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Fiber Reinforced Concrete for Sustainable Structures

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Fiber Reinforced Concrete for Sustainable Structures

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Preface

Fiber Reinforced Concrete for Sustainable Structures

In recent years, human sustainability has been increasingly associated with the integration of economic, social and environmental spheres. The cement-based materials industry is committed to minimizing any negative impact it may contribute to the natural environment. The papers included in this special publication discuss some of the sustainability aspects of using fibers in a chopped and textile form in concrete structures, including the role of fiber reinforcement in enhancing durability, optimized structure size, reduced weight, reduced footing dimensions and recyclability, lessons learned from real life situations and lay the foundation for Life Cycle Engineering Analysis with fiber reinforced concrete.

Recognizing the sustainability aspects of using fibers in cement-based materials, ACI Committee 544 Fiber Reinforced Concrete, together with 549 Thin Reinforced Cementitious Products and Ferrocement and 130 Sustainability of Concrete sponsored a technical session entitled Advances in Fiber Reinforced Concrete for Sustainable Structures at the Fall 2012 ACI Convention in Toronto and two technical sessions on the same topic at the Fall 2013 ACI Convention in Phoenix. Papers were presented by invited international experts from Belgium, Brazil, Canada, Italy, Israel, Turkey and the United States of America.

This Symposium Publication (SP) contains eight papers which provide insight on the state of the art of the topic in the academia, in the industry and in real life applications. The topics of the papers cover sustainability aspects of using fiber reinforced concrete ranging from durability and interface mechanisms of natural fiber reinforced concrete (FRC), evaluation of eco-mechanical performance of FRC, reducing carbon dioxide emissions of concrete, as well as applications of fiber reinforcement for self-consolidating concrete, bridge link slabs, extruded prefabricated elements, slab systems and fabric-reinforced cementitious matrix systems for strengthening unreinforced masonry walls. The papers included in this publication have been peer reviewed by international experts in the field according to the guidelines established by the American Concrete Institute.

On behalf of ACI Committee 544 Fiber Reinforced Concrete, and committees 549 Reinforced Cementitious Products and Ferrocement and 130 Sustainability of Concrete, the editors would like to thank all the authors for their contributions and the reviewers for their assistance, valuable suggestions and comments.

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On the Durability and Interface Mechanisms of Natural FRC: A Material for the Sustainable Construction Industry

by Flávio de Andrade Silva, João de Almeida Melo Filho, Saulo Rocha Ferreira and Romildo Dias Toledo Filho

Synopsis: The durability performance and interface transition zone of natural fiber reinforced concrete has always been a major concern. Natural fibers due to its hydrophilic nature present a high volume variation which may cause degradation in the fiber-matrix interface. Furthermore, natural FRC may undergo an enhanced aging process, while submitted to a humid environment during which they may suffer a reduction in ultimate strength and toughness. This paper presents how the use of a matrix with low content of calcium hydroxide can mitigate the embrittlement process of natural fibers. The durability performance of the composite systems is examined and the mechanisms for the significant delay in the fiber degradation when the total amount of calcium hydroxide is reduced from the matrix discussed. Furthermore, it is shown how the repeated wetting and drying cycles affects the fiber-matrix interface. Pull-out tests were performed in sisal fiber cement composite systems to study the mechanisms that influence the fiber-matrix bond. The results showed that the use of a matrix with low amount of calcium hydroxide improved the composite durability and that the wetting and drying process reduced the water absorption capacity of the fiber and increased the fiber-matrix bond.

Keywords: cement based composites, natural fibers, sisal, durability, interface, microstructure.

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INTRODUCTION

In the line of development of materials reinforced with natural fibers, many researches have been carried out on cementitious and polymeric matrix composites and promising results have been achieved, showing an improvement in durability, strength and ductility [1-5]. The use of natural fibers as reinforcement shows to be beneficial in many aspects, including sustainability, availability, low cost and low energy consumption. Natural fiber reinforced composites have the potentiality to become the ultimate green material option, minimizing the use of natural resources and overall lifetime impact.

Sisal as well as other natural fiber cement based composites produced with ordinary Portland cement (OPC) matrices undergo an enhanced aging process, while submitted to a humid environment during which they may suffer a reduction in ultimate strength and toughness. The aging process is due to fiber mineralization and results in a reduction of the tensile strength of fibers and a decrease of the fiber pull-out ligament after fracture. This mineralization process is a result of migration of hydration products (mainly $\text{Ca}(\text{OH})_2$) to the fiber structure [1,3]. Several works found in the literature discussed the durability problem of natural fibers when used in a cement based matrix and some of them presented counter-measures to avoid the fiber mineralization process [6-18]. The most promising treatment is the partial substitution of Portland cement by pozzolanic materials in order to reduce the amount of calcium hydroxide in the matrix.

Toledo and co-workers [9] evaluated sisal and coir fiber reinforced cement composites durability by means of accelerated aging processes. Counter-measures to avoid fiber degradation such as carbonation of the matrix in a CO_2 -rich environment, immersion of fibers in slurried silica fume prior to incorporation in the ordinary Portland cement matrix, partial replacement of OPC matrix by undensified silica fume or blast-furnace slag and a combination of fiber immersion in slurried silica fume and cement replacement was investigated. Regarding to the tests in specimens with partial cement replacement by pozzolanic materials the results obtained indicate that the treatment of the matrix with undensified silica fume was an effective means of slowing down the strength loss and embrittlement of the composites. The specimens incorporating slag were quite sensitive to the cycles of wet and dry and presented a strong deterioration with time.

The previous works [13,14] performed by the authors confirmed that the partial cement replacement by pozzolanic materials in order to complete the consumption of the calcium hydroxide produced during the cement hydration process is the most promising treatment resulting in a composite with increased durability. Results have shown that continuous sisal fiber cement-based composites produced with a

matrix with low contents of calcium hydroxide preserved its original toughness and strength even when subjected to 100 wetting and drying cycles.

Furthermore, due to the low bond strength of natural fibers to matrices based on Portland cement, which according to the literature varies between 0.32 and 0.72 MPa, it is necessary to use a high anchorage length to optimize the fiber-matrix stress transfer [19, 20]. Associated with a low chemical bond, the high water absorption capacity of sisal fibers causes variations in its volume, resulting in loss of physical bond with the matrix due to a fatigue degradation process in the interfacial transition zone.

A reduction in the fiber hydrophilicity can be achieved by drying and rewetting cycles [21] and treatment with acetic acid [22]. These treatments promoted a lower volumetric expansion of pulps and fibers of natural origin as well as alterations in their mechanical properties. Washing in warm water led to the same result by promoting modification of the surface layer of coir fibers, increasing the contact area and resulting in a better mechanical behavior of cement composites [23].

In the present work continuous sisal fiber cement based composites were produced using two matrices: one with 50% partial cement replacement by metakaolin (PC-MK) and the other composed by ordinary Portland cement only (PC). The two developed composites were subjected to laboratory controlled wetting and drying cycles. The composites were subjected to 5, 10, 15, 20 and 25 aging cycles and then tested under a four point bending load configuration. A high resolution digital camera was used to take and record images during the tests at regular intervals. The images were processed in an image analysis program to correlate crack spacing to the applied displacement after being submitted to the various cycles. Pull-out tests were performed in sisal fibers previously subjected to wetting and drying cycles. A microstructural investigation was performed, using a scanning electron microscope, to observe the degree of degradation in the fibers after being exposed to the cycles.

EXPERIMENTAL PROGRAM

Materials and processing

The sisal fibers were obtained from the sisal plant (see Figure 1) cultivated in farms located in the Bahia state, Brazil. They were extracted from the sisal plant leaves in the form of long fiber bundles. The fiber extraction from the leaf was done by semi-automatic raspadores. From a 100 kg of sisal leaves about 3.5 kg extractable fiber is obtained. These fibers were characterized mechanically by Silva et al. [24, 25, 26]. Monotonic tension tests were performed in fibers with gage lengths ranging from 10 to 40 mm. The sisal fibers presented mean elastic modulus and tensile strength around 19 GPa and 400 MPa, respectively.

Regarding to the sisal fiber microstructure it is formed by numerous individual fibers (fiber-cells) which are about 6 to 30 μm in diameter. The individual fiber-cells are linked together by means of the middle lamella. The chemical composition of the sisal fiber comprehends approximately 54-66% cellulose, 12-17% hemicellulose, 7-14% lignin, 1% pectin and 1-7% ash. To be used as reinforcement in the developed composite, the sisal fibers were washed in hot water, brushed to separate the individual fibers and cut to the size of the molds (400 mm). The fibers were weighted and separated into five different layers resulting in a total volume fraction of 6%. The sisal fibers were stitched by three cotton fibers to make a homogeneous spacing between the fibers so as to facilitate the molding process.

Two matrices were designed using the Portland cement CII F-32 defined by the Brazilian standard [27] as composed with filler (in mass: 85%<clinker<91%; 3%<gypsum<5%; 6%<filler<10%) with a 32 MPa compressive strength at 28 days. The PC matrix which was composed only by Portland cement and the PC-MK matrix which had a partial cement replacement by 50% of amorphous metakaolin. The amount of cement replacement by MK has been defined in the author's previous work [28]. The mortar matrix used in this study presented a mix design of 1:1:0.4 (cementitious material:sand:water by weight). In order to achieve the desired rheology (flow table spread of 400 mm) 2% of superplasticizer was used.

The matrix was produced using a bench-mounted mechanical mixer with a capacity of 20 liters. The cementitious materials were dry mixed for 30 seconds (for homogenization) with the subsequent addition of sand. The powder material was mixed for 30 seconds more and the superplasticizer previously diluted in the water was slowly poured into the running mixer and subsequently mixed for 3 minutes. For the

production of the laminates, the mortar mix was placed in a steel mold by a manual lay-out technique, one layer at a time, followed by one layer of fibers and vibration (see Figure 2). The total amount of fibers used as reinforcement were distributed over five layers and represents a volume fraction of 6%. The composites were fog cured for 28 days in a cure chamber with 100 % relative humidity (RH) and 23 ± 1 °C.

To mold the pull-out specimens a special mold was developed. After filling the mold with the matrix, the top cap was fixed and the fiber stretched slightly for alignment. The mortar was placed in plastic bags before being placed in the mold as to facilitate the casting process. The embedment length of 25mm was selected. After 24 hours, the specimens were demolded and placed in a fog room ($HR\% \geq 95\%$) to moist curing for 7 days for the pullout test.

Testing methodology

Durability testing—Four point bending tests were performed before and after controlled cycles of wetting and drying and at ages ranging from 28 days to 5 years. For the drying cycles a forced air flow chamber (FAFC) was used. The FAFC was designed in the author's previous work [13] in order to allow the control of the wind velocity and air temperature enabling a simulation of the environmental conditions to which the material can be subjected in practical applications. In the present study the FAFC was set to a temperature of 36 ± 1 °C and wind velocity of 0.5 m/s. The length of the wetting and drying cycles was determined in the author's previous work [13] as one day under water followed by two days of drying under the FAFC conditions. For the tests at the various ages the composites were stored in the FAFC at the same conditions as those described above.

The bending tests were carried out at an actuator displacement rate of 0.5 mm/min. Three specimens with geometry of 400 mm x 100 mm x 12 mm (length x width x thickness) were tested under a four point bending configuration (300 mm span). Displacements at mid-span were measured using electrical transducers (LVDT) and were continuously recorded, together with the corresponding loads.

The cracking development of the composite was recorded during the loading cycle of the bending test at regular time intervals for posterior image analysis. A Nikon D90 digital camera with an AF Micro Nikkor 60mm lens (f/2.8D) and frame grabber captured images of 4288 x 2848 pixels in resolution at 60 second intervals. Images were used to measure the crack spacing during bending tests performed before and after the aging cycles. Photos of the tension face in bending were taken using a mirror positioned at 45° with respect to the specimen.

Fiber-matrix interface testing—Pull-out tests were performed in sisal fibers previously submitted to wetting and drying cycles. This process leads the fiber to a hornification process: stiffening of the polymeric structure present in lignocellulosic materials. This is a result of repeated wetting and drying cycles which increase the degree of crosslink within the fiber microstructure. The process used in the present work consisted in immersing the fibers in water ($T \sim 22$ °C) and its removal after saturation for drying. The sisal fibers were placed in a container with water until, after three hours, it reached its maximum water absorption capacity. Then the drying process was started in a furnace at a temperature of 80 °C. The system used is equipped with a furnace with electronic temperature control, and connected to a scale, with precision of 0.01g. The furnace was programmed to reach 80 °C at a heating rate of 1 °C/min and to maintain this temperature for 16 hours. After 16 hours of drying, the furnace was cooled down to the temperature of 22 °C in order to avoid possible thermal shock to the fibers. This procedure was repeated ten times. More details can be obtained elsewhere [29].

The pull-out tests were performed in an electromechanical testing machine Shimadzu AG-X with a load cell of 1kN. The tests were carried out using a displacement rate of 0.1 mm/min. The samples were fixed in the machine grips through a system with hinged-fixed boundary conditions as shown in Figure 3. Five tests were performed for each an embedment length of 25mm after 7 days of curing in the fog room and a day of drying under the following conditions of temperature and humidity: $T: 22^\circ \text{C} \pm 1^\circ \text{C}$ and relative humidity of $43\% \pm 3\%$.

RESULTS AND DISCUSSION

Figure 4 shows one representative flexural stress-deflection curve for the PC-MK and PC composites tested at 28 days of age (no aging). The results of the evaluation for all curves are given in Table 1. In general it can be seen that both PC-MK and PC composites present a deflection hardening response with a multiple cracking formation. The flexural behavior begins with an elastic-linear range where both matrix and the fiber behave linearly up to a point where the matrix cracks (zone I). The PC-MK composite presented a limit of proportionality (LOP) of 6.67MPa while for the PC composite a value of 4.95MPa was reported. Standard deviations varied from 0.45 to 0.74MPa. The post LOP range was characterized by a multiple cracking formation (zone II) until no more cracks can form. The widening of the existing cracks takes place in region III where the crack spacing becomes constant. The computed crack spacing was 19.25mm for the PC-MK and 5.44mm for the PC composite. The failure of the composites occurred after a mid-span deflection of around 27mm (PC composite) and 31mm (PC-MK composite). The failure was followed by a strain softening response due to the localization and widening of one of the existing cracks (zone IV). The ultimate flexural strength values observed for the PC and PC-MK composites were 18.73 and 26.86MPa, respectively.

In the present work the toughness was measured as the area under the load vs. deflection curve up to the ultimate bending strength. The toughness obtained by the PC-MK composite (no aging) was 22% higher than that of the PC. In the same way as observed in the author's previous work [13] a superior number of cracks with lower width was reported for the PC composites (34 cracks) in comparison to the PC-MK (15 cracks). This behavior may indicate a higher fiber-matrix bond adhesion for the PC composite system.

Figure 5 shows one representative flexural stress-deflection curve for the PC-MK and PC composites tested under bending load after being exposed to 5, 10, 15, 20 and 25 cycles of wetting and drying. The results of the evaluation for all curves are given in Table 1. It can be observed that the LOP increased with the aging process in the two studied systems (refer to Table 1). This can be explained by the fact that more hydration products were formed as a result of the accelerated aging which led to an increase in the matrix strength. For the PC-MK system a ductile behavior with a multiple cracking formation is observed not only for the reference specimens but also for the aged ones. On the other hand the PC composites presented a progressive degradation process with the cycles. It can be seen that both the ductility and bending strength reduced to the same level of an unreinforced matrix after 25 cycles of wetting and drying.

From Figure 5 it can be seen that the accelerated aging process is more severe in the first 10 cycles for the PC composite. The PC system's toughness lowered from 13.94 to 3.67kJ/m² at 10 cycles and further decreased to 0.07kJ/m² after 25 cycles. The reduction in the bending strength reached the same value (7.4MPa) of the unreinforced matrix after 25 cycles. From these results we can first conclude that 10 cycles is a threshold level where most of the degradation in the fiber and fiber-matrix interface takes place and that the sisal fiber completely degrades when the PC composite is aged at 25 cycles.

For the PC-MK composite the toughness values decreased from 17.09 to 10.31kJ/m². The bending strength presented a reduction in the first 10 cycles from 28.86MPa to 21.64MPa. After 10 cycles of aging the variation in the mean bending strength values were not statistically representative. As no degradation was observed in the sisal fibers extracted from the composite, no reduction in the stiffness of the post-cracking region was observed and no changes in the cracking pattern occurred, the authors explain the decrease in bending strength and ductility as follow. In the first 10 cycles there was a change in the fiber-matrix interfacial shear mechanisms. The adhesional and frictional bond stresses may have lowered after the first 10 cycles as a result of an interface fatigue mechanism. This is due to the volumetric variation of the sisal fibers as a result of the wetting and drying cycles as illustrated in Figure 6. After 10 cycles the fibers undergo a hornification process which is characterized by the stiffening of the polymeric structure presented in the fiber cell wall as a result of the water removal. This process reduces the fiber volumetric variation mitigating the damage in the fiber-matrix interface. To prove this hypothesis fiber-matrix pull-out tests were performed in sisal fibers previously submitted to 10 cycles of wetting and drying. Figure 7 shows the pull-out test results of untreated sisal fibers (Figure 7(a)) and sisal fibers subjected to 10 cycles of wetting and drying (Figure 7(b)). It can be seen that for the cycled fibers the average pull-out force and the stiffness of the elastic linear range increases. Furthermore, the pull-out behavior at the post-peak region also changes showing that the frictional stress increases.

The effect of the aging cycles in the crack spacing is presented in Figure 8. The aging process seems not to affect the fracture behavior of the PC-MK composite. Its crack spacing is around 19mm with a standard deviation that ranges from 3 to 7mm. In a different manner the cycles are affecting the fracture process of the PC composite and changing its behavior from a multiple to a single cracking formation. Again it seems that there is a threshold level around 10 cycles for the PC composite. After this point the number of cracks drastically reduces from 34 to 15 and then to 1 (after 20 cycles).

A microstructural investigation was performed in the fibers extracted from the PC-MK and PC aged composites to investigate their degradation process. Figure 9 shows SEM micrographs of fibers in natura (reference) and after being exposed to 25 cycles of wetting and drying. As for comparison purposes all the micrographs show one single fiber cell obtained using the same magnification and the same working distance. In Figure 9 (a and b) it can be seen that the fiber structure of the sisal extracted from the PC-MK composite remains intact with no signs of degradation. In Figures 9 (c and d) it's presented the sisal fiber micro-structure after being exposed to 25 cycles inside the PC composite. The sisal micro-structure shows clear signs of degradation indicating that part of the material that composes the fiber cell wall was degenerated. This micro-structure analysis confirms that in the PC composite the fiber-cells are mineralized possibly due to the high calcium hydroxide concentration.

The addition of metakaolin has successfully sustained the capacity of energy absorption of the PC-MK composite, increasing its first crack strength and maintaining its ultimate strength through accelerated aging, proving to be a good solution for the durability issues of natural fiber reinforced cement based composites.

CONCLUSION

The following conclusions can be drawn from the present work on the durability mechanisms of sisal fiber cement based composites:

- Flexural tests performed after the accelerated aging cycles showed that the PC composite system completely loses its ductility and strength after 25 cycles of wetting and drying. It was observed that the accelerated aging process is more severe in the first 10 cycles for the PC composite. The residual mechanical parameters after 25 cycles were the same as those observed in un-reinforced matrices. The fracture process changed from a multiple cracking to a single cracking formation after 20 cycles.
- For PC-MK systems the mechanical performance was slight affected by the aging cycles. The cracking pattern has not been altered during the aging cycles and the crack spacing remained constant to around 19mm. A small reduction in strength and toughness were noticed during the first 10 cycles. The authors related this phenomenon to a fatigue in the fiber matrix-interface due to the volumetric changes of the sisal fiber with the wetting and drying cycles.
- Pull-out tests showed that fibers previously submitted to wetting and drying cycles present a higher stiffness in the linear elastic range, a higher adhesional and frictional bond. This is probably a result of the hornification process suffered by the fibers during wetting and drying. This process increases the degree of crosslink within the fiber microstructure resulting in a more stiff polymeric structure.
- Microstructural observation suggested that the sisal fibers undergo a mineralization process when used as reinforcement in conventional Portland cement matrices. The cell walls of the fibers were damaged after the wetting and drying cycles. No signs of fiber degradation were noticed for sisal fibers exposed to the aging process in PC-MK composites.
- The use of a matrix with low CH content seems to be a promising alternative for increasing the durability of natural fiber-cement based composites with aging. These materials have the potential of being used as non-structural elements in the construction industry.

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Table 1—Results of four point bending tests of PC-MK and PC composites before and after exposition to the accelerated aging cycles (mean $\pm$ standard deviation).

Mix	Aging time (Cycles)	LOP (MPa)	Displacement at LOP (mm)	Flexural strength (MPa)	Displacement at flexural strength (mm)	Toughness (kJ/m ²)	Number of cracks	Mean final crack spacing (mm)
PC-MK	0	6.67	0.51	26.86	26.15	17.09	15.0	19.25
		(0.74)	(0.073)	(0.75)	(1.36)	(1.53)	(2.1)	(4.94)
	5	8.57	0.55	24.95	26.13	13.70	14.0	15.54
		(0.29)	(0.015)	(1.58)	(1.85)	(0.99)	(1.0)	(7.00)
	10	8.11	0.54	21.64	25.64	14.18	11.0	20.00
		(1.24)	(0.085)	(0.89)	(1.57)	(1.27)	(1.0)	(3.00)
	15	7.64	0.53	22.63	27.14	12.39	11.0	19.00
		(1.23)	(0.064)	(0.46)	(0.74)	(1.49)	(0.6)	(3.00)
	20	7.78	0.51	21.24	24.90	11.80	12.0	18.40
		(0.24)	(0.093)	(0.32)	(0.81)	(1.48)	(3.1)	(3.10)
	25	7.90	0.53	20.58	25.07	10.31	11.0	17.24
		(0.28)	(0.055)	(0.16)	(0.25)	(0.32)	(1.2)	(5.80)
PC	0	4.95	0.46	18.73	27.49	13.94	34.0	5.44
		(0.45)	(0.015)	(1.36)	(0.74)	(2.75)	(2.1)	(2.12)
	5	6.55	0.47	15.87	20.89	7.83	16.0	9.00
		(0.79)	(0.066)	(0.03)	(0.09)	(0.27)	(2.0)	(2.90)
	10	6.39	0.49	10.98	13.57	3.67	15.0	12.52
		(0.73)	(0.065)	(0.86)	(0.70)	(0.88)	(1.5)	(6.18)
	15	6.90	0.44	9.07	8.50	1.68	7.0	21.00
		(0.21)	(0.053)	(0.86)	(1.11)	(0.30)	(1.0)	(11.92)
	20	6.85	0.47	6.85	0.47	0.36	1.0	91.00
		(0.77)	(0.038)	(0.39)	(0.04)	(0.07)	(0.6)	(2.00)
	25	6.93	0.49	6.93	0.49	0.07	1.0	91.00
		(0.42)	(0.065)	(0.42)	(0.06)	(0.007)	(0.0)	(2.36)

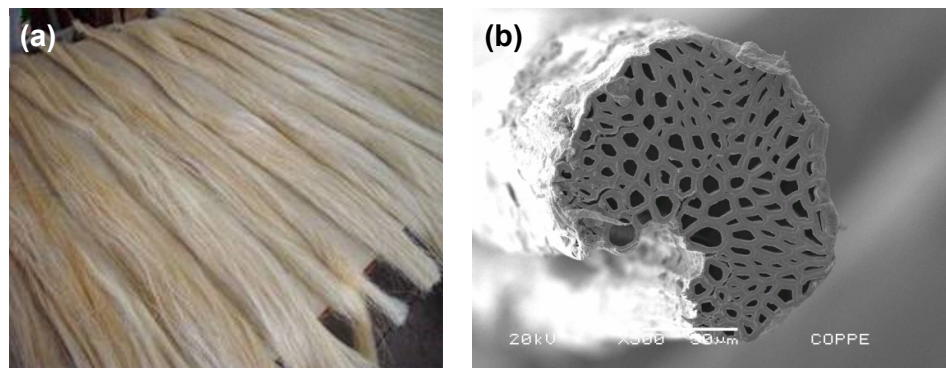


Figure 1—The sisal fiber: (a) after being washed in hot water and (b) its microstructure.

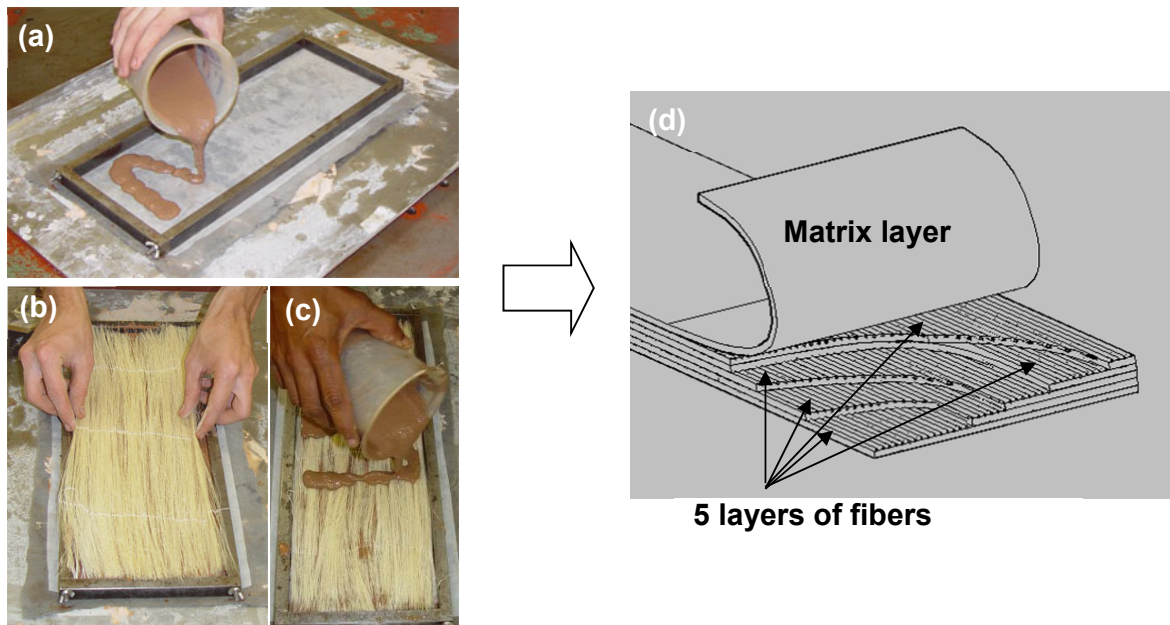


Figure 2—The composite molding procedure: (a) the first layer of matrix being poured in the mold, (b) placement of the first fiber layer, (c) placement of the second matrix layer and (d) an overview of the composite layers.

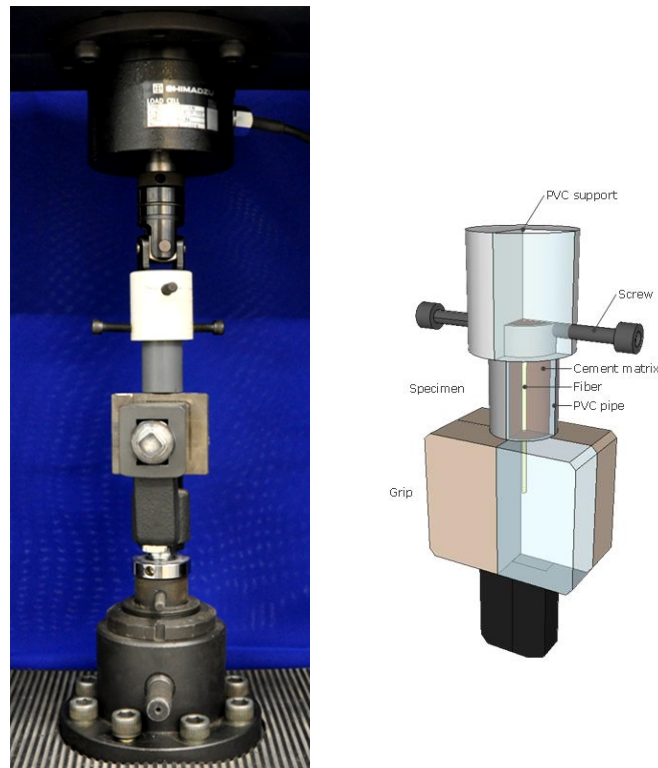


Figure 3—The pull-out test set-up.

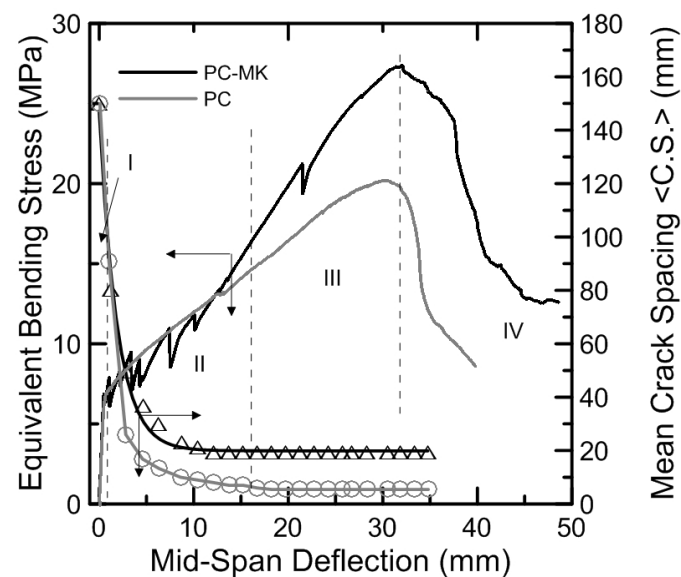


Figure 4—Flexural and fracture behavior of PC-MK and PC composites performed at 28 days of age.

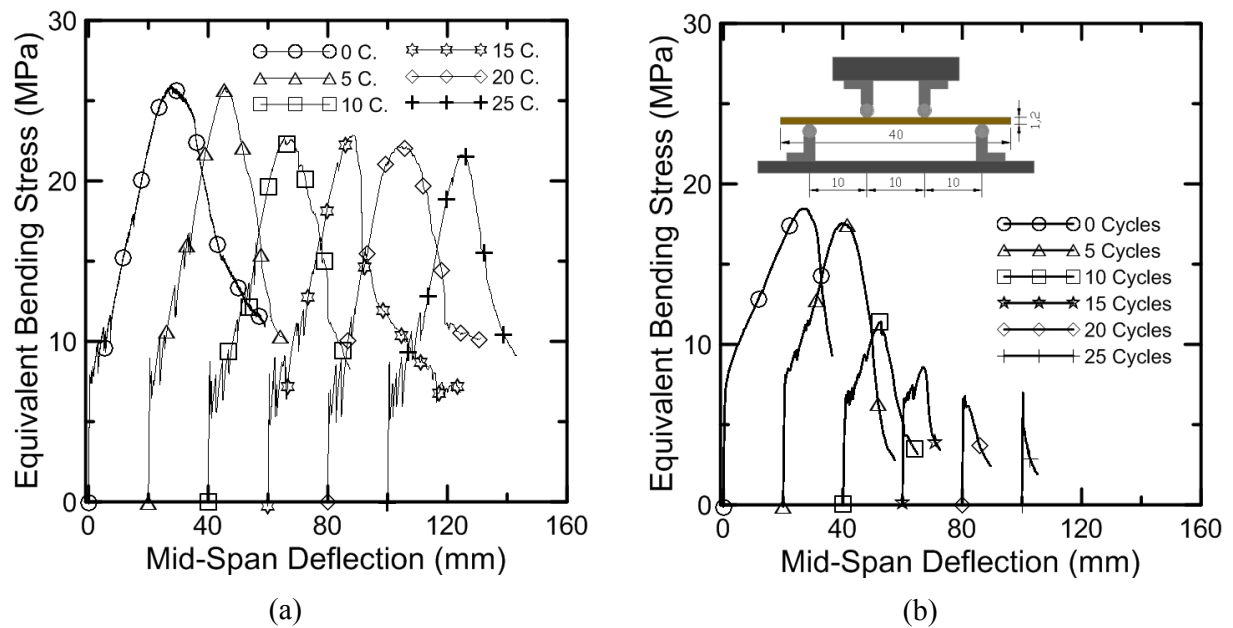


Figure 5—Effect of the wetting and drying cycles on the mechanical behavior under bending load of (a) PC-MK composite and (b) PC composite.

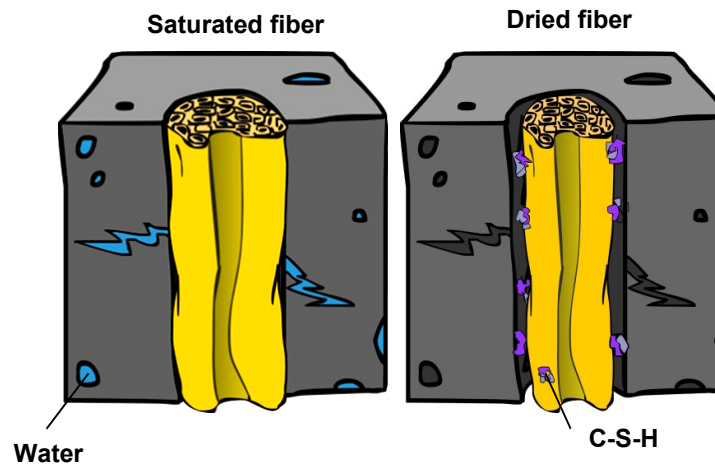


Figure 6—Idealized physical model of the volume variation of a sisal fiber inside a cement based matrix.

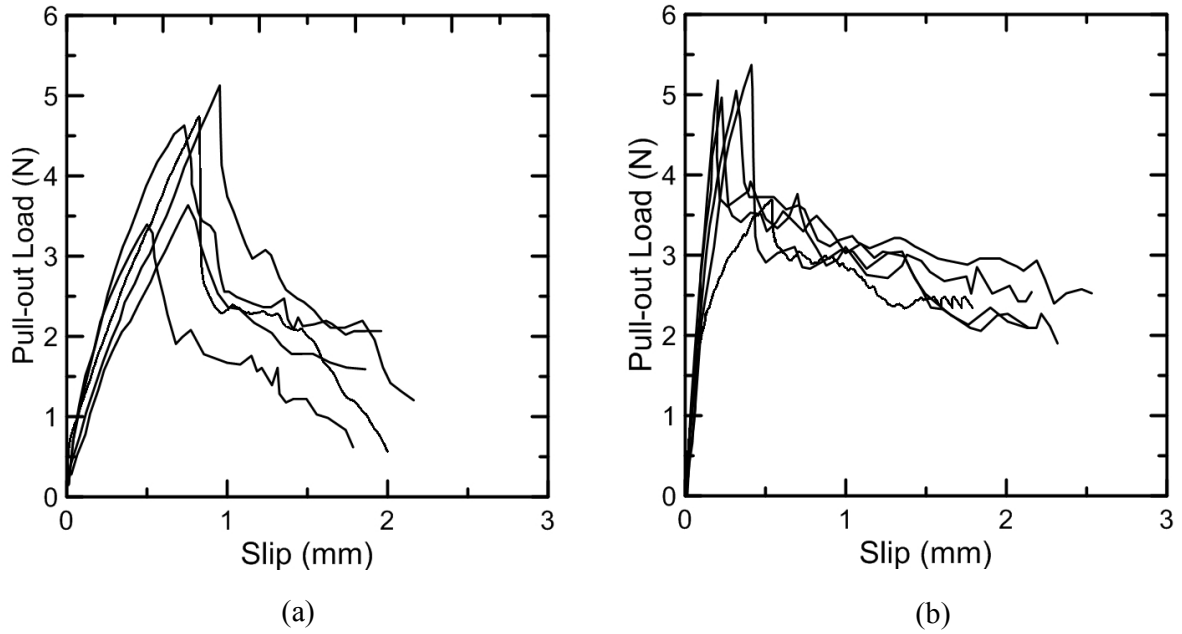


Figure 7—Sisal fiber-matrix pull-out behavior: (a) untreated fibers and (b) fibers previously subjected to 10 cycles of wetting and drying.

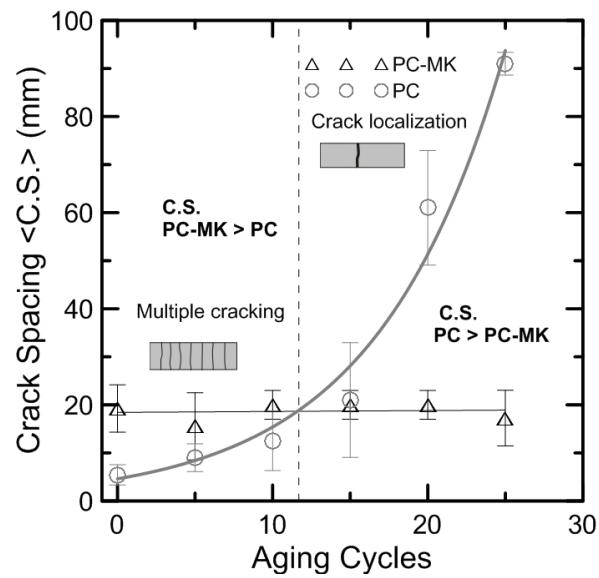


Figure 8— Effect of wetting and drying cycles on the crack spacing of PC-MK and PC composites.

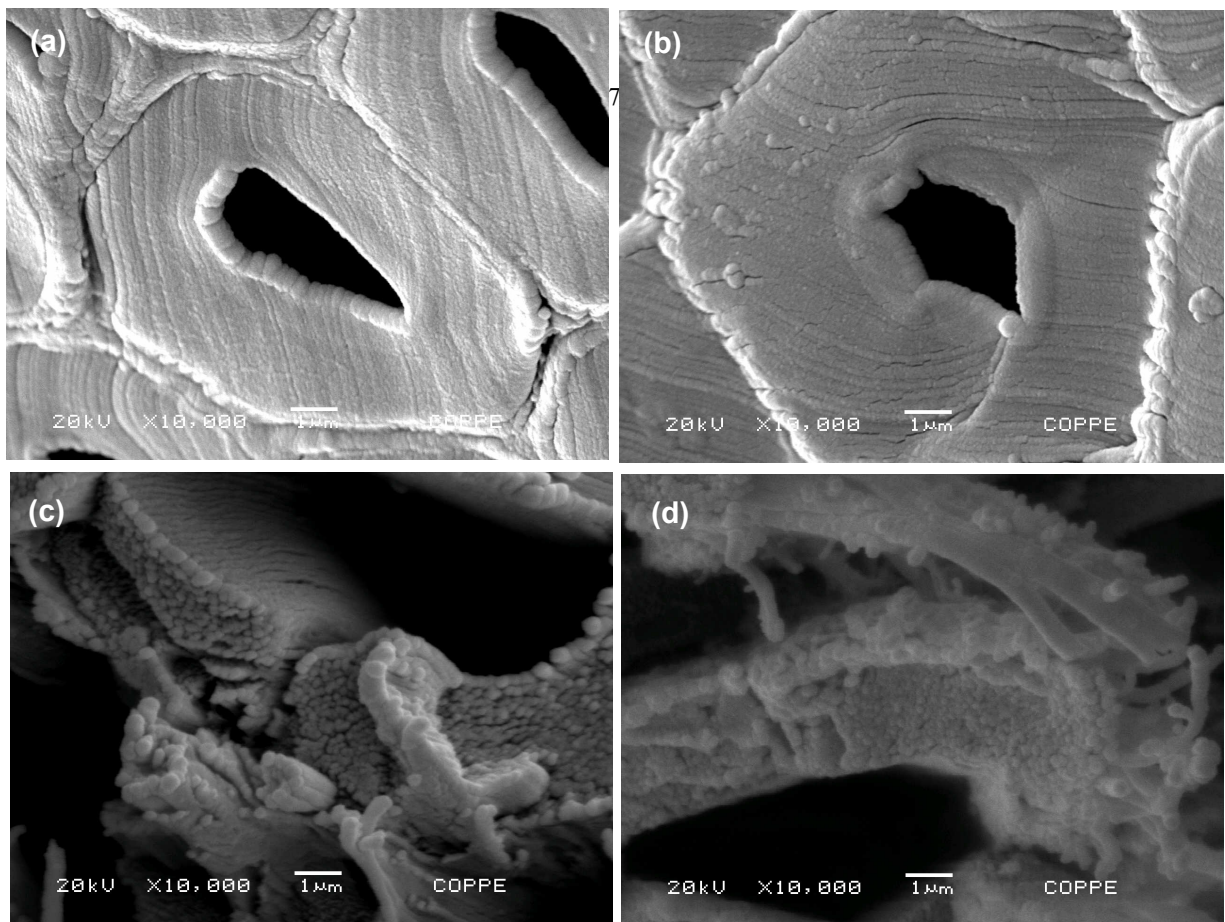


Figure 9—The effect of the wetting and drying cycles on the sisal fiber microstructure: (a) reference, (b) fiber extracted from a PC-MK matrix after 25 cycles, (c and d) fiber extracted from a PC matrix after 25 cycles.

Carbon Fiber Reinforced Self-Consolidating Concrete - Fresh and Mechanical Properties

M. Yakhlaf, K.A. Soudki

Synopsis: This paper discusses the effect of discrete pitch-based carbon fibers on the fresh and mechanical properties of self-consolidating concrete. A total of 5 non-air entrained carbon fiber reinforced self-consolidating concrete (CFRSCC) mixtures were produced incorporating fiber volume of 0%, 0.25%, 0.5%, 0.75% and 1% carbon fibers; the water-to-binder ratio (w/b) was 0.35. The fresh properties (filling ability, passing ability, and segregation) and mechanical properties (compressive strength, splitting tensile strength, modulus of rupture and toughness) of the concrete mixtures were determined. The test results revealed that at increasing amount of volume of carbon fibers decreased the filling ability and passing ability of concrete increased. The compressive strength decreased as the volume of carbon fibers increased. However, as the carbon fiber content increased the splitting tensile strength increased. Modulus of rupture and toughness of CFRSCC mixtures also increased as the volume of carbon fibers increased. The results show that it is possible to develop good crack resistant and sustainable CFRSCC mixtures for concrete structures.

Keywords: Carbon fibers; filling ability; passing ability; scanning electron micrographs (SEMs); segregation; self-consolidating concrete; modulus of rupture; toughness.

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INTRODUCTION

Self-consolidating concrete (SCC) is a special kind of concrete, which was developed in Japan. SCC flows under its own weight without the use of vibration [1]. In construction industry, Japan faced the shortage of skilled concrete workers to produce high-quality durable concrete structures; hence Japanese engineers and researchers started to develop a different kind of concrete that can be placed and finished with less skilled workers. As a result, the concept of SCC was first proposed in Japan in 1986 [1]. Ozawa and Maekawa carried out many studies to develop SCC at the University of Tokyo in Japan [2,3]. Japan was the first country that worked intensively to pragmatically use SCC in civil engineering structures [4]. In order for the concrete to be classified as self-consolidating concrete, the concrete has to have the key fresh properties of SCC; filling ability, passing ability, and segregation resistance [3,4]. SCC has been described as “the most revolutionary development in concrete” in construction over the last three decades [4]. The advantages of SCC include the following: faster construction, reduction of site workers, better and easy finishing, easy placing, good durability, reduction of noise level, and pollution [5]. SCC has been developed to compensate for the shortage of skilled labour in concrete industry. Thus, it has been rendered efficient and beneficial from both technological and economical standpoints. SCC can be used in all kinds of applications. For example, SCC can be used in big or small structures, simple or complicated buildings, horizontal or vertical structural members, precast or cast-in-place concrete components. In the United States, approximately 40% of precast production uses SCC, while approximately 2-4% of cast-in-place production uses SCC [6]. Recently, SCC has been used as a repair material in Canada and Switzerland since it has the capability to flow and fill restricted areas [7,8]. However, carbon fiber reinforced self-consolidating concrete (CFRSCC) has been used rarely in real applications (real world). Adding fibers to SCC decreases its workability and therefore it becomes progressively difficult to achieve SCC capacity [9]. For example, carbon fibers can affect negatively the SCC fresh properties such as filling ability and passing ability [10,11]. Carbon fibers may also restrict and prevent coarse aggregates from moving uniformly, thus causing segregation [12]. Despite their effect on workability, adding fibers to SCC may improve the mechanical properties of concrete [10]. Generally, concrete is a brittle material that fractures under tensile load. The addition of randomly dispersed fibers to SCC reduces the crack opening at the loading stage and assesses crack bridging, which can alter the behavior of concrete at failure [13]. Therefore, if self-consolidation is achieved in concrete the fibers will play a very important role in improving the mechanical properties.

Many studies were carried out to investigate the fresh and mechanical properties of SCC including steel, polypropylene, glass, and natural fibers [14-16]. The addition of carbon fibers to concrete affects the fresh properties of the SCC; however, they offer significant improvement to the mechanical properties such as flexural strength and toughness. In addition, impact resistance and fatigue resistance can be improved if the appropriate amount of carbon fibers is added to the concrete. Carbon fibers are attractive to engineers due to their low density and thermal conductivity [17,18]. Carbon fibers can be used to eliminate or to reduce the drying shrinkage problems as well as to limit crack width. Since the 1970s many studies have been conducted to investigate the effectiveness of carbon fibers on various properties of concrete [19,20]. Carbon fiber reinforced concrete (CFRC) has been used in many projects because of its good thermal conductivity, lightweight, and high modulus of elasticity. It has been also used to produce curtain walls, partition panel, and formwork for walls [12]. The incorporation of carbon fibers in self-consolidating concrete resulted in an improvement mechanical properties and electrical resistivity [21]. The addition of carbon fibers to concrete significantly improves mechanical properties such as flexural strength and toughness [21,22].

Two types of carbon fibers are commercially available for use in concrete; polyacrylonitrile (PAN)-based and pitch-based carbon fibers. PAN-based carbon fibers have a very high modulus of elasticity and a high tensile strength; they have been mostly used to produce aerospace and sport equipment [17,19]. Although PAN-based fibers were the first type of discrete short carbon fibers used in reinforced concrete, presently they are rarely used in civil engineering applications due to their high price. Pitch-based carbon fibers are usually used in civil engineering applications because of their lower price even though pitch-based carbon fibers have a lower modulus of elasticity than PAN-based fibers. Pitch-based carbon fibers are used in many industrial fields due to their lightweight, good chemical stability, and high heat and excellent abrasion resistance [17]. The use of pitch-based carbon fibers in reinforced concrete can increase flexural strength about 85%, flexural toughness about 205%, and compressive strength about 22%; on the other hand, the drying shrinkage can be decreased by up to 90% and the electrical resistivity up to 83% [23,24]. These advantages make pitch-based carbon fibers more attractive for use in SCC. Although many studies were conducted on the use of pitch-based carbon fibers in concrete, limited research has been carried out to produce SCC using this kind of fibers. In the present study, pitch-based discrete carbon fibers have been used to produce SCC. The freshly mixed carbon fiber reinforced SCC mixtures were tested for filling ability, passing ability, segregation resistance, air content, and unit weight. In addition, the distribution of carbon fibers in hardened SCC mixtures was examined using a Scanning Electron Microscope. From the test results, the effect of pitch-based carbon fibers on the mechanical properties was observed.

RESEARCH SIGNIFICANCE

Carbon fiber reinforced concrete, without SCC, properties has been well researched. Also, self-consolidating concrete (SCC) incorporating steel and polymer fibers has been extensively studied. However, limited research has been conducted on the use of carbon fibers in SCC. Incorporating carbon fibers in SCC can produce a high quality special concrete known as carbon fiber reinforced self-consolidating concrete (CFRSCC). CFRSCC would offer the benefits of both carbon fibers and SCC. The main purpose of this study was to examine the effects of discrete pitch-based carbon fibers on the fresh properties of SCC. The research can be useful to produce CFRSCC commercially for use in new or rehabilitated / repaired concrete structures.

EXPERIMENTAL PROGRAMME

Constituent materials of concrete

Type I cement that meets ASTM C150 requirements, crushed limestone (coarse aggregate, CA), manufactured sand (fine aggregate, FA), silica fume (SF), high-range water reducer (HRWR), pitch-based carbon fibers (CFs) and normal tap water (W) were used in this study. The manufactured sand was conform the specification OPSS 1002 [25]. Table 1 shows the physical properties of the concrete constituent materials.

Mix proportions of concretes

A total of five non-air entrained self-consolidating concrete mixtures incorporating 0-1 % by vol. pitch-based carbon fibers were developed in this study. Silica fume was kept constant at 10% by weight of binder. One mixture was a reference concrete without fibers and four mixtures had different fiber contents. Table 2 presents the details of the CFRSCC mixture proportions. The water/binder ratio (w/b ratio) was 0.35. HRWR was added to CFRSCC to enhance the workability of the mixtures: the dosage was between 7.2kg/m^3 to 38.5kg/m^3 (0.45lb/ft^3 to 2.4lb/ft^3).

Mixing method and preparation of fresh concretes

The concrete mixtures were prepared in a laboratory pan-type mixer of 50L maximum capacity. The coarse and the fine aggregates were charged and mixed together for about 60 seconds by adding a $\frac{1}{4}$ of the total mixing water. Then, the binder (cement along with silica fume) was added with a $\frac{1}{4}$ of the total mixing water and mixed for about 120 seconds. After that, mixing was stopped for resting and the mixer was covered with wet burlap to prevent loss of water. This was done to ensure that the aggregates are fully saturated. After the resting time of 180 seconds, for the control mix with no fibers, the remainder $\frac{1}{2}$ of the total mixing water blended with the HRWR was added into the mixer and the mixture was mixed for about 180 seconds. The same sequence was followed for mixtures with fibers, except that the fibers were added before adding the rest of the mixing water blended with HRWR. Various trial batches were prepared to obtain the optimum dosage of HRWR for the CFRSCC mixtures. The batch quantity was 25L for all concretes.

Test procedures

Fresh concrete mixtures were tested for filling ability, passing ability, and segregation resistance. ASTM standards were followed to determine the slump flow (filling ability), J-ring slump flow (passing ability), air content and unit weight of concrete. All the fresh properties were tested from the same batch of concrete and tests in the hardened states were: compressive strength, tensile strength, and fracture energy for hardened properties [26-32]. The segregation resistance of fresh concrete was determined following the procedure proposed by Nagataki and Fujiwara [33]. The details of fresh concrete test procedures have been described in a published paper of the authors [34].

Twelve concrete cylinders (100 mm diameter $\times$ 200 mm height) (4 in diameter $\times$ 8 in height) for the compression test, six concrete cylinders (100 mm diameter $\times$ 200 mm height) (4 in diameter $\times$ 8 in height) for the splitting tension test, and three prisms (100 mm wide $\times$ 100 mm deep $\times$ 350 mm long) (4 in wide $\times$ 4 in deep $\times$ 14 in long) for the fracture energy test (modulus of rupture and toughness) were cast immediately after testing fresh properties. The compressive strength of concrete was determined according to ASTM C39/C39M-09a [30]. The compression test was carried out at the concrete ages of 3, 7, 14 and 28 days. The results obtained from three test cylinders were averaged to determine the compressive strength of concrete. The splitting tensile strength of concretes was measured in accordance to ASTM C496/C496M-04 (2004) [31]. The splitting tension test was performed at the concrete ages of 14 and 28 days. The flexural strength (modulus of rupture) of concretes was determined by conducting the fracture energy test under third-point loading according to ASTM C1609/C1609M-10 (2010) [32]. The toughness of the concretes was also determined from the fracture energy test.

Scanning electron microscopy was taken to observe the distribution of carbon fibers in hardened concrete. This test was carried out using the prism specimens tested on the flexural strength and toughness. The specimens for this test were prepared from the fractured prism specimens by cutting them into 20 mm $\times$ 20 mm (1 in $\times$ 1 in) size (without affecting the fracture surface). The test specimens were cleaned and dried; then the fractured surface was coated with a thin gold coating (conductive material) in order to be properly scanned. These images are known as scanning electron micrographs (SEMs).

Test results and discussion

Filling ability

The filling ability was measured with respect to slump flow and T_{50} slump flow time. The results of the slump flow and T_{50} slump flow time are presented in Table 3. Carbon fibers greatly affected the slump flow of SCC. This is because, as the fiber volume increases, the interaction between carbon fibers can restrict the filling ability in SCC [35]. As shown from Table 3, the slump flow value for the mixtures varied from 625 mm to 730 mm (25 in to 29 in). The slump flow for SCC typically ranges from 550 mm to 850 mm (22 in to 33 in) [36-38]. 1% carbon fibers by volume were added to Mixture M5, which is the highest amount of fibers used in the present study; this mixture successfully fulfilled the slump flow requirements of SCC. However, it required a higher HRWR dosage than the rest of the concrete mixtures to achieve the target slump flow of SCC. This is because the filling ability of concrete was significantly reduced in this mixture due to the high volume of carbon fibers. A higher HRWR dosage was needed to improve the filling ability of CFRSCC mixtures. An increased HRWR dosage increases the deformability of concrete to achieve the target filling ability [39]. Deformability of concrete is defined as the ability of the concrete to undergo a change in its shape under its own weight, even in the restricted area that can interfere with its flow [40].

Mixtures M1 (0% carbon fibers) showed higher deformability than the other CFRSCC mixture with respect to T_{50} slump flow time. Table 3 presents the T_{50} slump flow times. T_{50} slump flow time increased with higher volumes of carbon fibers because the inclusion of fibers increases the viscosity of SCC mixture, and thus slows the flow of concrete. T_{50} slump flow time for the concrete mixtures without and with carbon fibers varied from 2.2 to 8 seconds. The T_{50} slump flow time of SCC typically varies in the range of 2-7 seconds [33,34]. Hence, the T_{50} slump flow time results for the concrete mixtures (M4 and M5) including 0.75% and 1% carbon fibers did not strictly meet the requirements for SCC. However, it should be mentioned that the aforementioned criteria were proposed for SCC without any fibers. Despite a higher T_{50} slump flow time, the concrete mixtures M4 and M5 passed the minimum criterion of slump flow for SCC. In fact, HRWR played a very significant role in improving the filling ability of SCC mixtures whereas carbon fibers decreased the filling ability. Therefore, finding the optimum balance between the amount of carbon fibers and the dosage of HRWR is important for concrete mixtures to be successful in meeting the requirements for SCC fresh properties. This study shows that carbon fibers with a content up to 0.75% can be used to produce SCC with acceptable filling ability.

Passing ability

The J-ring slump flow test was used to measure the passing ability of the concrete mixtures. As presented in Table 3, the J-ring slump flow of different CFRSCC mixtures varied from 625 to 730 mm (25 in to 29 in). The flow spread generally was smaller with the J-ring. The J-ring slump flow was used to calculate the blocking index. Subtracting the J-ring slump flow from the slump flow provided the blocking index. The difference between slump flow and J-ring slump flow was 0-50 mm (0-2 in); this is within the range specified in ASTM C 1621/C1621M-09b (2009) [27]. The difference between slump flow with and without J-Ring first decreases for medium fiber dosages and decreases at higher fiber dosages, which might be an indicator of reduced segregation resistance for higher fiber dosages (and HRWR dosage). The passing ability mainly is determined by the geometrical properties of the fibers and their dosage. A high HRWR dosage significantly decreases the yield value of the paste.

Segregation index (SI)

The sieve stability test was adopted to investigate the segregation resistance with respect to segregation index. The segregation index varied from 9% to 12% for concrete mixtures. The effect of carbon fibers on segregation index is presented in Table 3. All CFRSCC mixtures had a segregation index below the maximum limit of 18% reported by Perez et al. [40]. Mixture M1 had the highest segregation index (12%) whereas mixture M3 had the lowest segregation index (9%). In general, the segregation index decreased when the carbon fiber content increased. This is because the increased volume of carbon fibers decreased the fluidity of concrete mixture. SCC is more prone to segregation due to higher fluidity [40]. This segregation tendency is reduced in the presence of fibers [40]. Thus, the increased volume of carbon fibers greatly decreased the segregation of CFRSCC mixtures. Nevertheless, it should be mentioned that the HRWR dosage also affected the segregation index of concretes produced in the present study. The HRWR dosage significantly improves the filling ability and passing ability of CFRSCC by enhancing its fluidity, which affects the segregation index. For example, M4 and M5 required a very high dosage of HRWR, which is 6.7% and 8%, respectively. The very high dosages of HRWR increased the fluidity of these two concrete mixtures. Therefore, the effect of carbon fibers in reducing the segregation index was counter balanced in these two cases in the presence of a higher HRWR dosage. As a result, the segregation indices of the M4 and M5 concrete mixtures were still significant although they remained below the maximum limit.

Air content and unit weight

The air content of the CFRSCC mixtures was 1.4 to 3.5%, as presented in Table 2. The concrete mixtures were designed to be non-air entrained with an entrapped air content of 2% [29]. The air content results indicate that the carbon fibers did not cause any significant air entrapment. This is attributed to the high filling ability of concrete. A high filling ability facilitated to release the entrapped air-voids from concrete. The unit weights of the freshly mixed CFRSCC mixtures are presented in Table 2. The unit weight varied in the range of 2462 to 2415 kg/m³ (154 to 151 lb/ft³). The unit weight decreased as the carbon fibers increased; the reason is that carbon fibers were the lightest component in the concrete mixtures.

Compressive strength results

The compressive strength test results for different concretes are summarized in Figure 1. Mixture M1 achieved a compressive strength of 95 MPa (13779 psi) after 28 days, which was the highest compressive strength value while mixture M4 had a compressive strength of 60.2 MPa (8731 psi) after 28 days, which is the lowest compressive strength. The compressive strength of SCC generally decreased as the carbon fiber content increased as it can be seen from Figure 1. This is because the carbon fibers replaced some of the coarse and fine aggregates. The amount of coarse aggregates affects the compressive strength of the concrete mixtures [41]. As the coarse aggregates decreased, the compressive strength decreased because coarse aggregates are the strongest components in the concrete.

Effect of carbon fibers content on compressive strength—Carbon fibers affected the compressive strength of concretes. Mixture M1 achieved a compressive strength of 95 MPa (13779 psi) after 28 days, which was the highest compressive strength value while mixture M4 had a compressive strength of 60.2 MPa (8731 psi) after 28 days, which is the lowest compressive strength. The compressive strength of SCC generally decreased as the carbon fibers content increased as it can be seen from Figure 1. This is because the carbon fibers replaced some of the coarse and

fine aggregates. The amount of coarse aggregate affects the compressive strength of the concrete mixtures [41]. Also, the shortness of fibers length affected the compressive strength.

Splitting tensile strength results

The splitting tensile strength for different SCC mixtures is shown in Figure 2. The splitting tensile strength of SCC increased as the carbon fibers content increased. Mixture M1 (0% fibers content) had a splitting tensile strength of 4.20 MPa (609 psi) while mixture M5 (1% fibers content) had a tensile strength of 4.80 MPa (696 psi), as presented in Figure 2. The splitting tensile strength increased up to about 12% at 1% of carbon fibers content. This increase in splitting tensile strength was because the increased percentage of carbon fibers reduced the crack growth and thus led to a higher failure load. Once the load was applied on the specimens, the cracks started to appear and the concrete cylinder started to split in two parts. The fibers created a bridge through the split portions of the cylinder and prevented the two parts from splitting.

Modulus of rupture

The modulus of rupture results of the flexural tests for all concretes is summarized in Figure 3. As it can be seen from Figure 3, the modulus of rupture for the concrete mixtures ranged from 7.60 MPa to 8.05 MPa (1102 psi to 1168 psi). Mixture M5 (1% fiber content) had the highest modulus of rupture, while mixture M3 (0.5% fiber content) had the lowest modulus of rupture. Increasing the carbon fiber content increased the modulus of rupture of SCC compared to the control mixture M1 (0% fiber content). With carbon fiber contents of 1% and 0.25% an approximately the optimum modulus of rupture for the SCC mixtures was obtained. Fibers are able to reduce the crack opening. The increased number of fibers that cross the crack surface also increases the modulus of rupture.

Load deflection (P-Δ) curve

The load-deflection (P-Δ) response for different concrete mixtures is shown in Figure 4. The deflection data were calculated from the average of two LVDT values. The load-deflection curves consisted of an approximately linear curve up to the peak load and then the curve dropped gradually until the load reached zero. Mixture M1 (0% fibers content) had a brittle post-peak response with a maximum mid-span deflection less than 0.4 mm (0.016 in). Mixtures M2 (0.25% fiber content) to M5 (1% fiber content) had a slightly better post-peak response with a maximum mid-span deflection below 0.7 mm (0.028 in). Most of the mixtures did not reach a deflection of L/150 possibly because of the limited length of the fibers. However, the displacement at the peak load was identical with a mid-span deflection of 0.06 mm (0.0024 in) for all mixtures.

Toughness

The toughness values of the different SCC mixtures are presented in Figure 5. The toughness of the SCC mixtures ranged from 2475 N-mm to 3500 N-mm (22 to 30 lb-in). The carbon fibers increased the toughness. The carbon fibers helped the concrete mixtures to absorb more energy as it can be seen from Figure 5 and therefore the mixtures with carbon fibers had an improved toughness. Mixture M2 (0.25% fiber content) had the highest toughness of 3500 N-mm (30 lb-in), while mixture M1 (0% fiber content) had the lowest toughness of 2475 N-mm (22 lb-in). Mixture M3 to M5 with carbon fiber contents of 0.5% to 1% had a similar toughness regardless of fiber content. The toughness achieved with these mixtures was 31% higher than the control mixture (with no fibers), but 20% lower than the mixture with 0.25% fibers. These results suggest that the optimum fiber content is 0.25%.

Scanning electron micrograph

The scanning electron micrographs (SEMs) of the fracture surface for different hardened CFRSCC mixtures revealed that the carbon fibers were well distributed in the mortar matrix of all concrete mixtures. As evidence, the SEMs of the CFRSCC mixtures including 0% and 1% carbon fiber contents are provided in Figure 6. These figures show that no fiber clumping or balling occurred in concrete. This suggests that the fibers were well dispersed during the mixing of concrete. The use of silica fume (SF) along with superplasticizer (HRWR) facilitated the dispersion of carbon fibers in concrete. The conclusion is that silica fume improved the stability of the concrete. The same observation was found by Safiuddin 2010 and Chung 2010 [17,42]. Thus, it was understood that the fresh properties of concrete was not influenced by fiber clumping or balling. Two types of fibers failure (pullout and breakage) as shown in Figure 7 were observed. A similar observation was made in other research [43].

Acknowledgement

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Conclusions

Based on the test results of this study on carbon fiber reinforced self-consolidating concrete (CFRSCC), the following conclusions can be made:

- Carbon fibers affected the filling ability and passing ability of SCC mixtures. However, all mixtures have successfully met the SCC requirements on filling and passing ability.
- The T_{50} slump flow time increased with the increase in carbon fibers content because the inclusion of fibers slowed the flow of CFRSCC by making it more viscous.
- All CFRSCC mixtures clearly passed the segregation resistance requirement as their segregation index was significantly below the maximum limit (18%).
- The compressive strength of SCC mixtures decreased as the carbon fibers increased and the splitting tensile strength increased as the carbon fiber content increased. The reduction of compressive strength might be the result of the reduction of coarse aggregates.
- The flexural strength increased with the increase of fiber content.
- The toughness and the fracture energy increased with addition of fibers.
- Two types of fiber failure (pullout and breakage) were identified from Scanning electron micrographs (SEMs).

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Table 1 - Physical properties of carbon fibers

Items	Properties
Pitch-based carbon fibers (CF)	Relative density: 1.85 Tensile strength: 1770MPa (256707 psi) Tensile modulus: 180MPa (26105 psi) Length: 10mm (0.39) Diameter: 17 μ m (6.69×10^{-4})

Table 2 -Details of concrete mixture proportions

Concrete mixture	w/b ratio	CA kg (lb)	FA kg (lb)	Binder (B)		CFs		W		HRWR (% B)
				C kg (lb)	SF kg (lb)	(vol. %)	kg (lb)	kg (lb)		
M1	0.35	784.2 (1725)	958.5 (2109)	432.7 (952)	48.1 (106)	0.00	0.0 (0.0)	189.8 (416)		1.50
M2	0.35	778.4 (1712)	951.4 (2093)	432.7 (952)	48.1 (106)	0.25	4.7 (10)	189.8 (416)		2.00
M3	0.35	767.1 (1688)	937.6 (2063)	432.7 (952)	48.1 (106)	0.50	9.5 (21)	189.8 (416)		3.50
M4	0.35	746.4 (1642)	912.3 (2007)	432.7 (952)	48.1 (106)	0.75	14.2 (31)	189.8 (416)		6.70
M5	0.35	736.2 (1620)	899.8 (1980)	432.7 (952)	48.1 (106)	1.00	18.9 (42)	189.8 (416)		8.00

Notation: CA= coarse aggregate, FA= fine aggregate, C= cement, CFs = carbon fibers content, SF= silica fume, W= water, HRWR= high range water reducer.

Table 3 - Properties of fresh concretes

Concrete mixture	w/b ratio	CFs (%)	Slump flow mm (in)	T ₅₀ slump flow (sec.)	J-ring slump flow mm (in)	Segregation index (%)	Air content (%)	Unit weight kg/m ³ (lb/ft ³)
M1	0.35	0.00	720 (28)	2.2	705 (28)	12	1.4	2462 (154)
M2	0.35	0.25	745 (29)	3.5	730 (29)	11.9	2	2456 (153)
M3	0.35	0.50	700 (28)	6	625 (25)	9	2.4	2450 (153)
M4	0.35	0.75	685 (27)	8	665 (26)	11	2	2443 (152)
M5	0.35	1.00	720 (28)	8	715 (28)	10	2	2415 (151)

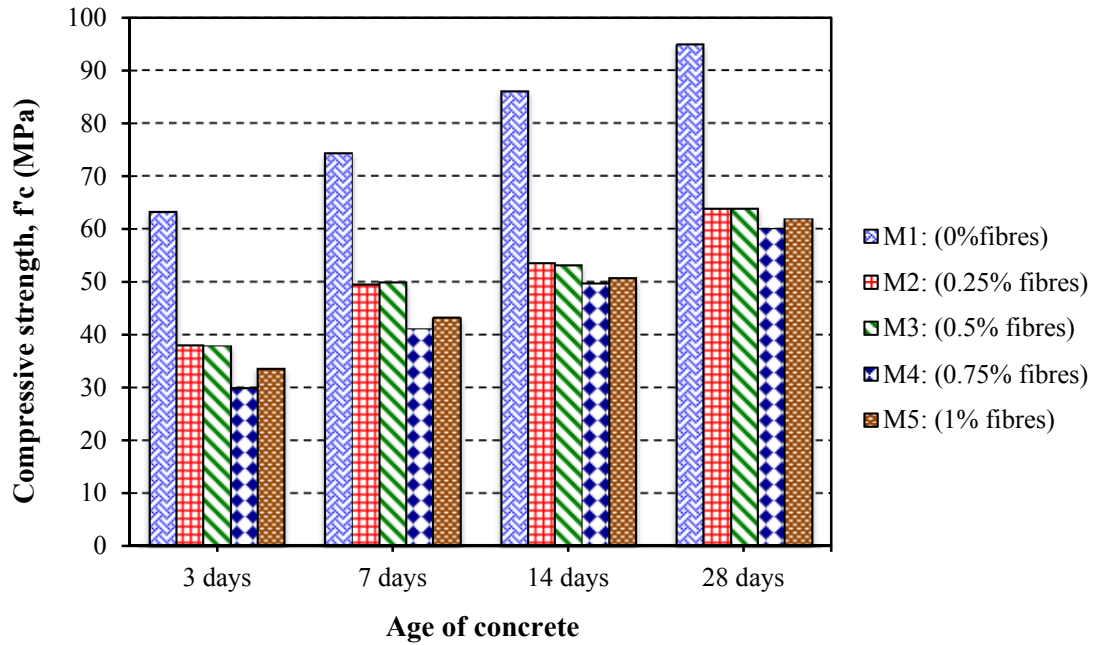


Figure 1–Compressive strength of CFRSCC mixtures

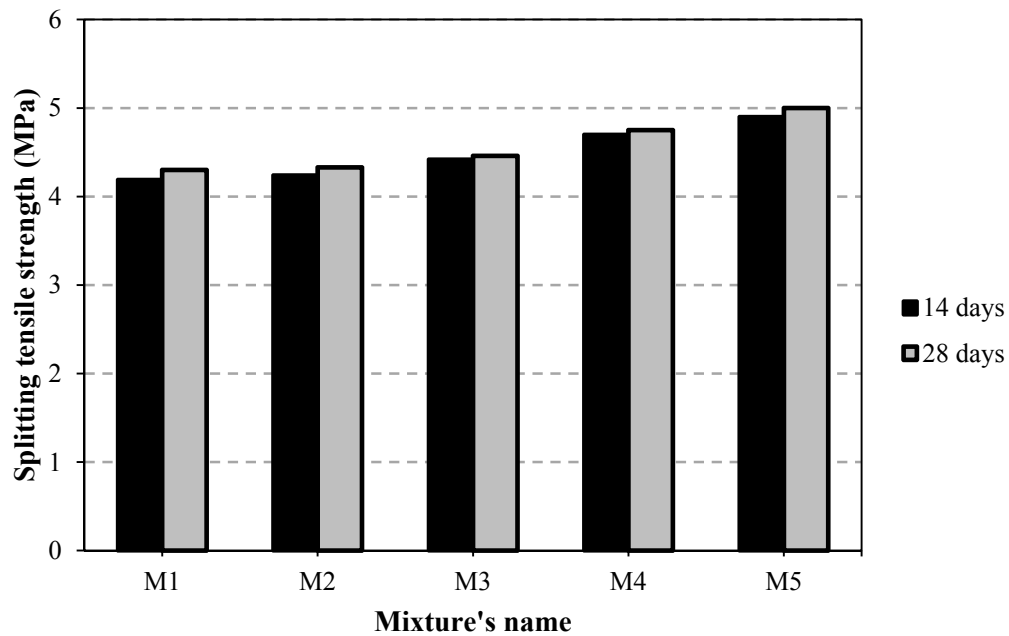


Figure 2 –Splitting tensile strength of CFRSCC mixtures

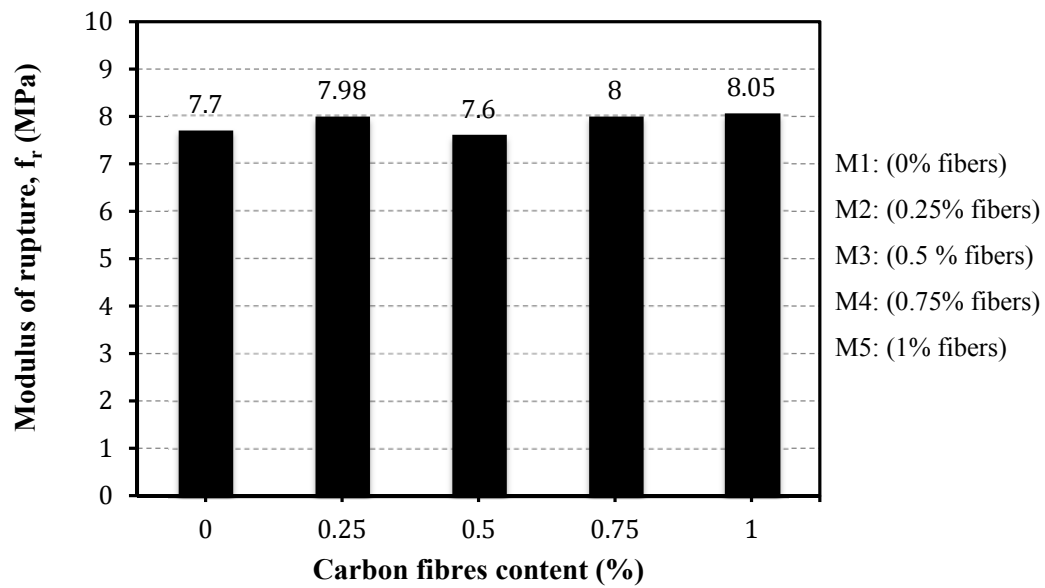


Figure 3–Modulus of rupture of CFRSCC mixtures

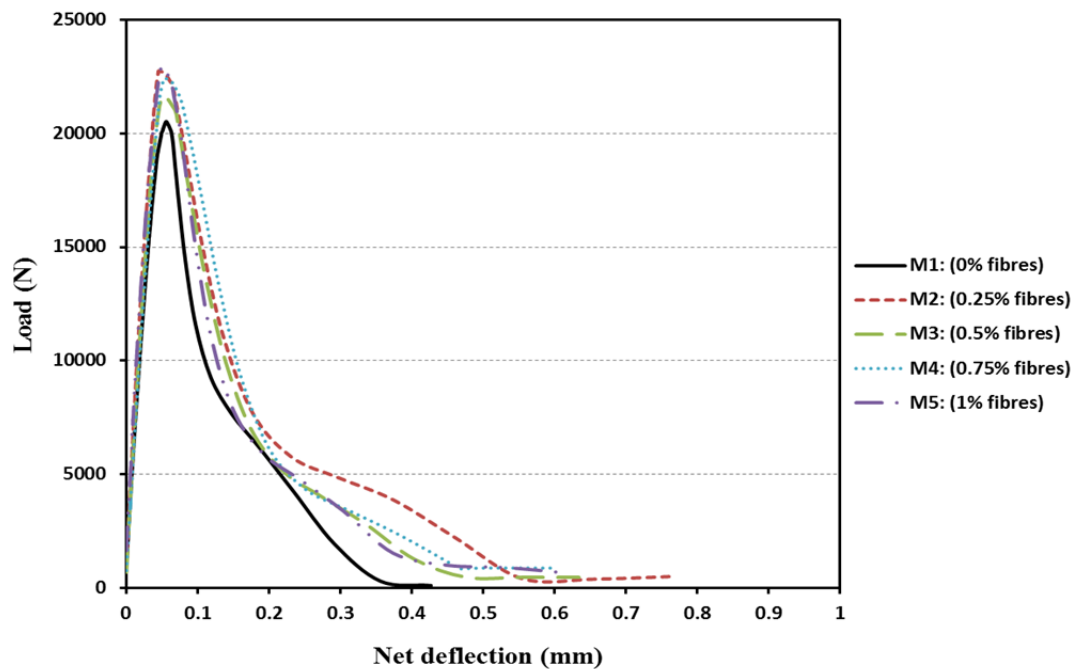


Figure 4 –Load deflection relationship of CFRSCC mixtures

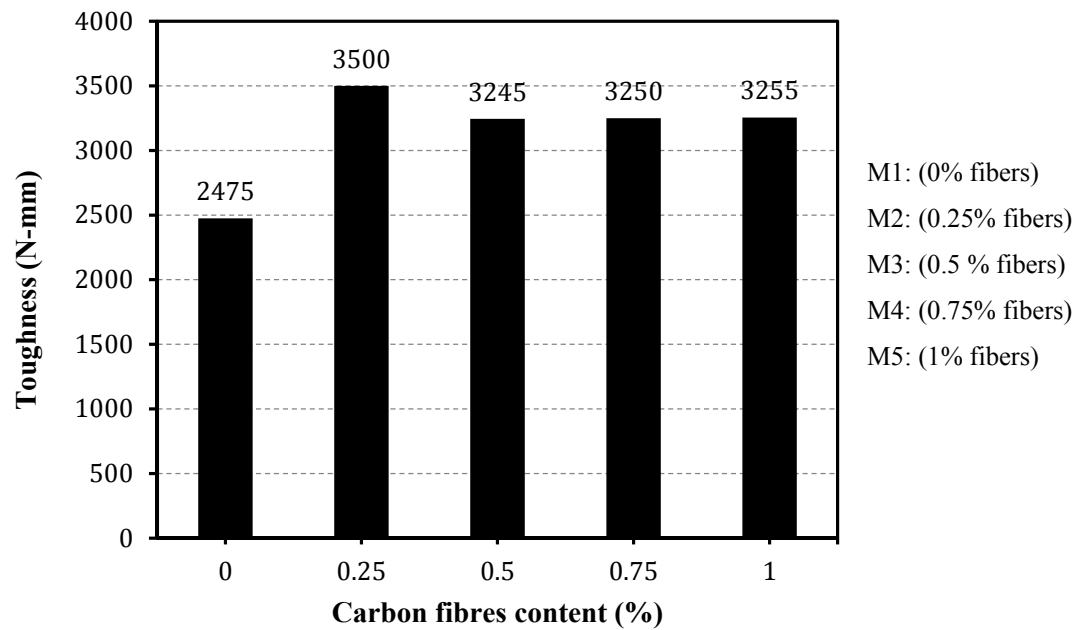


Figure 5 –Toughness for CFRSCC mixtures