Journal of Engineering and Applied Sciences 1 (2) : 112-116, 2006

Hybrid Fiber Reinforced Self-compacting Concrete: Fiber Synergy at Low Fiber Volume Fraction

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Abstract: In most cases, Fiber Reinforced Self-Compacting Concrete (FRSCC) contains only one type of fiber. The use of two or more types of fibers in a suitable combination may potentially not only improve the overal properties of self-compacting concrete, but may also result in performance synergie. The combining of fibers, often called hybridization, is investigated in this paper for a cimentous matrix. Control, single, two fibers hybrid composites were cast using different fiber type steel and polypropylene with different sizes. Flexural toughness tests were performed and results were extensively analysed to identify synergy, if any, associated with various fiber combinations. Based on various analysis schemes, the paper identifies fiber combinations that demonstrate maximum synergy in terms of flexural toughness.

Key words: Self-compacting, concrete, hybrid, fibers, toughness, energy

INTRODUCTION

The concept of the Self Compacting Concrete (SCC), was created and developped at the end of the eighties after the developpement of new organic additives. The interest of those concretes appeared only at the end of the nineties. Self-compacting concrete is a brittle material with a low strain capacity. Reinforcement of self-compacting concrete with short randomly distributed fibers can address some of the concerns related to self-compacting concrete brittleness and poor resistance to crack growth. Fibers, used as reinforcement, can be effective in arresting cracks at both micro and macro-levels. At the micro-level, fibers inhibit the initiation and growth of cracks and after the micro-cracks coalesce into macro-cracks, fibers provide mechanisms that abate their unstable propagation, provide effective bridging and impart sources of strength gain, toughness and ductility[1,2]

Different types of fibers provide different mechanical behaviours and a controlled mix of them, so called hybrid, are now developpped to customise the mechanical response of the material. It is possible to mix fibers of differents sizes, from micro to macro, or of different mechanical properties, or both together.

It has been shown recently[3] that by using the concept of hybridization with two different fibers incorporated in a common cement matrix, the hybrid composite can offer more attractive engineering properties because the presence of one fiber enables the more efficient utilization of the potential properties of the other fiber. However, the hybrid composites studied by previous researchers were focused on cement paste or mortar. The mechanical properties of hybrid fiber reinforced self-compacting concrete at low fiber volume fraction have not been studied previously.

Associations of fibers of differents characteristies begin to be used. Banthia and al[4] showed that the association of synthetic and metal fibers can give to the cimentous composite more ductility than what give metal fibers to concrete. Kawamata and al[5] have tried to use for self-compacting concrete associations of long and short fibers according to these authors, the short fibers prevent the formation of the small cracks, delaying thus the formation of the macro cracks that will be taken by the longest fibers and will need a greater dissipation energy. In this way the ductility of the material will be increased.

However, the fibers are too expensive and the concurrence between the manufacturers is hard : looking for a relation between proportion and fibers number seems to be a solution.

The present work deals with a mix of fibers of similar sizes and differents properties and different length. Mixes of fibers of different natures has already been tried, usually to provide or enhance a multicracking behaviour in high performance hybrid fiber reinforced composite[4].

The goal of this study its to reduce the costs more or less high of the fibers, in other words, to optimize the quantitative proportions (kg m^{-3}) of the fibers by taking account of the economic factors: to reach the desired resistance with the least proportion (lowest cost).

Basic choices

Fibers used: Both are macro fibers, there lengths are, respectively 20 and 30 mm for the steel fibers and 50 mm for polypropylene.

Table 1: Properties of the fibers used

Fiber type	Amorphous metal	Polypropylene
Length	20 mm 30 mm	50 mm
Cross section	Rectangular 1,6*0,03 mm	Roughly rectangular1,6*0,4mm
Density	7,2	0,92
Tensile strength	2000 Mpa	310 Mpa
Elastic modulus	140 Gpa	4,3 Gpa
Alcali, acid, salts resistance	stainless	high

Table 2: Self-compacting concrete mix proportions

Components	Kg m^{-3}
Cement CPA	340
Filler	213
Sand 0-4 mm	884
Gravel 4-10 mm	553
Superplasticiser SP (sika 3030)	4,08
Amorphous metal fibers	Variable content and length
Syntetic (polypropylene)fibers	4,5
Water	210

The high bond and high modulus ones are amorphous metal fibers. They are flexible, ribbon like and totally stainless. For this reason they can be used with no reservation in self- compacting concrete.

The low modulus and slipping fibers are polypropylene ones. Designed to be used in replacement of steel fibers, they have similar geometry. They are straight, 50 mm in length, roughly 1.6*1 mm in cross section. They are auto-fibrillating and, although being made of a single piece of polypropylene, they look like a bundle of thinner fibers stuck together. This property provides an improved bond with the cement matrix.

The characteristics of these two fibers types are detailed and compared in Table 1.

Mixes investigated: The target was fiber reinforced Self- Compacting Concrete (SCC). The investigated fiber (l=30mm) content were 10kg m^{-3} (0.13% by volume) and 6.75 kg m^{-3} when we use fiber (l = 20 mm) for the amorphous metal fibers and 4.5 kg m^{-3} (0.5 % by volume) for the polypropylene fibers. The hybrid mix was the associate of the contents for the respective fiber types, that is to say 10 kg m^{-3} of amorphous fibers (l = 30 mm) plus 4.5 kg m^{-3} of polypropylene fibers and 6.75 kg m^{-3} of amorphous fibers (l = 20mm) plus 4.5 kg m^{-3} of polypropylene fibers. The behaviour of the matrix itself, with no fibers, was also investigated. The different mixes will be designated as illustrated in the following example: self-compacting concrete with no fibers = SCC, self-compacting concrete with 10 kg m^{-3} of amorphous metal fibers (l = 30 mm) = SCCMF1, self-compacting concrete with 6.75 kg m^{-3} of amorphous fibers (l = 20 mm) = SCCMF2, self-compacting concrete with 4.5 kg m^{-3} of polypropylene fibers = SCCSF, hybrid self-compacting mix with 10 kg m^{-3} of amorphous metal fibers (l = 30 mm) plus 4.5 kg m^{-3} of polypropylene fibers = SCCFMS1, hybrid self-compacting mix with 6.75 kg m^{-3} of amorphous metal fibers (l = 20 mm) plus 4.5 kg m^{-3} of polypropylene fibers = SCCFMS2.

Starting from a reference composition[6,7] each mix type was optimised for its fibre reinforcement. For the self placing mixes, the sand/gravel ratio and the filler content were varied until obtaining the required workability with no segregation. The compositions and the workability parameters of all the mixes are given in Table 2.

For the self-compacting concretes containing hybrid fibers, the dosage of superplasticizer was increased properly to maintain a good workability. The mixtures were batched in 30-l vertical axis concrete mixer. The cement, sand and fibers were dry-mixed for 30s. This was followed by the addition of coarse aggregate, water and the superplasticizer, with a mixing time of 5 min. The specimens were demolded after 1 day and then placed in a curing room with 90% relative humidity and tested at 7 day age.

Testing procedures: For each mixture, nine specimens (six 100*100 mm cubes and three 100*100*500 mm beams) were prepared. The compressive and splitting tensile tests were carried out on the 100*100 mm cube specimens. The four- point loading flexural tests were carried out at a loading rate of 0.05 mm/mn on the 100*100*500 mm beams according to the requirements of ASTM C 1018[8]. A notch 10 mm deep was cut at mid length of the prisms. During the flexural test, the load and the midspan deflection were recorded on a computerized data recording system and the load-displacement curve was drawn.

RESULTS

All test results are summarized in Table 3, while graphical representations of the results are displayed in Fig 1 and 2. Each strength value presented in Table 3 is the average of three specimens. A total of 54 specimens were tested in this investigation.

Compressive strength: Table 3, it was found that among the two types of fibers, amorphous steel fibers (l = 30 mm) gave the highest, polypropylene fibers gave the lowest compressive strength. When the fibers used in hybrid form, it obviously increased strength in the case of amorphous steel fibers (l = 20 mm)-pp fibers (sccfms2). In the case of amorphous steel fibers (l = 30 mm)-pp fibers, it slightly increased strength compared to simple amorphous steel and simple pp fibers.

Table3: Total energy consumed and toughness index

Type of concrete	σ'c en MPa	MOR (MPa)	Energy en Knmm E_{5mm}	Toughness index I_5	I_{10}	I_{30}
SCC	36.03	4.01	2.30	3.06	3.85	4.55
SCCMF1	38.5	5.11	18.10	2.50	4.50	6.57
SCCMF2	38.36	5.44	26.06	2.92	3.78	14.56
SCCSF	36.4	4.8	38.56	3.50	8.88	17.73
SCCFMS1	38.5	5.11	30.72	3.20	4.65	8.31
SCCFMS2	41.4	6.15	39.04	4.96	10.74	18.80

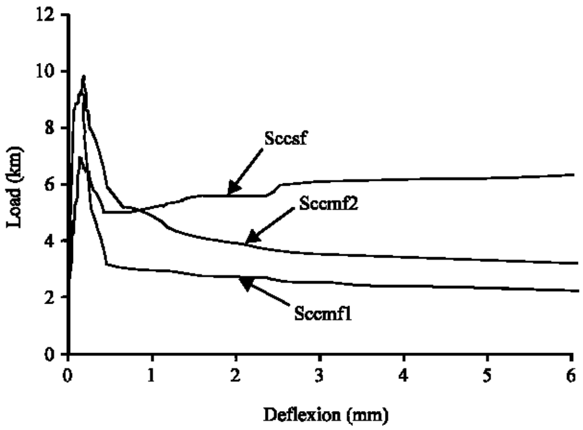

Fig. 1: Plots of flexural load versus deflexion for simple fiber-reinforced self-compacting concrete beams

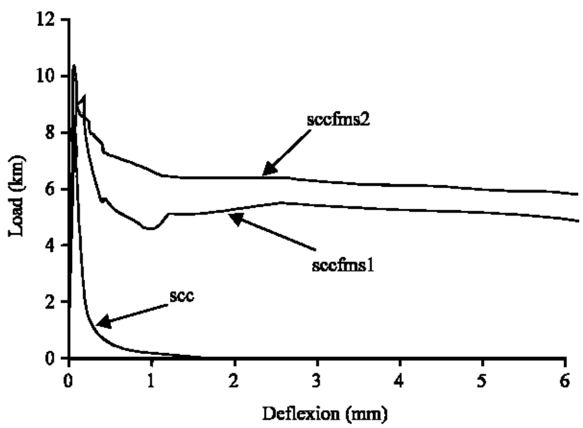

Fig. 2: Plots of flexural load versus deflexion for hybrid fiber-reinforced self-compacting concrete beams

Modulus Of Rupture (MOR): Fiber addition increased MOR with all fibers. Among the two types of fibers, amorphous steel fibers gave the highest MOR. When the fibers were used in hybrid form, it increased MOR in the case of amorphous steel fibers (l = 20 mm)-pp fibers compared to any of the simple fibers. In the case of amorphous steel fibers (l = 30 mm)-pp fibers, it slightly increased MOR when compared to simple pp fibers and amorphous steel fibers.

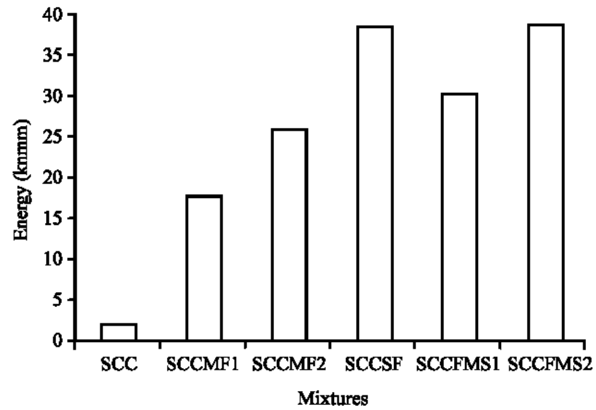

Fig. 3: The variation of rupture energies for different mixtures

Flexural toughness: By bridging across macrocrack and reducing its opening, the fibers obviously affect the postpeak flexural softening response of the self-compacting concrete. Figure 1 and 2 compare the load deflection of self-compacting concrete beams reinforced with amorphous steel fibers l = 20 mm and l = 30 mm, pp fibers and their two hybrid forms. From the figures, it was found that for the unreinforced self compacting concrete, the material demonstrated relative brittle behaviour, the load decreases rapidly with increase of midspan deflection after peak load. However, for the reinforced self compacting concretes, the decrease trends were flatter. Moreover the load platform or pseudohardening responses appeared generally, which were much dependent on the type of the added fibers and their combinations. A summary of calculated toughness indices is reported in Table 3. The data showed that the toughness was increased with all fibers[9]. Among the three individual fibers, pp fibers gave the highest flexural toughness values for all of indice I_5, I_{10} and I_{30}, while steel (l = 30 mm) fibers gave the lowest toughness index of I_{30} and steel fibers (l = 20 mm) gave the lowest toughness indices of I_5 and I_{10}. However, in hybrid form, the ductility characteristics were dramatically improved in case of pp-steel fibers (l = 20 mm). It gave the highest flexural toughness, which was much higher compared to that of simple pp fibers or steel fibers, especially for the index of I_{30}, as shown in Fig. 2. Steel fibers (l = 20 mm)-pp fibers and steel fibers (l = 30 mm)-pp fibers demonstrated similar flexural toughness when compared to simple pp fibers or steel fibers.

Energetic approach: For each composition energy was computed till a deflection of 5 mm (E_{5mm}). This energy is an indicative of the mix toughness, particularly in post-fissuration domain[4]. The more it is high the more the cementic composite is tough. The results are shown in Table 4 and plotted in Fig. 5.

We notice first of all the fibers importance in changing the toughness of hybrid fibers self-compacting concrete. The highest energy value is observed for SCCFMS2 which contain exactly the same number of metallic fibers as SCCFMS1 but with different dimensions (the fibers in sccfms2 are shorter).

The toughness index during the loading have been also calculated for each type of concrete and the results are presented in Table 3.

For each mix the dissipated energy until the first crack were calculated. We observe that toughness increases for all hybrids mix relatively to SCC without fiber. However SCCFMS1 gives the lowest toughness index relatively to other hybrids mix, but with a failure energy intermediate when compared to other mix. This is probably due to the length of metallic fibers (slenderness). It is proved that The short fibers were the most adapted in such cases. These short metallic fibers are rondomly mixed in the cementous matrix with workability and remarkable setting that gave them a better uniform distribution[4]. The synergy (in term of toughness index) between different mix has been analysed and better performances are obtained with hybrid mix of short fibers as shown in Table 3.

DISCUSSION AND CONCLUSION

In order to strengthen the matrix, the specific fiber spacing must be decreased to reduce the allowable flaw size[3]. This may be achieved by using short fibers, such as steel fibers (l = 20 mm). These fibers can provide bridging of the micro-cracks before they reach the critical flaw size. To provide the toughening component, fibers of high ultimate strain capacity are required so that they can bridge the macrocracks in cimentous matrix and pp fibers or steel fibers are used for this purpose. Between these two fibers, pp was a low modulus fiber, the hybrid systems containing pp appeared to be less effective in controlling matrix crack opening. From the test results above, it was found that the main advantage of polypropylene fiber addition is the resulting high compressive and splitting tensile strengths, while the main advantage of steel fiber addition is the resulting high MOR and flexural toughness. Therefore, the pp-steel fiber (l = 20 mm) hybrid was the most benefical for the improvement of strength and flexural toughness. A clear synergy was observed in the hybrid self-compacting concrete containing steel fibers (l = 20 mm) and pp fibers. From Table 3, improvement of 15% in compressive strength, 53% in MOR and 62_313% in toughness indices were obtained for pp-amorphous steel fiber (l = 20 mm) hybrid composite compared to unreinforced self compacting concrete.

As can be seen in Fig. 2, the load carrying capacity for the amorphous steel fiber (l = 30 mm)-pp hybrid decreases rapidly in the postpeak region. The brittle response may be attributed to the length of fibers. However, the decrease in load was recovered as the steel fibers began to pull out from matrix. The toughness of amorphous steel fibers (l = 20 mm) -pp hybrids represented an increase of about 186 and 6% for I_{30} compared to simple steel fibers (l = 30 mm) and pp fibers, respectively.

Obviously, the presence of pp fibers had increased the resistance of the composite reinforced with randomly distributed short steel fibers and vice versa. As a result, the potential strength capacities of pp fibers or steel fibers were better utilized and the strength and flexural toughness of steel fibers (l = 20 mm)- pp hybrids were hence higher than the all other composites.

Various conclusions can be drawn from this experimental study. The test results first indicated that at same number of fiber l = 30 mm and l = 20 mm, it is possible to obtain with l = 20 mm, material with the enhanced strength and improved toughness from hybrid fibers.

While the addition of fibers does not enhance the compressive strength of the mix, but the hybrids form clearly enhances the MOR.

Hybrids based on steel fibers (l = 20mm) and polypropylene fibers demonstrated some synergy.

Of the two amorphous steel fibers investigated, the short fiber is clearly far more effective in producing synergy in hybrids than the length fiber.

While hybrid fiber reinforced self compacting concrete are promising and have been used in several areas[10], there is much further research needed to develop the science and rationale necessary for their optimization.

Further tests are carried out for the case of polypropylene fibers lenght and will be the object of futur paper in the same journal.

ACKNOWLEDGEMENTS

I would like to thank all the staff of laboratory of materials and durability of construction (LMDC), INSA UPS Toulouse and especially Mr A. Turatsinze reader and Mme G.Arliguie laboratory director for their welcome and help to acheive this work.

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