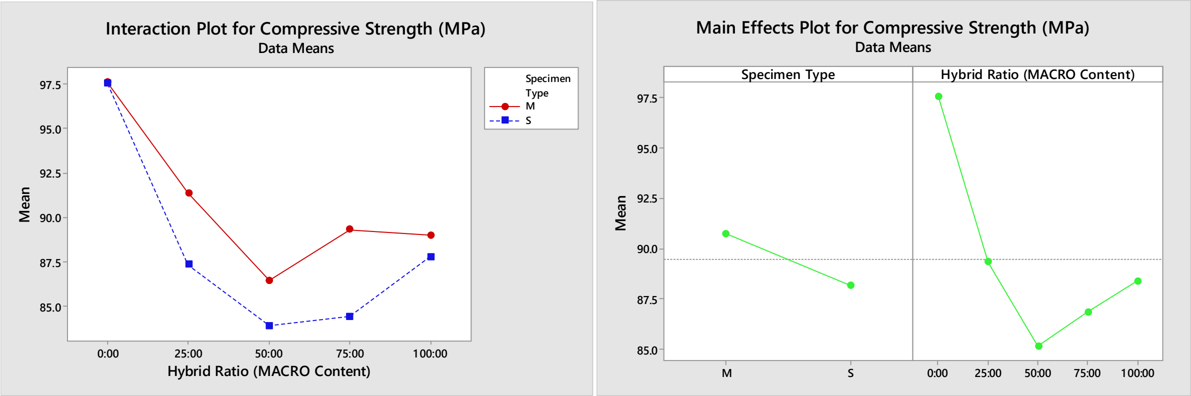


(a) (b)

Figure 6(a-b): Graphs of slump flow against specimen types with steel hybridisation ratios

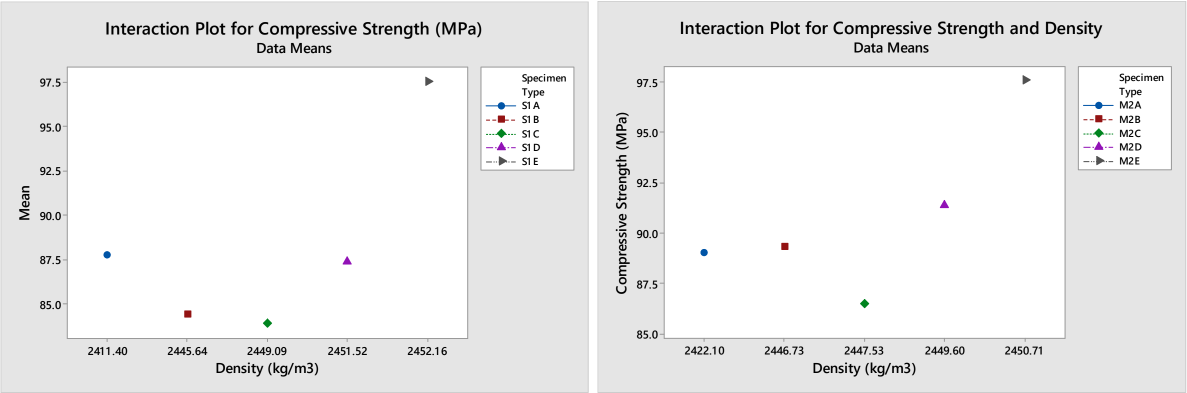
Density and Compressive Strength

Density and compressive strength test results have been derived using hardened cube specimens as described in BS EN 12390 (2009) – 7 & -3 respectively. The obtained results in both conditions are presented in Figure 7(a-d). The results show no benefit in the density and compressive strength with steel fibre hybridisation when compared to a non-hybrid matrix using macro steel fibre only. However the effects of steel fibre hybridisation show nearly similar trend in both conditions but higher compressive strengths are seen in specimen type M2.



(a) (b)

Figure 7(a-b): Graphs of compressive strength against specimen types and steel hybridisation ratios



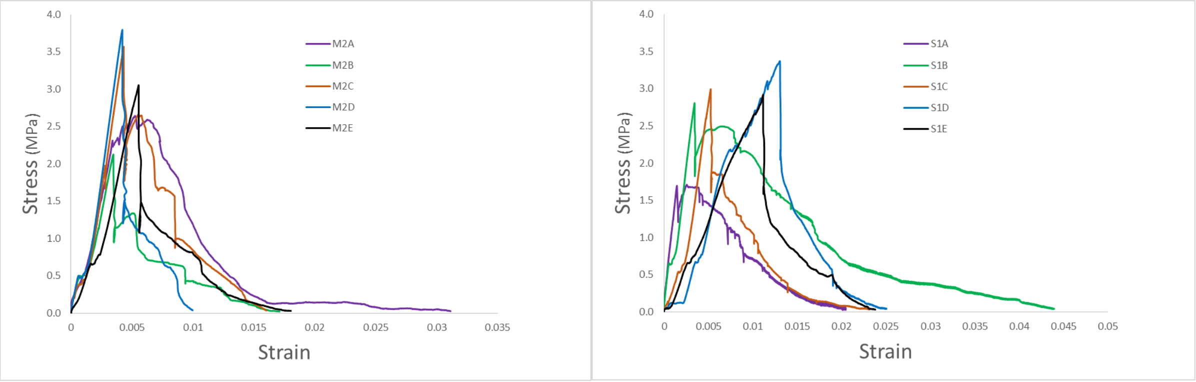
(c) (d)

Figure 7(c-d): Graphs of compressive strength against density and steel hybridisation ratios

Stress-Strain Curve

The force-displacement curve shown in Figure 8(a-b) gives the effect of steel fibre hybridisation using S1 and M2 macro hooked end steel fibres with straight micro steel fibre, aspect ratios of 65. The pre-cracking zone shows a linear relationship with an increase in the first crack load in both conditions when compared to 100% macro steel fibre content except for M2B. The increase in the first crack load with steel fibre hybridisation is due to the micro steel fibre preventing the formation of micro cracks under load in agreement with Markovic (2006) “synergy” effect in previous work.

Under M2 condition, a sudden drop in the load at first crack is observed followed by a lower residual stress depicting the inability of steel fibre hybridisation to exhibit hardening behaviour in the post cracking stage as observed with M2A. The cracking strain of M2B, M2C and M2D slightly increased as a result of the increase in first crack load observed. There have been an observable decrease in the residual stresses when compared to M2A (100% macro steel fibre type) which accounts for the decrease in fracture energy with M2B, M2C and M2D. Figure 8a indicates a bi-linear softening behaviour during stress degradation in the post cracking process for steel fibre hybridisation. Furthermore, the graph 8a also shows a reduction of the ultimate strain when comparing steel fibre hybridisation to 100% macro steel fibre content (M2A) between strain values of 0.01 to 0.017.
Under S1 condition, the ultimate strain increased when comparing steel fibre hybridisation to 100% macro steel fibre content (S1A) between strain values of 0.024 – 0.044. The low residual stresses observed after a sudden drop in the load at first crack depicts the inability of steel fibre hybridisation to exhibit hardening behaviour in the post cracking phase due to the reduced content of macro steel fibre. However, the increase in the first crack load, residual stresses and the ultimate strain accounts for the increase in fracture energy with S1B, S1C and S1D. The value of the residual stress and stiffness with S1B, S1C and S1D is affected by the ratio of macro steel fibre content, higher ratio show higher residual stress and stiffness. Figure 8b, indicates a bi-linear softening behaviour during plastic deformation in the post cracking stage.

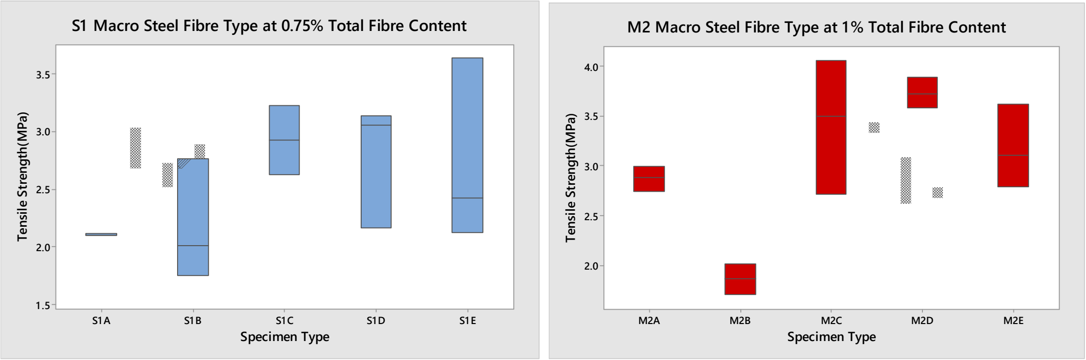


(a) (b)

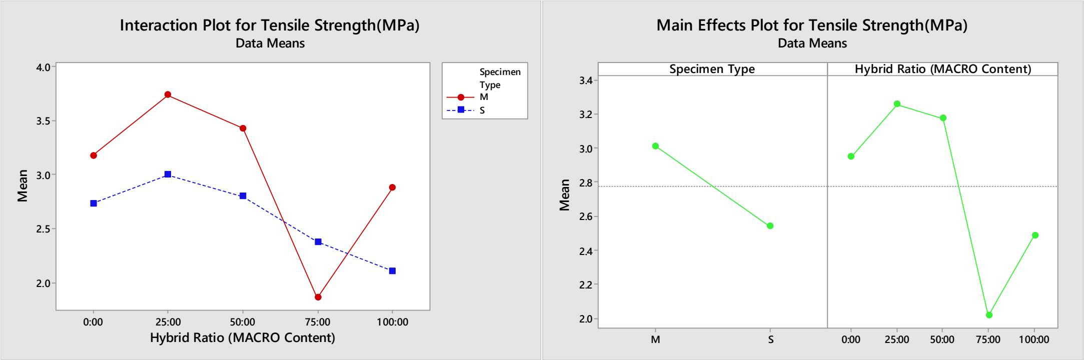
Figure 8(a-b): Stress –Strain curve for steel fibre hybridisation using M2 and S1 type macro hooked end steel fibre

Tensile strength

Figure 9(a-b) shows the tensile strength calculated from the failure load at first crack. The results indicate an increase in the tensile strength up to a maximum of 36% and 48% at initial crack propagation with steel fibre hybridisation for M2 and S1 macro steel fibre types respectively. The improvement in the tensile strength for both conditions (M2 and S1) with steel fibre hybridisation is observed at a macro-micro steel fibre ratio content of (0.25:0.75). Furthermore, Fig 9(a-b) indicate a significant difference in the means for M2 (P- Value = 0.001) and no significant difference for S1 (P-value = 0.245) with steel fibre hybridisation. The standard deviation was greater for S1 than for M2. Fig 9(c-d) show graphs of a statistical analysis which further confirm a significant effect of both specimen types (P-value = 0.009) and steel fibre hybridisation (P-value = 0.000). The effects of steel fibre hybridisation do not show a similar trend in both specimen types but higher values of tensile strengths are seen in specimen type M2 as macro steel fibre content decreases. The increase in the tensile strength with steel fibre hybridisation (same fibre aspect ratio) in both conditions is in agreement with Makorvic (2006) previous work (different fibre aspect ratio), that when both short and long fibres are present, there is a 'synergy', where short fibres help the long fibres to generate as high tensile stresses as possible compared to concrete with one single type of fibre only. The increase in micro steel fibre content contributes in preventing micro-cracks (Akcay et al 2012) especially between the interface of mortar and coarse aggregate (Benaicha et al 2013) which is generally present in self-compacting concrete. However, the increase in the tensile strength observed in this experiment for both conditions can also be attributed to the improved adhesion, bond interface characteristics between the micro steel fibre and the cement paste in relation to the maximum aggregate size in preventing micro crack formation.



(a) (b)

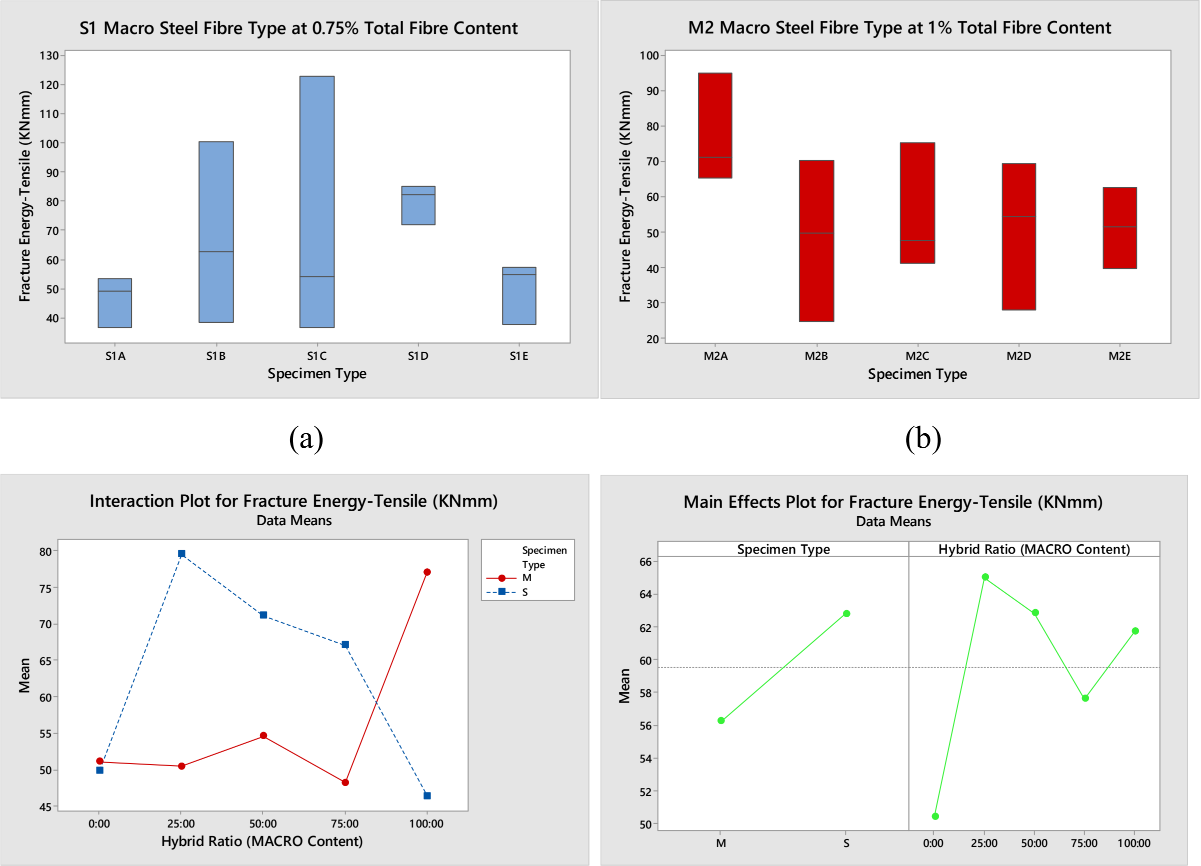


(c) (d)

Figure 9(a-d): Graphs of tensile strength against specimen types with steel hybridisation ratios

Fracture energy

- The fracture energy has been calculated from the area under the stress-strain curve. The results obtained in both condition as shown in Figure 10(a-b) indicate that steel fibre hybridisation increases the fracture energy with S1 macro steel fibre type up to a maximum of 70% when compared to a non-hybrid concrete matrix with macro steel fibre only; and a decrease is observed with M2 steel fibre type based on average values. However, during the one way analysis of variance in relation to the effect of steel fibre hybridisation in the data as shown in Fig 10(a-b), there is no indication of significant difference in the means of both M2 and S1 steel fibre types (P- Value of 0.343 and 0.488 respectively). Fig 10(c-d) presents a 2 way Anova confirming the above findings for M2B, M2C, M2D (P-value = 0.431) and S1B, S1C, S1D (P-value = 0.805). The effects of steel fibre hybridisation do not present similar trends in both specimen type but higher values of energy are seen in specimen type S1 as macro steel fibre content decreases. The decrease in fracture energy observed in M2 macro steel fibre type M2B, M2C and M2D coming as a result of inadequate alignment and orientation of macro steel fibres perpendicular to the cracks. The actual number of macro steel fibre crossing the cracks and the extent of embedment of the individual hooks and fibre length across the cracked section affect the performance of this type of steel fibre under the applied load conditions (Dupont 2003; Lofgren 2005). Furthermore, the decrease in the fracture energy for this specific type of macro hooked end steel fibre (M2) indicates a lack in the utilisation of the multiple steel fibre hook, its geometry and tensile strength as observed in the pull-out test at the crack zone due to the additional frictional resistance and bond anchorage interlock between steel fibre and concrete matrix. This enhancement in performance during pull-out test also results from the increase in the linear effective length of the M2 macro steel fibre thereby increasing the hook anchorage efficiency and bond stresses (Okeh et al 2016).



(a) (b)

(c) (d)

Figure 10(a-d): Graphs of area under load extension curve against specimen types with steel hybridisation ratios

FINDINGS

The study investigated the effect of steel fibre hybridisation using macro hooked ends and micro straight ends steel fibres in self-compacting concrete on the material properties under uniaxial tension load. The following findings are presented:

- The workability of the wet concrete mix is affected with steel fibre hybridisation. The increase in the ratio of micro steel fibre content reduces the workability in both conditions up to a maximum of 7%.

- There is no significant increase in the density and compressive strength with steel fibre hybridisation in both conditions.
- There is a reduction in the cracking strain and ultimate strain with M2 steel fibre type, but an increase in both strains with S1 steel fibre type with steel fibre hybridisation. This behaviour is due to the increase or decrease in the first crack load and stiffness.
- The residual stresses in the post cracking zone during stress degradation influences the total fracture energy in both conditions which can be attributed to the efficiency of the macro steel fibre in bridging the cracks after initial crack propagation.
- Generally, a bi-linear softening behaviour can be used to describe the stress degradation in the post-cracking stage during plastic deformation. This behaviour is due to the low residual stress generated as a result of the reduced amount of macro steel fibre content in steel fibre hybridisation.
- Steel fibre hybridisation increases the tensile strength as expected up to a maximum of 48% with the optimum strength observed at 25% MAC + 75% MIC steel fibre content for both conditions due to the delay in the formation of micro cracks. However, the increase in tensile strength is only statistically significant in the case of M2 steel fibre. This delay in crack propagation is attributed to the influence of micro steel fibre content in the hybrid steel fibre concrete matrix providing improved adhesion and interface bond characteristics for 10mm maximum aggregate size.
- Steel fibre hybridisation using S1 macro steel fibre type with total fibre dosage of 0.75% increases the fracture energy up to a maximum of 70% with optimum energy characteristics observed at 25% MAC + 75% MIC steel fibre content. The value of the residual stress and stiffness is affected by the ratio of macro steel fibre content, higher ratio show higher residual stress and stiffness.
- Steel fibre hybridisation using M2 macro steel fibre type with total fibre dosage of 1% decreased the fracture energy when used in self-compacting concrete. This response indicates a lack in the utilisation of the multiple steel fibre hook, its geometry and tensile strength as observed in the pull-out test at the crack zone due to the additional frictional resistance and

bond anchorage interlock between steel fibre and concrete matrix. This enhancement in performance during pull-out test also results from the increase in the linear effective length of the M2 macro steel fibre thereby increasing the hook anchorage efficiency and bond stresses (Okeh et al 2016) which was not observed in this experiment. Furthermore, the efficiency of the macro steel fibre across the crack is also affected by several factors such as alignment, orientation, number of fibre crossing the crack(s) and the extent of embedment. (Dupont 2003; Lofgren 2005).

CONCLUSIONS

- The study suggest that the incorporation of S1 type macro hooked end steel fibre with total fibre dosage of 0.75% in steel fibre hybridisation with micro steel fibre can still be used for vertical application in areas of high congestion of steel reinforcement as recommended by EFNARC 2005 (SP3) in relation to workability. However, M2 type with total fibre dosage of 1% in steel fibre hybridisation can only be considered for such application when surface finish is not important and more control given to segregation resistance if not it should be used for normal application (SP2).
- There is a benefit with steel fibre hybridisation in both conditions with regards to the tensile strength which will increase the load carrying capacity.
- The cracking strain and ultimate strain is affected as a result of steel fibre hybridisation. An increase is observed when using S1 and a decrease with M2 macro hooked ends steel fibres.
- A bi-linear softening behaviour is proposed to be used in describing the stress degradation during the post cracking phase of M2 and S1 mix design with steel fibre hybridisation. The ratio of macro steel fibre content appear to influence residual stresses after first crack but does not give rise to any hardening behaviour but affects the stiffness in S1 condition only.
- There is an improvement in the material properties for both the pre and post cracking phase in steel fibre hybridisation when S1 (0.75% total fibre content) with single hook is utilised, with the optimum tensile strength and fracture energy performance characteristics being

observed at S2D mix design (75% macro steel fibre replacement with micro steel fibre). Optimum performance for M2 (1% total fibre content) with multiple hooks is observed at M2D for strength with no effect seen for energy due to the inefficient utilisation of the hooks.

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