Maejo Int. J. Sci. Technol. **2010**, *4*(02), 169-184

Maejo International Journal of Science and Technology

ISSN 1905-7873
Available online at www.mijst.mju.ac.th

Full Paper

Study on the flexural properties of metallic-hybrid-fibre-reinforced concrete

Rashid Hameed*, Anaclet Turatsinze, Frédéric Duprat and Alain Sellier

Université de Toulouse, UPS –INSA, LMDC (Laboratoire Matériaux et Durabilité des Constructions), 135 avenue de Rangueil, F- 31077 Toulouse Cedex 04, France

* Corresponding author, e-mail: rhameed@insa-toulouse.fr

Received: 21 October 2009 / Accepted: 27 April 2010 / Published: 4 May 2010

Abstract: This contribution investigates the flexural properties of metallic-hybrid-fibre-reinforced concrete. Two types of fibres were used: amorphous metallic straight fibre characterised as non-slipping fibre due to its rough surface and large specific surface area, and carbon steel hook-ended fibre characterised as slipping fibre. Three types of concrete: control, single-fibre-reinforced and hybrid-fibre-reinforced were prepared. The fibre was incorporated at 20 and 40 kg/m^3 for single-fibre-reinforced concrete, and at 20, 40 and 80 kg/m^3 for hybrid-fibre-reinforced concrete. The flexural properties were studied using three-point bending tests. From the experimental results obtained with fibre-reinforced concrete containing single fibre, addition of high-bonding amorphous metallic fibre delays the formation of micro-cracks and results in high peak load whereas carbon steel hook-ended fibre contributes towards the flexural toughness (energy absorption capacity) by bridging macro-cracks in the post peak region. The test results on hybrid-fibre-reinforced concrete show that the two metallic fibres when used in hybrid form result in superior performance compared to their single-fibre-reinforced counterparts. Superior performance as a result of fibre hybridisation is interpreted as a positive synergetic effect between the fibres. The procedure of assessing the positive synergetic effect is also discussed.

Keywords: hybrid-fibre-reinforced concrete, metallic fibres, flexural properties, positive synergetic effect

---

Introduction

Concrete is characterised as a brittle material with low tensile strength and low strain capacity. To reduce the brittleness and increase the resistance to cracking, reinforcement with short randomly distributed fibres has been successfully used [1-2] and the resulting composite is known as fibre-

Maejo Int. J. Sci. Technol. **2010**, *4*(02), 169-184

reinforced concrete (FRC). The performance of FRC depends on many factors such as fibre material properties, fibre geometry, fibre volume content, matrix properties and interface properties [3].

Most types of FRC used in practice contain only one type of fibre. However, it is known that failure in concrete is a gradual, multi-scale process. The pre-existing cracks in concrete are of the order of microns. Under an applied load, these cracks grow and eventually join together to form macro-cracks. A macro-crack propagates at a stable rate until it attains conditions of unstable propagation and a rapid fracture is precipitated. The gradual and multi-scale nature of fracture in concrete implies that a given fibre can provide reinforcement only at one level and within a limited range of strains [4]. For optimal result therefore different types of fibres may be combined and the resulting composite is known as hybrid-fibre-reinforced concrete (HyFRC).

According to Qian and Stroeven [5], the basic purpose in using hybrid fibre is to control cracks at different size levels in different zones of concrete (cement paste or interfacial transition zone between paste and aggregate) at different curing ages and stress levels or loading stages. The hybridisation of fibres in concrete can be done in different ways such as by combining different aspect ratios, geometry, moduli and tensile strength of fibres [6]. Recently many research studies on HyFRC have been carried out and a brief overview of some of the important studies has been reported [7].

Although different kinds of fibres were used (such as steel, carbon, glass and polypropylene), the majority of research studies on HyFRC seem to focus on steel-polypropylene fibre-reinforced concrete [8]. However, polypropylene fibre has a low Young's modulus and, as a consequence, it cannot prevent the formation and propagation of cracks at a high-stress level, nor can it bridge wider cracks. Therefore, its action is limited to small-crack openings. On the contrary, steel fibre has a considerably higher Young's modulus as compared to polypropylene fibre. This leads to an improved potential for crack control at high-stress level [9].

For the structural application of HyFRC, a suitable combination of two different fibres, in which one fibre can resist the cracks effectively at micro-level as soon as they are initiated and the other fibre can control the crack opening at macro-level, can result in a composite exhibiting properties required for a particular application. In this study, composites containing a high-performance and adhering amorphous stainless metallic fibre and a hook-ended carbon steel fibre both in single and hybrid forms are investigated under flexural loading.

In the present state of the knowledge of FRC, much data are available on the behaviour of hook-ended carbon steel fibre, but very limited data are available on the behaviour of high-modulus, adhering amorphous stainless metallic fibres produced in France. Carbon steel hook-ended fibre is characterised as a slipping fibre due to its smooth surface and are usually pulled out, instead of broken, from the matrix at larger crack openings. Amorphous metallic fibre on the other hand is considered to be a high-performance fibre because of its high-bonding strength with the matrix due to its rough surface and large aspect ratio [10-11]. Moreover, it also has a high elastic modulus compared to polypropylene fibre. Amorphous metallic fibre is considered to be very efficient in the first phase of crack opening. Afterwards, as its high bonding with the concrete matrix prevents it from slipping, it breaks one after another and the through-crack bearing capacity decreases sharply [10]. Moreover, being corrosion-resistant, this fibre has drawn the attention of researchers working on the application of FRC in aggressive environments [12].

Maejo Int. J. Sci. Technol. **2010**, *4*(02), 169-184

Taking into account the non-slipping behaviour of the high-performance, adhering amorphous metallic fibre and the slipping behaviour of the carbon steel hook-ended fibre, the major objective of this work is to make different composites containing these two fibres in both single and hybrid forms and to test their flexural properties. Another objective is to investigate the presence of synergetic effect of these fibres when used in hybrid form.

Materials and Methods

Test series

The experimental study was carried out in two test series. Series I was carried out to investigate the properties of mono-fibre-reinforced concrete. Series II was then carried out to investigate the properties of HyFRC and then to identify the positive synergetic effect of the two fibres if present.

Type of fibre used

Two types of macro-metallic fibre, 30 mm in length were used. Type-I fibre (named in this study as MF1) was an amorphous metallic fibre produced by Saint-Gobain Seva, France. It was composed of Fe and Cr (80%) and P, C and Si (20%) in mass. In two different corrosion tests on this fibre by immersing in HCl (0.1 N) for 24 hours and in $FeCl_3$ (0.4N) for another 24 hours, no corrosion was observed [13]. Due to its rough surface and large specific surface area, this fibre was characterised by a high degree of bonding with the concrete matrix.

Following is the process of producing the amorphous metallic fibre (MF1) [14]. Molten alloy was placed in a crucible the lower section of which was perforated and fitted with a capillary tube a few millimetres in diameter. Underneath the crucible, a water-cooled wheel with notches at regular intervals rotated at high speed. The alloy fell onto this wheel and underwent hyperquenching. The jet of metal was cut at each notch to form the fibre. The production process is illustrated in Figure 1. The pieces of fibre are shinny, flexible, very thin and ribbon-like as shown in Figure 2.

Figure 1. Production process of amorphous metallic fibre

Maejo Int. J. Sci. Technol. **2010**, *4*(02), 169-184

Type-II metallic fibre (named in this study as MF2) was made using carbon steel wire produced by Bekaert, Belgium, and was characterised by a weak bond with the matrix owing to its smooth surface and less specific surface area compared to type-I fibre. It was circular with hook-ends. The wire pieces usually adhered to one another in clips of certain number of wires (Figure 2). When these clips were put in the mix, the adhesive dissolved and individual pieces of fibre were distributed evenly throughout the mix. The characteristics of these two types of metallic fibre (MF1 and MF2) are given in Table 1.

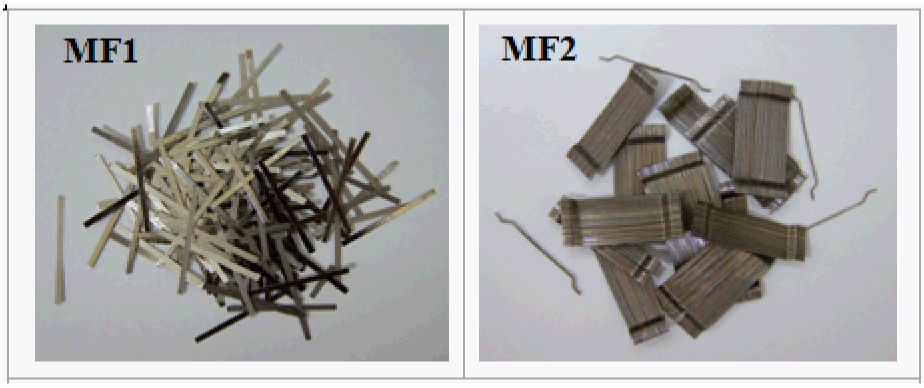

Figure 2. Amorphous metallic fibre (MF1) and carbon steel fibre (MF2)

Table 1. Properties of fibres investigated in this study

Fibre	Fibre type	Dimension (mm)				Geometry	E (GPa)	Tensile strength (MPa)	Density (g/cm^3)	Cross section
		L	W	T	D					
MF1	amorphous metal	30	1.6	0.03	-	Straight	140	2000	7.2	Rectangular
MF2	carbon steel	30	-	-	0.5	Hook-ended	210	1200	7.8	Circular

Note: L = length, W = width, T = thickness, D = diameter, E = modulus of elasticity

Concrete constituents

A CEM I 52.5R cement (average particle size, *d50*: 14 µm), river aggregates, viz. 0/4-mm fine aggregate (sand) and 4/10-mm coarse aggregate (gravel), and a super-plasticiser were used to design the concrete studied in this investigation. The quantity of each constituent of the concrete is given in Table 2.

Table 2. Constituents of control concrete

Cement (Kg/m^3)	Sand (Kg/m^3)	Gravel (Kg/m^3)	Water (Kg/m^3)	Super-plasticiser (Kg/m^3)
322	872	967	193	1.61

Maejo Int. J. Sci. Technol. **2010**, *4*(02), 169-184

A total of eight concrete mixtures: one control, four mono-fibre reinforced and three hybrid-fibre reinforced, were investigated. Fibre type and dosage for all the concrete mixtures are given in Table 3 along with the slump value of each mixture. Each concrete mixture was labelled according to the type and quantity of fibre. For example, C20MF1 denotes concrete with 20 kg/m^3 of MF1 fibre, and C40HyF stands for concrete with 40 kg/m^3 of hybrid fibre. Regarding the slump value, it can be observed that the values for fibre-free concrete and fibred concretes containing only MF2 fibre are not significantly different: the addition of MF2 fibre does not change significantly the fresh properties of the matrix. On the contrary, addition of MF1 fibre reduces significantly the slump value, but, by using a vibrating table, no difficulty in moulding the specimens was encountered even at 40 kg/m^3 of MF1 fibre.

Table 3. Fibre content in different concrete mixtures and their slump values

Concrete mixture	Mixture type	Content of fibres (kg/m^3)		Total quantity of fibre (kg/m^3)	Slump (mm)
		MF1	MF2		
CCONT	Control	---	---	---	170
C20MF1	Mono-fibre	20	---	20	70
C40MF1		40	---	40	45
C20MF2		---	20	20	155
C40MF2		---	40	40	130
C20HyF	Hybrid fibre	10	10	20	100
C40HyF		20	20	40	60
C80HyF		40	40	80	40

Specimen preparation and test method

For each concrete mixture, five 100x100x500-mm prismatic specimens were cast. The concrete was placed in each mould in two layers. After each layer, the mould was placed on a vibrating table for compaction. There was no difficulty in moulding the specimens; all mixes flowed easily under an external vibration (vibrating table). Specimens were demoulded after 24 hours and then placed in a curing room with 100% relative humidity and 20ºC temperature until the day of testing. These prismatic specimens were used to determine the flexural properties, i.e. modulus of rupture (MOR), residual flexural tensile strength (RFTS) and flexural toughness (FT). Three-point bending tests were performed on notched beams as shown in Figure 3, using a universal testing machine manufactured in Laboratory of Materials and Durability of Structures, Toulouse, France. The maximum loading capacity of the machine is 50 kN.

A notch, 17.5 mm deep and 3 mm wide, was cut in the centre of each prismatic specimen with a concrete saw. All tests were controlled by crack mouth opening displacement (CMOD) using linear variable differential transducer (LVDT). CMOD rate was kept at 0.01mm/min up to 0.1 mm crack opening, and then it was increased to 0.2 mm/min until the completion of the test. The mid-span deflection was also measured using LVDT. CMOD, force and deflection were automatically recorded

Maejo Int. J. Sci. Technol. **2010**, *4*(02), 169-184

using data acquisition system. The testing setup and arrangement of displacement sensors (LVDT) is shown in Figure 3.

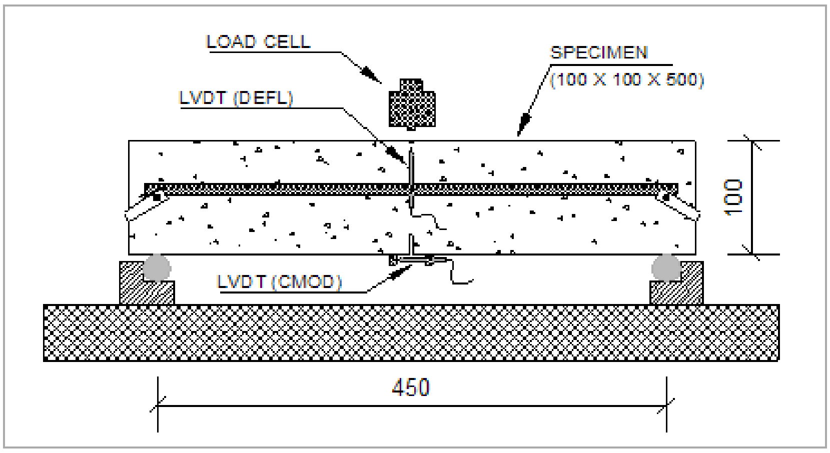

Figure 3. Testing setup for three-point bending test

Results and Discussion

Representative curves of load-CMOD and load-deflection behaviour of all the concrete mixtures are shown in Figures 4 and 5 respectively, where it can be observed that reinforced matrices exhibit high strength and toughness compared to un-reinforced matrix. It is important to mention here that each representative curve shown here is not an average of five samples. In fact, after plotting the curves of all samples of each composition, a single representative curve was selected. However, the values of each flexural property (i.e. MOR, RFTS and FT) given in the following sections are the average of those from five samples of each composition.

Modulus of rupture (MOR)

The modulus of rupture (MOR) of all concrete mixtures of series I (mono-fibre-reinforced) and II (hybrid-fibre-reinforced) was calculated from the maximum load attained in the test using elastic analysis. The average value for each mixture is shown in Figure 6 along with scatter of test results. It can be observed in series-I testing that the addition of MF1 metallic fibre provides appreciable increase in MOR, whose value also increases with increase in fibre content as expected. On the other hand, addition of MF2 metallic fibre does not provide any significant increase in MOR at the dosage of 20 kg/m^3 (C20MF2), although at 40 kg/m^3 (C40MF2) the MOR is increased by 35.3% compared to control concrete (CCONT). In series-II testing (Figure 6), the highest MOR is exhibited by C80HyF concrete mixture. In the case of C40HyF, MOR increases appreciably compared to that of C40MF2, but it is lower than the value attained by C40MF1. A similar trend is observed in the case of concrete mixtures containing fibre at 20 kg/m^3 dosage in hybrid and single forms: MOR of C20HyF is higher than that of C20MF2 but lower than that of C20MF1. Percentage increase in MOR for each FRC compared to fibre-free concrete is shown in Figure 7. It should be mentioned here that the comparison of C40HyF with C20MF1 and C20MF2, and that of C80HyF with C40MF1 and C40MF2 are more important for the investigation of synergetic effect which is discussed later in this paper.

Maejo Int. J. Sci. Technol. **2010**, *4*(02), 169-184

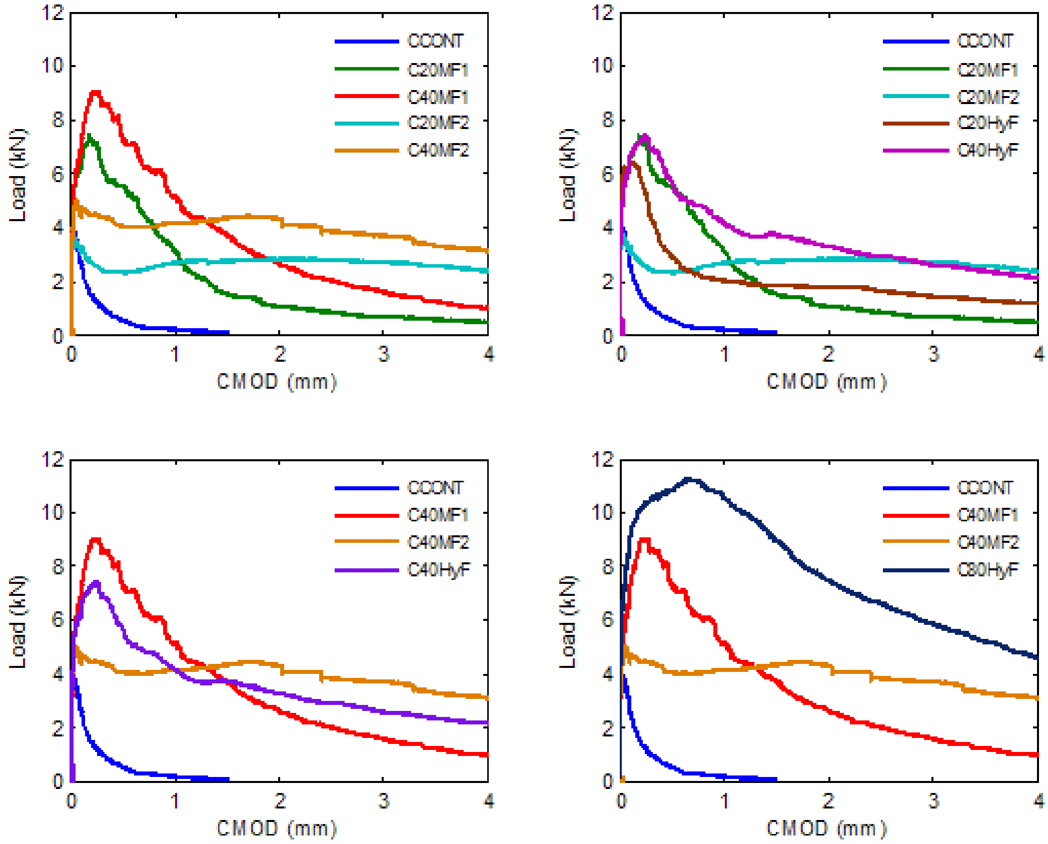

Figure 4. Load versus CMOD curves

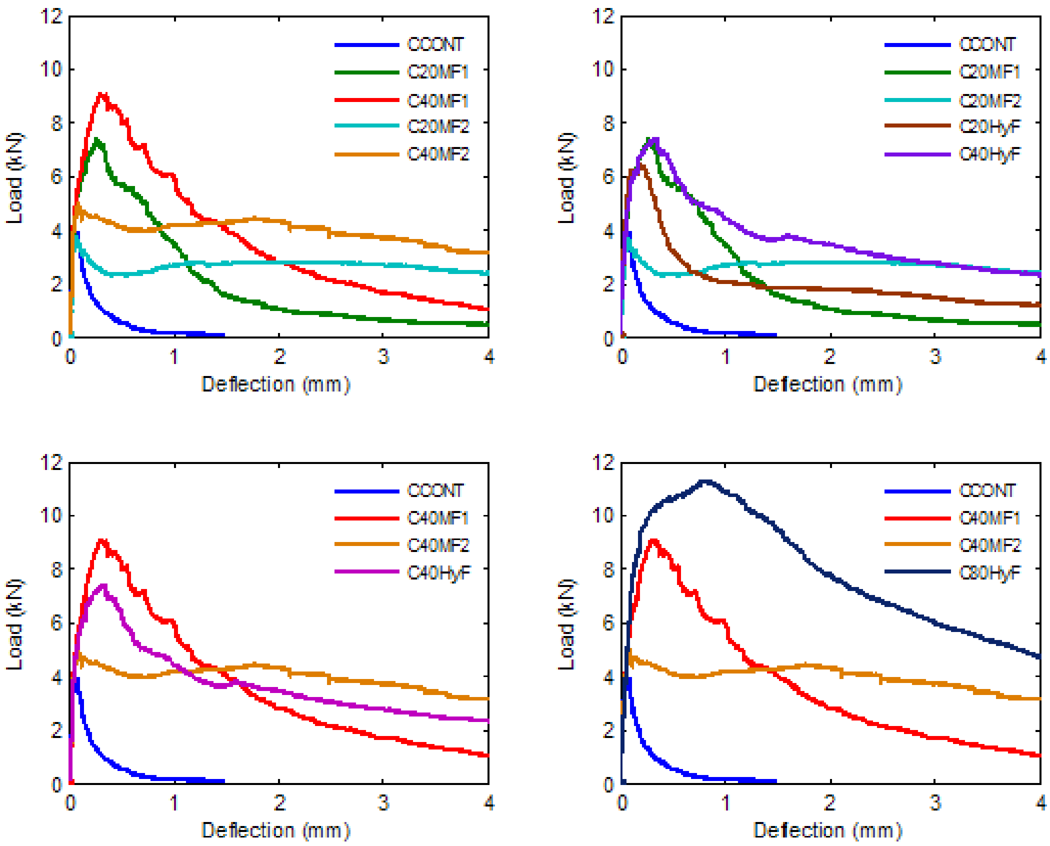

Figure 5. Load versus deflection curves

Maejo Int. J. Sci. Technol. **2010**, *4*(02), 169-184

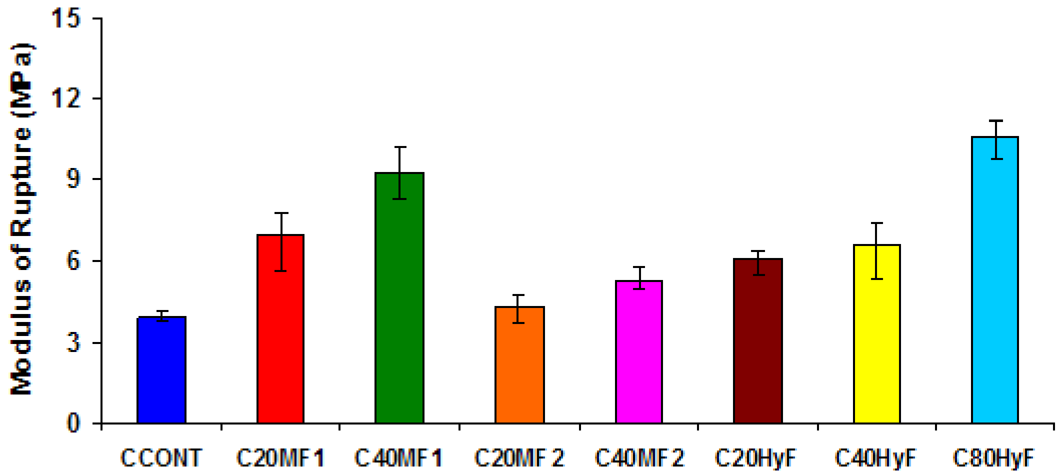

Figure 6. Average values of MOR

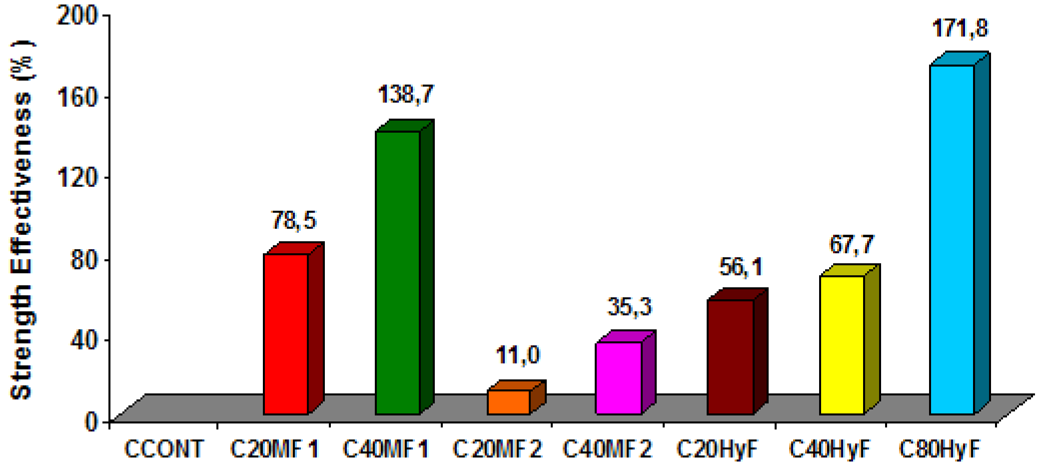

Figure 7. Percentage increase in MOR compared to CCONT (control)

Residual flexural tensile strength (RFTS)

FRC has the potential of exhibiting higher strength and ductility in comparison with un-reinforced mortar or concrete, which fails in tension immediately after the formation of the first macro-crack [3]. In this study, the procedure proposed in European standard NF EN 14651 [15] is used to calculate the RFTS of FRC using the expression:

$$f_{R,j} = \frac{3F_j l}{2bh_{sp}^2} \qquad (1)$$

where $f_{R,j}$ is RFTS corresponding to CMOD = CMOD$_j$ (j=1,2,3,4); F_j is the load corresponding to CMOD$_j$; l is the span length; b is the width and h_{sp} is the distance between the tip of the notch and the top of the specimen. In this study, RFTS has been determined at CMOD values of 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5 and 4.0 mm. Average values of RFTS of different concrete mixtures are shown in Figure 8.

Maejo Int. J. Sci. Technol. **2010**, *4*(02), 169-184

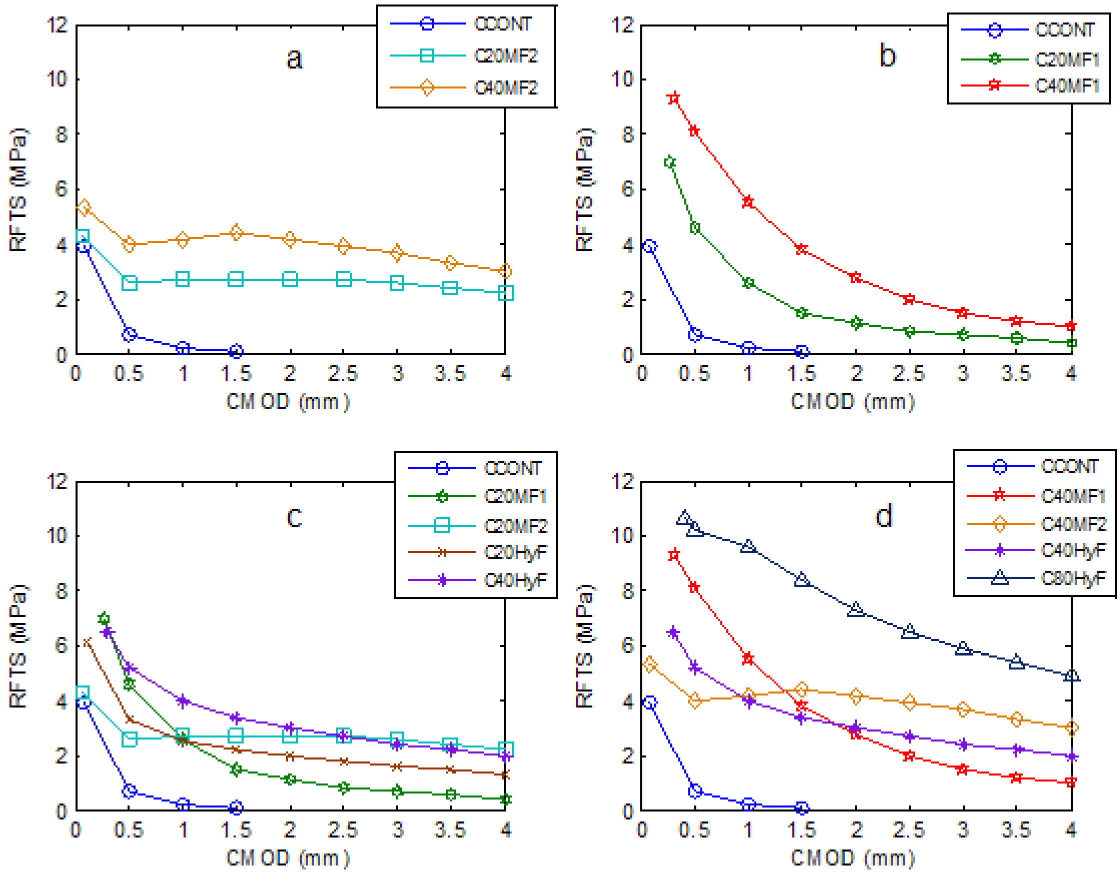

Figure 8. RFTS of different concrete mixtures as a function of CMOD

Figure 8a shows a comparison of different quantities of MF2 metallic fibre in the mix. When the quantity is increased from 20 to 40 kg/m^3, the RFTS is greater at all CMOD values as expected. With both volume fractions of MF2 fibre, after the peak load, a very small drop in the load bearing capacity is followed by an appreciable value of residual strength up to crack width of 4 mm.

Figure 8b shows a comparison of different quantities of MF1 metallic fibre in the mix. Similar to MF2 fibre, when the quantity is increased from 20 to 40 kg/m^3, the RFTS is greater. Unlike MF2 metallic fibre, after the peak load, RFTS is observed to drop gradually with the increase of CMOD, indicating a relatively brittle behaviour. The RFTS is seen to approach a value less than 1 MPa at crack width of 4 mm.

Figure 8c shows a comparison of C20MF1 and C20MF2 containing mono-fibre at 20 kg/m^3 with C20HyF and C40HyF containing hybrid fibre 10 and 20 kg/m^3 of each fibre respectively. In the case of mono-fibre concrete, it is observed that after the peak load at CMOD of 1 mm, the response of the two fibres in terms of RFTS is reversed: at smaller crack opening, the mix reinforced with MF1 fibre exhibits greater RFTS while at larger crack opening, RFTS of the mix containing only MF2 is high. In the case of the C20HyF hybrid mix, the residual strength values are found to be higher than those of C20MF2 and lower than those of C20MF1 at CMOD < 1 mm, while after 1 mm the reverse happens. As a result of different actions of the two fibres at different loading levels, the hybrid mix containing each fibre at 20 kg/m^3 (40HyF) exhibits greater values of RFTS over a wide range of crack opening.

Maejo Int. J. Sci. Technol. **2010**, *4*(02), 169-184

Figure 8d shows a comparison of C40MF1 and C40MF2 containing single fibre at 40 kg/m^3 with C40HyF and C80HyF containing hybrid fibre at 20 kg/m^3 and 40 kg/m^3 of each fibre respectively. A similar trend as mentioned above for Figure 8c was observed. In the case of C40HyF hybrid mix, RFTS is observed to be higher than that of C40MF2 and lower than that exhibited by C40MF1 up to the crack opening of 1 mm. At 1-1.7 mm CMOD, the RFTS is lower than that of both mono-fibre concretes, but beyond 1.7 mm it is higher than that of C40MF1 but lower than that of C40MF2. The hybrid mix containing each fibre at 40 kg/m^3 (C80HyF) exhibits greater values of RFTS compared to all types of mix over a wide range of crack opening.

Flexural toughness (FT)

To mitigate the hazard for structures subjected to dynamic loads such as seismic, impact and blast, high-energy absorbing materials are needed [3]. Flexural toughness (or energy absorption capacity) is measured by the area under the load-deflection curve as shown in Figure 5. Flexural toughness also demonstrates the ductile behaviour of the material. The effect of fibre addition, fibre type and hybridisation of fibres on FT is illustrated in Figure 9 using FT values calculated as area under the load-deflection curve up to 4 mm deflection. Addition of metallic fibres is observed to increase FT of the brittle matrix appreciably. Moreover, the effectiveness of fibre increases with increase in fibre content; this is true for both types of metallic fibres. As far as the effect of fibre type is concerned, it is observed that at both fibre dosages (20 and 40 kg/m^3), MF2 fibre is more effective than MF1 fibre. Among the hybrid concrete mixtures in series II, C80HyF mix exhibits the highest value of FT, which is significantly greater than that of the control concrete. In the case of C20HyF, the value is the same as for C20MF1 but less than that attained by C20MF2. For C40HyF the FT is found to be higher than that of C40MF1 but lower than that of C40MF2 although the difference is small in both cases.

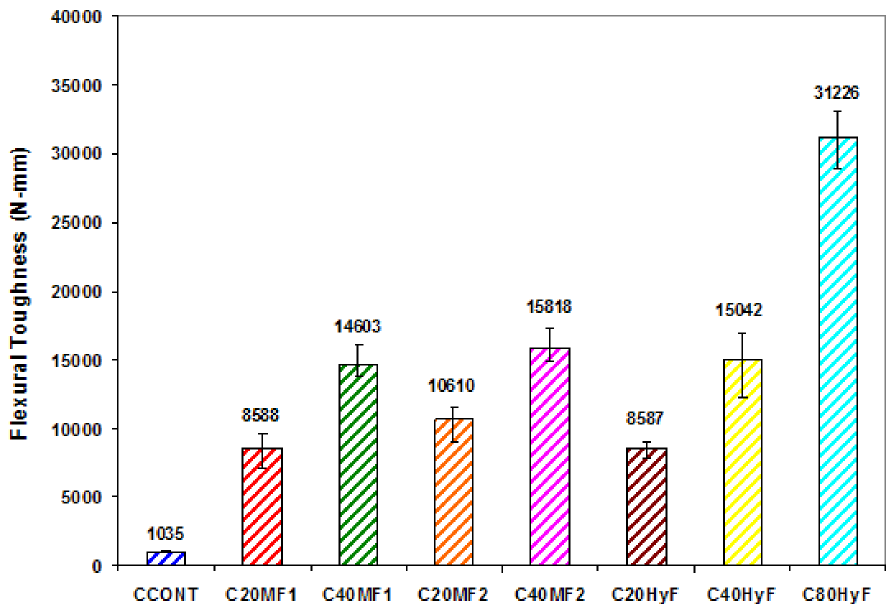

Figure 9. FT values of all concrete mixtures

Maejo Int. J. Sci. Technol. **2010**, *4*(02), 169-184

Synergetic effect

In FRC composites, one can consider that the contribution of various components are additive and this implies [10]:

$$F(C_f) = F(C) + \sum_{i=1}^{n} F(f_i) \tag{2}$$

where *F(C_f)* is the mono-fibre concrete response; *F(C)* is the matrix response and *F(f_i)* is the fibre contribution. Symbol *n* indicates the number of fibres present in the matrix. Similarly, for HyFRC, Eq.2 becomes

$$F(HyC_f) = F(C) + \sum_{i=1}^{n} F(af_i) + \sum_{j=1}^{m} F(cf_j) \tag{3}$$

where *n* and *m* indicate the number of amorphous metallic and carbon steel fibres respectively, symbol a is for amorphous metallic fibre and symbol c is for carbon steel fibre.

Simple arithmetic sum of responses from two single fibres in the reinforced concrete can be represented by:

$$\left\{F(C) + \sum_{i=1}^{n} F(af_i)\right\} + \left\{F(C) + \sum_{j=1}^{m} F(cf_j)\right\} \tag{4}$$

To determine the synergetic effect between fibres, the sum of responses from single-fibre reinforcement are compared to the response from hybrid-fibre reinforcement. Note that while adding response from mono-fibre reinforcement (Eq. 4), the matrix contribution is added twice. For true determination of synergetic effect, one matrix effect should then be subtracted from the expression. Based on this consideration, for positive synergetic effect between the two fibres used in HyFRC the following equation should be satisfied:

$$F(HyC_f) > \left\langle \left(F(C) + \sum_{i=1}^{n} F(af_i) \right) + \left(F(C) + \sum_{j=1}^{m} F(cf_j) \right) - F(C) \right\rangle \tag{5}$$

In this study, the synergetic effect has been investigated in two formulations of HyFRC, i.e. C40HyF and C80HyF, in terms of MOR, RFTS and FT. For a hybrid concrete, a positive synergetic effect exists between two fibres if their combined response is greater than the arithmetic sum of responses from mono-fibre concretes each containing single fibre at the same volume fraction as in the hybrid combination.

In Figures 10-11, it is observed that no synergetic effect exists in terms of MOR and FT at fibre quantity of 40 kg/m^3 (C40HyF). However, at 80 kg/m^3 (C80HyF), a small positive synergetic effect for both properties exists between the fibres. A similar result can also be observed for RFTS as shown in Figure 12: synergetic effect does not exist at a total fibre quantity of 40 kg/m^3 (C40HyF), but it does when both fibres are combined to the total quantity of 80 kg/m^3 (C80HyF).

Another important fact about the synergetic effect is that if one fibre is efficient at micro-cracking level and the other fibre is at macro-cracking one, and when both fibres are present in HyFRC, resulting in improved response at both levels (micro- and macro-cracking), this can also be interpreted as a synergetic effect. In this case, it is not necessary that the response of the hybrid

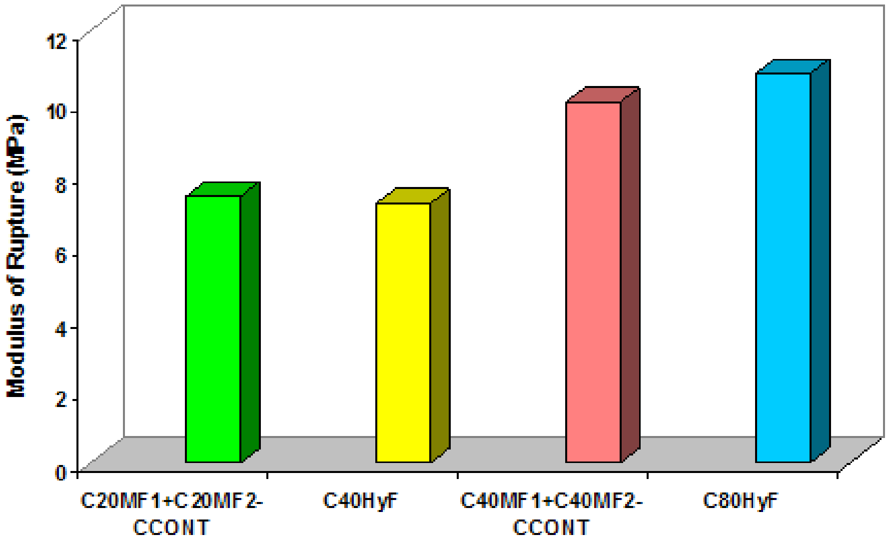

Figure 10. Synergy assessment in terms of MOR

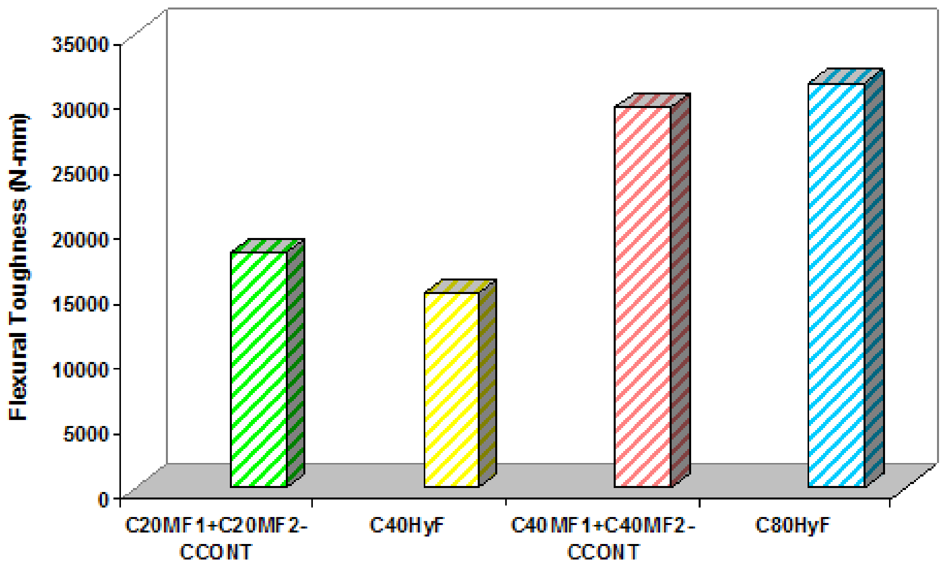

Figure 11. Synergy assessment in terms of FT

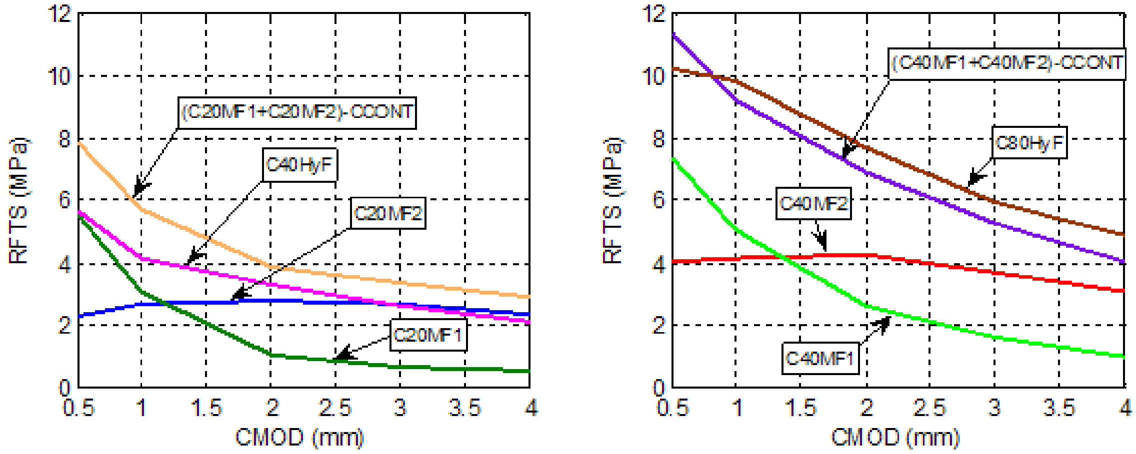

Figure 12. Synergy assessment in terms of RFTS

Maejo Int. J. Sci. Technol. **2010**, *4*(02), 169-184

composite in terms of one particular property must be greater than the sum of responses of the single-fibre-reinforced concretes. In this study, type-I fibre (MF1) is effective at micro-cracking level and type-II fibre (MF2) is effective at macro-cracking level. As a result, the hybrid composition exhibits a globally improved flexural behaviour at both cracking levels.

From all the above experimental results, it is clear that there is a marked difference in the responses of two metallic fibres used in this study. At low level of deflection or CMOD, the high-bonding non-slipping fibre (MF1) shows high efficiency whereas at high level of crack opening or deflection, the low-bonding slipping hook-ended fibre (MF2) exhibits better performance.

Since micro-cracking in a specimen subjected to flexure is initiated prior to the peak load (at 60% of the peak load) [16], high-bonding amorphous metallic fibre (MF1) stops the development of these micro cracks and as a result the peak resistance of the composite increases. With the increase of crack opening, the stress increases in the fibre and a stage comes when localised tensile stress in the part of fibre between the crack edges exceeds its tensile strength and the fibre breaks instead of pulling out from the matrix. During tests on specimens with MF1 fibre, after the peak load, the sound produced by the breaking of fibres could be heard, and this breaking was also visible when the fractured surface of the specimen was examined (Figure 13). Similar observations were also made by Pons et al. [10]. Due to the sudden breaking of fibres, a rapid drop in the load bearing capacity was observed and the RFTS approached a negligible value very quickly over a very short range of CMOD or deflection. Increase in peak load capacity and a high value of RFTS over a short plateau are two main factors which cause increase in the area under the load-deflection curve (i.e. flexural toughness or energy absorption capacity).

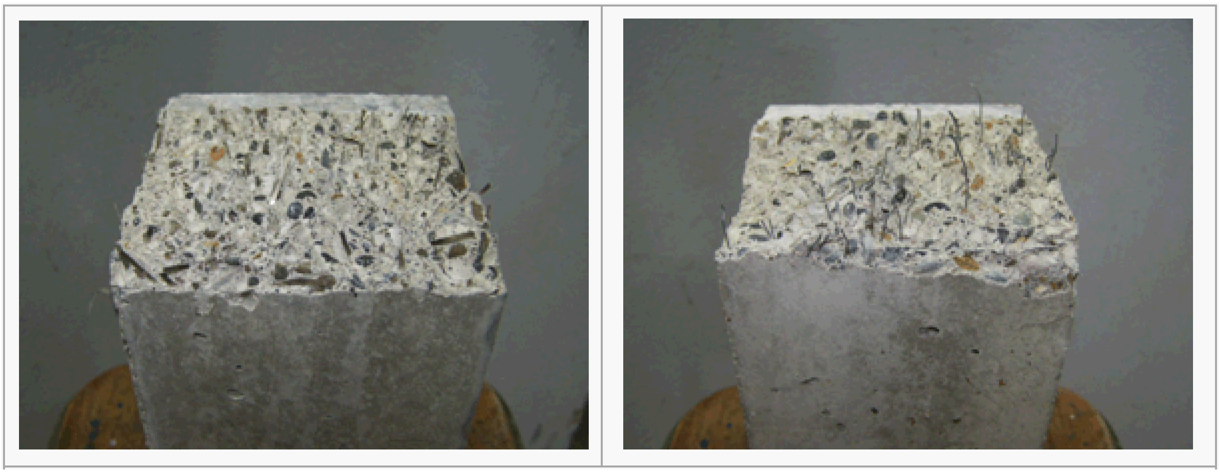

Figure 13. Fractured surface of specimen with MF1 fibre (left) and with MF2 fibre (right)

The slipping, low-bonding hook-ended fibre (MF2) at a dosage of 20 kg/m^3 did not significantly increase the peak resistance although at 40 kg/m^3, peak resistance was increased by 35.3% compared to control concrete. Being ductile and having adequate anchorage in the matrix

Maejo Int. J. Sci. Technol. **2010**, *4*(02), 169-184

through hook ends, the fibre is effective in bridging macro-cracks. After the peak load, a drop in the load-carrying capacity was observed, but soon after, the fibre started acting and bridged the macro-cracks. Crack bridging by the fibre resulted in significant RFTS, which was observed to be attained over a long plateau. Finally, these individual fibres were pulled out from the concrete matrix instead of breakage as shown in Figure 13 and their hook ends were turned straight.

Since the two fibres were observed to act differently at two levels, viz. micro-cracking and macro-cracking levels, hybridisation of these fibres resulted in an improved flexural response at both loading stages in terms of strength and energy absorption capacity. For HyFRC at a total fibre quantity of 80 kg/m^3 (40 kg/m^3 of each fibre), positive synergetic effect between metallic fibres resulted in maximum flexural response compared to all other mixtures containing fibres in single or hybrid forms. Moreover, two combined actions, one of amorphous metal fibre to stop the micro-cracking mechanism and the other of carbon steel hooked-ended fibre to stop the propagation of macro-cracks, were another positive synergetic effect between the two metallic fibres.

However, it should also be mentioned here that by keeping the same fibre volume in a composite, mechanical performance of the FRC composite can also be improved by changing the constituents of the cement-based matrix. Maximum aggregate particle size (d_{max}) usually governs the length of the fibre, i.e. length of fibre (l_f) should be equal or greater than 3 times of d_{max} [17]. If d_{max} is reduced, fibre with shorter length can be selected, and for the same dosage the number of the shorter fibre will increase. Moreover, by reducing d_{max}, the matrix compactness will also improve. Increased number of fibres and improved compactness of the matrix can result in improved mechanical response of the FRC, which sometime leads to the development of ultra-high performance fibre-reinforced concrete composite [18].

Conclusions

On the basis of three-point bending tests performed on notched prismatic specimens constructed with mono- and hybrid-fibre-reinforced concretes containing two different fibres used in this study, the following conclusions can be drawn:

- Adhering amorphous stainless metallic fibre, due to its high-bonding with the matrix, is very effective in controlling the micro-cracking mechanism, which results in an improved behaviour in terms of smaller crack openings at peak resistance. On the other hand, high-modulus hook-ended carbon steel fibre is effective in controlling macro-cracks over a wide range and at high stress level. As a result, the toughness of the material is significantly increased. It should also be noted that these fibres also have very different properties in terms of fibre geometry and tensile strength. These variables are also effective on flexural performance of beam samples at different loading levels.
- The use of metallic fibres in hybrid form investigated in this study has resulted in improved behaviour of the composite regarding cracking control, strength and toughness. For such structural application as in water retaining structures, hybrid combination of these fibres could be promising.
- The response of the hybrid mixture containing both fibres at a total quantity of 80 kg/m^3 (40 kg/m^3 of each fibre) in terms of modulus of rupture, residual flexural tensile strength and

Maejo Int. J. Sci. Technol. **2010**, *4*(02), 169-184

flexural toughness has shown that there exists a positive synergetic effect between the metallic fibres used in this study.

Future Work

In the ongoing research work, more fibre composites containing fibres in single and hybrid forms at the same dosage will be tested and results will be compared to further highlight the benefits of mixing metallic fibres used in this study. For example, mono-fibre composition containing fibres at the dosage of 80 kg/m^3 will be tested in comparison with the hybrid composition containing both fibres at a total quantity of 80 kg/m^3.

Acknowledgement

The authors would like to thank the Higher Education Commission of Pakistan for the financial support for this experimental study.

References

1. N. Banthia and M. Sappakittipakorn, "Toughness enhancement in steel fiber reinforced concrete through fiber hybridization", *Cem. Concr. Res.,* **2007**, *37*, 1366-1372.
2. N. Banthia and R. Gupta, "Hybrid fiber reinforced concrete (HyFRC): Fiber synergy in high strength matrices", *Mater. Struct.*, **2004**, *37*, 707-716.
3. D. J. Kim, A. E. Naaman and S. El-Tawil, "Comparative flexural behaviour of four fiber reinforced cementitious composites", *Cem. Concr. Compos.*, **2008**, *30*, 917-928.
4. N. Banthia and S. M. Soleimani, "Flexural response of hybrid fiber-reinforced cementitious composites", *ACI Mater. J.*, **2005**, *102*, 382-389.
5. C. Qian and P. Stroeven, "Fracture properties of concrete reinforced with steel-polypropylene hybrid fibers", *Cem. Concr. Compos.*, **2000**, *22*, 343-351.
6. S. F. U. Ahmed and M. Maalej, "Tensile strain hardening behaviour of hybrid steel-polyethylene fiber reinforced cementitious composites", *Construct. Build. Mater.*, **2009**, *23*, 96-106.
7. L. Kucharska, A. M. Brandt and D. Logon, "Hybrid fiber reinforcement-- Is superposition of effects of different fibers always valid?", Proceedings of Non-Traditional Cement and Concrete International Symposium, 11-13 June **2002**, Brno, Czech Republic, pp. 376-386.
8. M. Hsie, C. Tu and P. S. Song, "Mechanical properties of polypropylene hybrid fiber-reinforced concrete", *Mater. Sci. Eng. A*, **2008**, *494*, 153-157.
9. C. X. Qian and P. Stroeven, "Development of hybrid polypropylene-steel fiber-reinforced concrete", *Cem. Concr. Res.*, **2000**, *30*, 63-69.
10. G. Pons, M. Mouret, M. Alcantrara and J. L. Granju, "Mechanical behaviour of self-compacting concrete with hybrid fiber reinforcement", *Mater. Struct.*, **2007**, *40*, 201-210.
11. J. L. Granju, "Thin bonded overlays: About the role of fiber reinforcement on the limitation of their debonding", *Adv. Cem. Based Mater.*, **1996**, *4*, 21-27.

Maejo Int. J. Sci. Technol. **2010**, *4*(02), 169-184

12. J. Catalot, "Corrosion resistance of amorphous metallic fibres: Use for repair of waste and rainwater sewers by fibre reinforced shotcrete", Proceedings of 7th International Congress CEOCOR, 30 May - 2 June **2006**, Mondorf-les-Bains, Luxembourg.
13. C. Redon and J-L Chermant, "Damage mechanics applied to concrete reinforced with amorphous cast iron fibers, concrete subjected to compression", *Cem. Concr. Compos.*, **1999**, *21*, 197-204.
14. Saint-Gobain Seva, FibraFlex Department, France, "Flexible non-oxidising metallic fibre for concrete reinforcement", www.fibraflex.com (Retrieval date: April **2009**).
15. "Test method for metallic fibered concrete – Measuring the flexural tensile strength (limit of proportionality, residual)", *European Standard*, November **2005**, Method No. NF EN 14651.
16. A. Turatsinze and A. Bascoul, "Restrained crack widening in mode I crack propagation for mortar and concrete", *Adv. Cem. Based Mater.*, **1996**, *4*, 77-92.
17. P. Rossi, "A Textbook about Concrete with Steel Fibers" (in French), Presses de l'Ecole Nationale des Ponts et Chausses, Paris, **1998**.
18. "Interim Recommendations for Ultra High Performance Fiber-Reinforced Concrete", Association Française de Génie Civil (AFGC), Bagneux (France), January **2002**.