Research Article

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Mechanical properties of steel and polymer fiber reinforced concrete

<https://doi.org/10.1515/jmbm-2019-0014>

Received Oct 07, 2019; accepted Nov 02, 2019

Abstract: The present study aimed to investigate the influence of a number of fiber parameters including fiber type, content and hybridization on strength and ductility of polymer fiber reinforced concrete (PFRC) and steel fiber reinforced concrete (SFRC) used mostly in tunneling practices as the primary shotcrete lining. Numerous cylindrical and prismatic beams were casted and undergone various tests in which main previously mentioned fiber traits varied. It was understood that SFRC excels at every mechanical feature in comparison to PFRC; however, such transcendence found predominant in compressive strength but marginal in flexural and tensile strength. Despite being classified under different compressive strength classes (SFRC in the upper and PFRC in the lower class) according to EFNARC, both FRC types fell under a similar flexural class (at 4% of fiber fraction); a result possibly in debt to excellent bonding properties and more slender polymer fibers. Tensile strength of PFRC was measured lower than SFRC. Augmentation of fiber content positively affected mechanical characteristics of FRC at most cases. Hybridization of different fibers at a specific range of fiber mixing proportions was observed to have advantageous impacts on ductility and strength of a more corrosive resistant and cost efficient hybrid fiber reinforced concrete (HFRC).

Keywords: Fiber reinforced concrete, Polymer fibers, Steel fibers, Shotcrete

1 Introduction

Concrete, as a mixture of Portland cement, aggregates, water and variety of additives, has been one of the most commonly used materials in almost every construction project because of its low cost production and convenient mechanical properties. However, non-homogenous and brittle nature of concrete brings about considerable lower tensile strength in comparison to its compressive strength. Customarily, to compensate for such weakness, reinforcing components, most common of which are steel bars, are embedded in structural elements of concrete. Shotcrete, being one of the broadly used types of concrete, is no exception. Although enjoying from a unique process of casting, in which concrete is sprayed onto the surface enabling it to form either a thin or thick layer, the brittleness of the final product has left engineers no choice but to adopt a reinforcement technique to overcome its fragileness. A wire mesh had been employed as the solution since it improves tensile strength of the shotcrete and contributes to a rise in ductility before its drawbacks, in particular, difficulty of installation, corrosion susceptibility of steel wires and their role in preventing complete infiltration of the mortar or concrete into the wire mesh resulting in generation of numerous voids, persuaded engineers to look for other methods which did not suffer such flaws [1, 2]. The application of structural fibers to enhance several mechanical characteristics of concrete including increase in residual stress and energy absorption capacity along with significant durability improvements, has gained popularity due to their extreme ease of use and wide availability [3].

Reinforcing fibers utilized in production of concrete are classified into four basic categories of steel, synthetic, glass and natural fiber materials [1]. As every project calls for a particular set of considerations, the reinforcing fibers, each of which have their advantages and deficiencies, used in each case must be different. Steel fiber material comprises a large proportion of fiber reinforcing material used in concrete which comes in various shapes and forms. Due to their long use in concrete construction projects and various researches, a fair understanding of how such material behaves in concrete has been established. On the other

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hand, as most of such research suggest, a myriad of parameters including the amount of reinforcement used, length of the fibers and the chemical composition of which fiber are made, have an undeniable correlation with overall behavior of the final composite element. Furthermore, since the addition of steel reinforcing fibers imposes extra cost to projects and complicates spraying procedure, it is imperative to derive a precise fiber/concrete ratio whereby the desirable performance in the structural element is attained.

Synthetic fibers have recently attracted attention as they offer beneficial improvements to both hardened and early concrete. Some of these assets include impact and abrasion resistance, reduced plastic shrinkage and settlement cracking and contraction of permeability [4]. Polymer fibers are a chemically produced subdivision of synthetic fibers. Polymer fibers are ordinarily made from a variety of petrochemical sources such as polyolefins, polyvinyl chloride, polyethylene and phenol-formaldehyde etc. [5]. Polypropylene fibers are also one of the most commonly used types of synthetic fibers due to having a relatively low cost of production and convenient deformability properties [6]. Polymer fibers are classified into two categories namely: macro fiber and micro fibers. Micro fibers are manufactured with diameters less than 100 micrometer whose length ranges from 5 to 30 millimeters. Despite being considerably effective in terms of reduction of plastic shrinkage cracking, micro fibers hardly influence strength and deformability characteristics of hardened concrete. Employment of macro polymer fibers (MPF) in shotcrete as a replacement for steel fibers has been reported to be advantageous with regard to increased energy absorption capacity with less addition of fibers per volume. Furthermore, resistance to corrosive environments and less damage to concrete spraying equipment (thanks to their flexibility) in a few tunnels in which polymer fiber reinforced concrete (PFRC) were utilized, is also acknowledged [7]. A number of studies on polymer fiber reinforced concrete (PFRC) has been carried out; however, attempts at developing a model for prediction of tensile, compressive and energy absorption behavior of such material have not been completely successful.

In the present study, a thorough comparison between steel fiber reinforced concrete (SFRC) and polymer fiber reinforced concrete (PFRC) was investigated. In doing so, the influence of a number of variables including the proportion of fibers used, fiber type, hybridization and fiber energy-absorption capacity were taken into consideration as they have a positive correlation with the performance of PFRCs. European specification for sprayed concrete guidelines have been invoked as the reference for the experimental assessment.

2 Experimental program

2.1 Materials used and mixing procedure

In the present study, fiber reinforced concrete was mixed in the laboratory and numerous specimens correspondent to various fiber contents were prepared for testing. Water to cement ratio of 0.45 was adopted for the mixture using type 2 Portland cement. Mixing proportions utilized in this study is given in Table 1. Grain remnants on sieve No. 100 were used as the fine aggregates in the mix and had been washed. Coarse aggregate with maximum grain size of 12 mm were used. Plain concrete uniaxial compressive strength was measured 33 MPa after 28 days. Since this study aims to take every feature of shotcrete mixture into account, as similar as possible to what is mixed in the tunneling application, an accelerator was used in the mixture. Hooked steel fiber reinforcements with length of 30 mm and wavy polymer fiber reinforcements were employed in making of specimens. The mechanical and chemical composition of reinforcements used is provided in Table 2 according to the manufacturers' specification sheets. Reinforcing polymer fibers used in this study were of a macro type fiber with nominal length of 40 mm, going by the commercial name of "Baumex" manufactured form "Bautech" Inc. (Figure 1). Polymer fibers have proven to possess an excellent bond with early concrete enabling them to be conveniently used in shotcrete [7].

In order to make sure that the fibers were aptly dispersed through the specimens, a multi-stage evaluation was employed. This evaluation takes the dispersibility of both fresh and hardened FRC into consideration by two distinct approaches. In the first place, a "wash" analysis was performed on the early FRC whose instructions were carefully followed from [8] according to which, 50 Liters of PFRC were mixed based on the mixing proportions in Table 1 containing polymer fiber volume percentage of 4%. Thereupon, a sample of 7 Liters of the early PFRC, from the mixture, was poured into a 0.09 mm sieve and washed only after the air content of the sample was precisely measured through pressure method (ASTM C231). The remnants on the sieve were left alone for 24 hours and then intensively dried in the oven for 24 hours. Subsequently to drying, all the polymer fibers were extracted and weighted. After repeating the analysis 4 times, the average volume percentage of the polymer fibers was derived to be 3.946%. Table 3 tabulates the results found in every repetition. As the second stage of the fiber dispersion assessment, two specimen beams with dimensions of 100*100*500 mm were casted using the identical mixture adopted in the preced-

Table 1: Concrete mixing proportions

W/C (%)	S/a (%)	G _{max} (mm)	W	C	Unit weight (kg/m ³)	G	Fiber content V _f (%)	SP (%)	Slump (mm)	Air (%)
43.5	55.7	9.3	174	200	1002.6	797.4	PF-SF PF-SF PF-SF	0.65 0.8 1.4	118±20	4±1

Table 2: Physical and mechanical features of fibers used

Fiber	Length (mm)	Equivalent diameter (mm)	Width (mm)	Slenderness (L _r /d _e)	Tensile strength (MPa)	Elastic modulus (GPa)	Shear modulus (GPa)	Unit weight (kg/m ³)	Alkali/acid resistance	Electrical conductivity	Composition
Polymer fiber	40	0.78	1.1	51.3	450	3.6	1.28	910	Yes	No	Synthetic polymer
Steel fiber	30	0.69	-	43.4	1200	200	77	7810	No	Yes	Alloy

Table 3: The result of the wash analysis for PPRC

Rep No.	Volume of PPRC (cm ³)	Retrieved weight (g)	Retrieved volume (cm ³)	Volume of PPRC (cm ³)	Retrieved weight (g)	Retrieved volume (cm ³)	Volume of PPRC (cm ³)
1	7000	2508.5	2756.6	7000	2508.5	2756.6	7000
2		2588.7	2844.8		2588.7	2844.8	
3		2476.0	2720.9		2476.0	2720.9	
4		2481.1	2726.5		2481.1	2726.5	
Ave.		2513.6	2762.2		2513.6	2762.2	
St. dev.		86.6	95.2		86.6	95.2

Figure 1: Fiber reinforcements used in this study (a. hooked steel fibers; b. polymer fibers)

Figure 2: Ultra sonic testing of beam specimens as a fiber dispersion assessor

ing stage. Following 28 days of curing, the beam length was marked into 10 sections each of which measuring 50 mm and an ultrasound test was carried out on each section (Figure 2). The average wave speed measured from each section was derived at 73 m/s, with a standard deviation of 0.0867. The results obtained on both stages indicated that the dispersibility of PFRC was convenient.

2.2 Test setup and procedure to analyze the effects of fiber properties

2.2.1 Flexure tests

To investigate the effects of fiber reinforcements on the flexural properties of FRC, third point loading flexural

tests were carried out on beam specimens according to ASTM-C1609 [9]. In doing so, three prismatic beams were cast dedicated to each set of variables with dimensions of 100*100*500 mm. Specimens had been kept in the laboratory temperature to harden for 12 hours before molds were removed and specimen were moved to a water basin in order to cure for 28 days. Uniaxial load was applied using a Dartec loading machine with maximum applicable load of 1000 KN. The rate of loading was chosen within the suggested loading range provided by ASTM-C1609 [9], at 0.2 mm/min. Four linear variable differential transducers (LVDTs) were adopted to measure displacements which were placed at the beams middle span. Since the displacements of the beams are required to be measured at middle depth along the beams length, two steel flanges were attached to either side of the specimens providing a support of two of the LVDTs so that the proper measurement is conducted. Loading was continued until a displacement of 2.5 mm was attained.

2.2.2 Compressive and tensile strength tests

According to American Society for Testing Materials [10, 11], numerous tests were performed on cylindrical and beam specimens to compare mechanical behavior of polymer fiber reinforced concrete (PFRC) and steel fiber reinforced concrete (SFRC). A variety of tests including uniaxial compressive strength test, direct uniaxial tensile strength test and tensile strength in bending were conducted.

Figure 3: Testing procedure for different conducted tests in this study a. uniaxial direct tensile test; b. uniaxial compressive test; c. four-point loading test

Although there is no standardized guideline for assessing direct uniaxial tensile strength for concrete due to complications made by specimen preparation and testing device setup, since one of the main objectives of using fibers is to enhance tensile characteristics of plain concrete, ultimate tensile strength of FRC is required to be evaluated. Hence, uniaxial direct tensile strength tests were carried out whose testing procedure can be explained as follows. A variety of specimen shapes have been made to evaluate direct tensile strength of concrete members in a few previous studies which include dumbbell shaped, prismatic and cylindrical specimens. Based on the equipment furnished in the laboratory, in the present study, cylindrical specimens of 70 mm in diameter and 140 mm in height were opted to undergo direct tensile testing. In doing so, several panels, varying in fiber reinforcement fraction, measuring $1000 \times 1000 \times 150$ mm were casted from which cores were extracted and prepared such that they fulfill the exact required specimens dimension stated above. After allowing specimens to cure for 28 days, both ends of each specimen were glued to Dartec machine removable steel anchors using UHU Plus adhesive. The specimens were then setup firmly in the machine using screws such that a minor tensile stress is exerted through them making no movement possible thereafter. A tensile load with a displacement rate of 0.2 mm/min was successively applied by the machine until the complete separation of the two halves of specimens was reached. Figure 3a illustrates performing uniaxial direct tensile tests.

Uniaxial compressive test is the most practical and commonly practiced method of assessing strength of materials. A diverse range of standards have been designated to formalized uniaxial compressive test including BS and ASTM, each of which suggesting a distinct specimen shape and dimension. With regard to the uniaxial compressive

test specimens fabricated in this study, Standards [10–12] were considered as the reference; consequently, cylindrical specimens of 70 mm in diameter and 140 mm in height were casted in pursuance of evaluating elasticity modulus and uniaxial compressive strength. A uniaxial force was applied to specimens by means of a servo-controlled Dartec loading machine set to displacement control mode with the rate of 0.12 mm/min. Loading was continued beyond the specimens peak stress until a residual stress equal to ten percent of compressive strength and post peak behavior of specimens was attained. Diagonal deformations of each specimen were measured by use of three LVDTs, two of which were installed transversely and one perpendicularly to the two proceedings in order to determine the elasticity modulus. Figure 3b illustrates testing procedure of the uniaxial compressive test.

Tensile strength in bending or flexure strength tests were conducted on several prismatic beam specimens under third point loading on a 450 mm span according to ASTM-C78/C78M [13]. The cross-section of the specimens were 100×100 mm² and its length was measure at 600 mm. A uniaxial force was applied on the mid-span of the specimen at a rate of 0.2 mm/min and kept on until a deflection of 0.5 mm occurred and thereupon, the displacement rate was increased to 1 mm/min until an ultimate deflection of 4 mm was achieved. Figure 3c demonstrates a specimen during flexure strength test.

3 Experimental results and discussion

3.1 Effects of fiber properties and proportion on the flexural behavior of FRC

3.1.1 Effect of fiber type

As highlighted in the previous sections, the fiber type to be adopted in the mixture has profound effects on mechanical behavior of FRC elements. In this section, the influence of using two types of reinforcing fibers including polymer fibers and steel fibers on compressive, flexure and tensile strength of PFRC and SFRC specimens are discussed. Uniaxial compressive strength of cylindrical specimens for PFRC and SFRC is delineated in Figure 4 by means of compressive load-deflection curves. In derivation of stress, the continuous normal load applied during the test was divided to the nominal surface area of the specimens and in regard with that of strain, axial deformation of the specimens divided by their length were taken into account. Compressive strength and residual strength of each specimen were assumed as the peak stress and the stress value at the axial strain of 0.02. Three tests were performed for each variable and the average curve was used for the comparison. It should be brought to attention that the effect of fiber type is assessed while fiber proportions of both specimens were similar, thus the acquired results for specimens with 4% volumetric fiber content is depicted, as the impact of fiber amount is deliberated in the later section. Furthermore, the load-deflection curve of a non-fiber reinforced, plain concrete (PC) is also included. According to Figure 4,

Figure 4: Average Compressive load-deflection curves of the tested specimens

uniaxial compressive strength of the PFRC specimens was not significantly increased by addition of fibers since polymer fibers do not enjoy a high shear modulus required to resist the shearing failure mechanism in compression. However, the SFRC specimens showed a rather noticeable rise in both peak and residual strength which are attributed to steel fibers high elastic and shear modulus. Notwithstanding the minor rise in compressive strength in PFRC specimens, one can understand from the load-deflection curves presented that the performance of polymer fiber reinforced concrete (PFRC) in post-peak portion of the curves was certainly improved. A gradual reduction of strength and higher residual strength are two main benefits accompanied with employment of polymer fibers in concrete. Numerous post peak changes can be observed in both SFRC and PFRC curves, which represent local cracks in concrete resulting in a reduction of compressive strength following by an immediate strength rise caused by tensile resistance of fibers. This changes exhibit that in spite of the numerous cracks made, the specimens were not completely destroyed as reinforcing fibers did allow for further widening of the cracks. Figure 5 demonstrates several compressive parameters of the FRC specimens tested (Compressive strength, Residual strength, tangent modulus and the deflection at peak stress). It should be mentioned that the comparative charts are based on test results obtained from specimens containing 4% of fiber. As can be perceived from the chart, compressive strength of the PFRC specimens did not exceed that of the PC and in fact, a marginal 3.9% reduction in compressive strength was observed. On the other hand, SFRC specimens attained a considerable 49% increase in compressive strength. Residual strength of PFRC specimens was increased by 70% in comparison to PC and that of SFRC specimens showed a 106% boost in residual strength, which implies that the overall load bearing capability of FRC improved substantially. The elasticity modulus of PFRC at 50% of peak compressive strength (E_{50}) was also increased by 34% based on Figure 5; furthermore this parameter increased nearly 30% for the SFRC specimens. Another parameter which is usually a matter of immense importance is the deflection at which maximum stress is reached (d_{ps}). The grater this parameter, the more deflection is accommodated before peak strength is attained and hence more time will be provided to reinforce the weakened elements. With regard to Figure 5, d_{ps} was decreased for PFRC specimens by 24% and increased for SFRC specimens by 9% indicating that in compression, first cracks appear earlier in PFRC elements in comparison with those in SFRC elements. This is in line with finding of previous research [14].

Figure 5: Several compressive features of the tested specimens

Figure 6: Average flexural load- deflection curves of the tested specimens

Third-point bending test results on PFRC and SFRC are illustrated in Figure 6. The flexural capacity of specimens were derived using the formula PL/bh^2 in which P is the maximum load endured by the beam specimens, L is the span length between the supports with b being the sample width and h its height. What is observed in Figure 6 is the average curves obtained after tests on three identical specimens for both reinforcement types; albeit the differences of the three tests were less than 10%. In addition, three plain concrete (PC) beams were casted whose average test result is also brought in Figure 6. As seen, adoption of reinforcing fibers in both PFRC and SFRC specimens caused maximum applied load to increase tangibly. In comparison, SFRC specimens exceeded in flexural strength than that of PFRC specimens. This low difference in flexural strengths can be ascribed to the high tensile strength of polymer reinforcing fibers, which, in spite of their low

shear modulus, prevent cracks from widening and spreading and thus leading to higher bending capacities. The bond quality of fiber to concrete is one important parameter that PFRC excels in due to higher fiber slenderness associated with longer polymer fibers length in comparison to steel fibers. One noteworthy difference observed in flexural curves obtained is post peak performance of the fiber reinforced specimens. The SFRC specimens exhibited a gradual decrease in strength and hardening behavior although in case of the PFRC specimens stress value decreased almost immediately after peak strength and thereupon maintained a constant residual strength which is referred to as the softening behavior. Figure 7 delineates several flexural parameters of the tested specimens (Ultimate bending strength, residual bending strength at deflection of $1/150$, residual strength at deflection of $1/600$ and specimens toughness at deflection of $1/150$). Looking at the chart, one can understand that ultimate bending strength of SFRC and PFRC increased by 54% and 21% respectively. Residual strength at $1/600$ deflection was substantially risen for the SFRC specimens yet for the PFRC beams increased less significantly. On the other hand, residual strength at $1/150$ deflection for PFRC surpassed that of SFRC trivially. Toughness of the specimens (T_{150}) were also calculated at the deflection of $1/150$. Toughness was derived by measuring the area under load-deflection curve at the deflection of $1/150$. It is interesting to draw attention to the fact that T_{150} calculated for SFRC nearly increased by 900% and 850% for SFRC and PFRC, respectively. Therefore, employment of reinforcing fibers was proved to have great impact toward betterment of bending performance of the specimens.

Direct tensile test results acquired through the experiments are provided in Figure 8. Comparison of curves for the SFRC and PC specimens clearly shows an improve-

Figure 7: Several flexural features of the tested specimens

Figure 8: Average tensile load-deflection curves of the tested specimens a) SFRC specimens; b) PFRC specimens

ment in the strength of SFRC samples. Both maximum tensile strength and residual tensile strength increased noticeably as the result of fibers undertaking tensile load while the concrete matrix was cracked and lost load carrying ability. A similar tensile strength increase was observed in PFRC specimens while no boost in residual strength was achieved. It is worth mentioning that a quite large difference between results obtained for similar variables was observed which might highlight the part fiber orientation plays in determination of direct tensile strength of reinforced samples. Those specimens whose fibers were aligned more vertically than those of other specimens, experienced higher overall tensile strength. Furthermore, in SFRC and PFRC specimens, the tensile strengths were postponed as the result of mobilized tensile strength in reinforcing fibers which prevented cracks from widening and dispersing through concrete body. With the increase in tensile load, however, PFRC retained the tensile load longer before reaching the peak strength and thus gained greater

d_{ps} . SFRC specimens experienced a steady residual tensile stress after a post-peak deflection hardening behavior, which is in accordance with previous research done [15]. However, PFRC did not availed residual tensile strength and only displayed deflection softening post-peak behavior [5]. Looking closely at the separated halves of each specimen, one can easily recognize ruptured polymer fibers in PFRC specimens whilst in SFRC specimens, steel fibers were mostly pulled out (Figure 9). As can be seen, in the specimens with higher ratio of polymer fiber, failure in polymer fibers leads to less than a 0.3 MPa of strength difference in comparison to specimens in which greater amounts of steel fibers - which were mostly stretched or pulled out - were used. This, truly portrays the perfect bond created between the concrete matrix and polymer fibers which caters complete and efficient use of tensile strength of the fibers.

3.1.2 Effect of fiber amount

A considerable number of studies has been carried out on investigating the effects of reinforcing fiber amount on mechanical behavior of FRC elements [16–19]. Most research in this regard has reported an increase in strength and durability properties of tested specimens. However, due to the variety of employed reinforcing fibers in concrete constructions, additional research on particular mixing proportions, lengths and types of fibers used may offer designers better insight on deciding what product to use.

This section presents the results obtained from different tests on specimens in which reinforcing fibers were used with various fiber contents. To investigate this, specimens with three volumetric fiber contents of 1.5%, 2.5%

Table 4: The results obtained from the tests conducted in this study

Fiber type	Fiber content (%)	Compressive strength (MPa)	Flexural strength (MPa)	Tensile strength (MPa)	Compressive strength class	Residual strength class
PFRC	1.5%	36.4	5.31	1.87	C36/45	0
	2.5%	35.1	5.51	1.94	C32/40	0
	4%	32.7	5.76	2.14	C32/40	2
SFRC	1.5%	47.3	5.51	1.91	C44/55	0
	2.5%	49.2	5.93	2.21	C48/60	1
	4%	53.3	7.35	2.37	C48/60	3
PC	0	34.8	4.67	2.03	-	-

Figure 9: Different specimens following direct tensile testing (ripped polymer fibers are marked). a. Hybrid specimen with 50%PF+50%SF, b. Hybrid specimen 75%SF+25%PF, Hybrid specimen with 75% PF+25%SF. As can be seen, polymer fibers are mostly ripped yet steel fibers only stretched, were deformed or were pulled out **Figure 10:** Results obtained from the tests at different proportions of polymer fiber amount a. compressive test b. flexural test c. direct tensile test

Figure 11: Results obtained from the tests at different proportions of steel fiber amount a. compressive test b. flexural test c. direct tensile test

Figure 12: Results obtained from the tests at 4% of hybrid fiber amount a. compressive test b. flexural test c. direct tensile test

and 4%, containing polymer and steel reinforcing fibers, were prepared and tested. Table 4 summarizes some of the average strength parameters of PFRC and SFRC specimen and their relative fiber fraction. Figure 10 demonstrates compressive load-deflection curves of PFRC specimen subsequent to different tests. It is evident from Figure 10a, that by increasing fiber fraction, compressive strength of PFRC specimens decreased trivially. This reduction of strength can be explained based on the fact that existence of the fibers not only did not contribute to improvement of load bearing capacity of the specimens, but adversely affected it as shear modulus of fibers are substantially lower than that of the concrete. Post-peak behavior of the curves however were modified; as the fiber content was increased, strength reduction became more gradual and deflection-hardening behavior was prevailed. Residual strength was also risen as more fiber was added in the mixture. SFRC specimens however enjoyed an increase in both peak and residual strengths as the fiber fraction was increased (Figure 11a). Figure 10b illustrates flexural load-deflection curves of PFRC specimen tested

through third-point flexural test. The acquired results indicate that as the volumetric fiber fraction used in the specimen increased from 1.5% to 2.5%, there has been almost no augmentation in bending strength in beam specimens. Even so, accretion of the fiber content from 2.5 to 4% led to a 6% increase in flexural strength. Residual flexural strength, in similarity to maximum bending strength, experienced approximately no change when fiber content was raised from 1.5% to 2.5%, but gained a considerable boost as fiber fraction was raised to 4% and accordingly, so did the T_{150} and f_{150} . Furthermore, a higher maximum flexural strength was reached at a slightly larger deflection which only implies that the overall ductility of the beam specimens was enhanced. A analogous trend was observed in SFRC specimens though the residual flexural strengths were increased with the increase in fiber content (Figure 11b). Figure 10c represents direct tensile strength test curves obtained for PFRC specimens containing different fiber amounts. As can be seen, by increasing polymer fiber content of specimens from 1.5% to 2.5%, maximum tensile load endured was risen, though this increase

in strength has been somewhat minor. By further accretion of fiber fraction to 4% the same amount of boost in maximum tensile load was observed, which can be associated with abundance of vertically aligned fibers located in the failure plane. It should be brought to notice that as the fiber content was raised, peak tensile strength was reached in a less displacement. Despite the rise in tensile strength, reduction of peak strength displacement (T_{sd}) may affect PFRC performance negatively, especially in tunneling practice where T_{sd} is deemed a predominant designing parameter [19]. Figure 11c demonstrates tensile load-deflection curves of SFRC specimens based on which one can notice beneficial effects of increasing fiber content on residual and peak strength. In accordance with Table 4, one can understand the influence of increasing fiber content of specimens on strength parameters of the SFRC specimens has been mostly incremental similar to what had been encountered with PFRC specimens, nonetheless, the boost in the SFRC specimens strength characteristics is higher than those of PFRC specimens.

3.1.3 Effect of hybridization together with fiber content

Utilization of reinforcing fibers in concrete was undoubtedly proven advantageous in the previous sections of this study, same as it had been proposed in earlier research [5, 14, 20, 21]. Nevertheless, either of PFRC or SFRC specimens exhibited few shortcomings in performance, which might be considered undesirable and would rather be avoided. In this regard, hybridization of polymer fibers and hooked steel fibers was investigated. In furtherance of evaluating an efficient fiber mixing proportion, three distinct mixing proportions including 75% steel fiber+25% polymer fibers, 50% steel fibers+50% polymer fibers and 25% steel fibers+75% polymer fibers were implemented. Furthermore, fiber content dependency analysis was performed to study optimum fiber fraction causing the most convenient mechanical performance in which three total fiber contents namely 1.5%, 2.5% and 4% were considered. Figure 12 demonstrates the aftermaths of hybridization on compressive, flexural and tensile behavior of FRC specimens. Figure 13a-c also represents several strength parameters of hybrid specimens in relation with associated fiber content. In order to highlight the effects of fiber hybridization, resulting curves of specimens containing 4% reinforcing fiber is depicted. In keeping with Figure 12, hybrid fiber reinforced concrete (HFRC) specimens excelled in performance comparing to PFRC and SFRC. In contrast with the results procured for PFRC, HFRC specimens gained higher peak strength thanks to the steel fiber proportion of rein-

forcements. Moreover, SFRC specimen which mostly had lower d_{ps} , improved in that respect. Post-peak behavior of HFRC specimens seems to be idealized as a gradual reduction of strength together with a sufficient residual stress guarantees a safe and predictable design. Peak stress was also occurred in grater strains and deflections granting the elements a ductile behavior, which is highly beneficial in concrete supporting structures. Specifically speaking, in tensile strength tests, inclusion of polymer reinforcing fibers which demonstrated better bonding with concrete that steel fibers marginally enhanced tensile peak and residual strength. It should be mentioned that further increasing polymer fiber proportion to 75% in the mixture diminished overall mechanical properties of the HFRC specimens thereupon, 25% of total fiber fraction was found an optimal amount of polymer fiber proportion in HFRC tested specimens.

3.2 Classification of strength and ductility of the FRC specimens

Prior to utilizing fiber reinforced concrete (FRC) in construction, the strength and ductility characteristics of the final reinforced product must be warily determined in accordance with international codes and standards proposed. European specification for sprayed shotcrete [22] has particularized strength and ductility properties of fiber-reinforced shotcrete into a number of classes enabling design engineers to simply characterize the available shotcrete type and employ it in the tunneling practices. In the following sections, specimens containing 4%, 1.5% and 2.5% of polymer fibers were compared with SFRC specimens with the identical fraction of fibers mixture and their strength and ductility class was specified. Compressive and bending strength were considered as the conclusive parameters in respect to strength class, however flexural residual strength was solely considered for investigating ductility.

3.2.1 Influence of fiber type and content on the strength classification

Uniaxial compressive and third point loading tests were carried out to investigate the strength class of PFRC and SFRC specimens whose results are summarized in Table 5. EFNARC takes compressive strength of cylindrical and cube specimens into account as a mean of classification such that each class surpasses their preceding class by 4 MPa with 24 MPa being the lowest strength bound and 48

Figure 13: a) Several flexural strength parameters of HFR specimens at different fiber content and 75%SF+25%PF proportion; b) Several flexural strength parameters of HFR specimens at different fiber content and 50%SF+50%PF proportion; c) Several flexural strength parameters of HFR specimens at different fiber content and 25%SF+75%PF proportion

Table 5: The results obtained from the tests and the classification according to EFNARC

Fiber type	Fiber content (%)		Compressive strength (MPa)	Flexural strength (MPa)	Compressive strength class	Residual strength class
Hybrid	4%	75%S+25%P	46.35	4.08	C48/60	2
		50%S+50%P	41.22	3.82	C48/60	2
		25%S+75%P	38.25	3.32	C36/45	0

MPa the highest for cylindrical specimens. Compressive strength of all specimens were increased by time despite the fiber type or content. However, the accretion in SFRC specimen noticeably exceeded that of PFRC and thus for fiber content of 4%, the former was classified as C48/60 whereas the latter was categorized as C32/40. The main factor producing such sizable difference between the two FRC types lies within the considerable discrepancy between the shear modulus of fiber reinforcements. Another cause for the strength distinction can be associated with the greater number of polymer fibers at the same volumetric content due to their much lower specific density. Greater number of fibers not only did not contribute much to resisting the failure in the compressive test, but also took up spaces which could have been filled with cement matrix. Not to mention the greater porosity introduced, prevented high compressive strengths to be achieved. This is on par with findings of Yang Jun-Mo *et al.* [19] on amorphous fiber reinforced shotcrete (AFRS) specimens. They concluded that regardless of having higher tensile and shear modulus, AFRS specimens were categorized at a lower level of strength than steel fiber reinforced shotcrete (SFRS) specimens as the result of increased entrapped air caused by the existence of more amorphous fibers in each specimen at the same fiber content value. Likewise, Song PS *et al.* [23] proclaimed that increasing the amount of steel fiber might lead to the reduction of compressive strength.

On the contrary, the results obtained from the third-point loading test suggested that increasing the fiber amount in both PFRC and SFRC specimens brought about higher flexural strengths (Table 5). Furthermore, unlike their compressive strength classes, PFRC and SFRC were classified under the analogous flexural strength class namely C44/55. The strength difference in bending tests between the two FRC specimens were also indeed less than that in compressive tests. This, additionally, can stem from the greater number of polymer fibers in the beam specimens. Conversely to what uniaxial compressive test results implied, abundance of polymer fibers in flexural tests not only did not decreased the final flexural strength of the specimens, but also worked in their favor as prevented more cracks to develop and their excellent bond with the

matrix postponed the failure point. Won *et al.* [24] and Nayar *et al.* [25] concluded the same incremental trend of bending strength with the increase in fiber amount. Based on the findings in the present study it is suggested that the classification is modified so that it would be able to differentiate between FRC types, especially at the higher strength values.

3.2.2 Influence of hybridization on the strength classification

The results of the uniaxial compressive tests on core specimens containing various fiber mixing proportions the total reinforcement volume (4% of the entire mix) is presented in Table 5. EFNARC provides a separate classification for core specimens which was used here as the evaluation reference. It should be brought to attention that since core specimens were extracted from casted plates, it was nearly impossible to ensure that the hybridization ratio was consistent in all specimen. However almost all tested specimens lied inside the standard deviation value of 5% and thus the assumption of the consistency of hybridization fiber proportions was considered valid. As expected, hybrid FRC specimens demonstrated higher compressive strength comparing the PFRC specimens and lower than those of SFRC specimens. However, EFNARC suggests lower strength values for core specimens in comparison with cylindrical specimens and thus both SFRC and hybrid fiber reinforced concrete (HFRC) specimens were classified as C48/60. EFNARC does not present flexural test guidelines for core specimens; consequently, the effect of hybridization on flexural strength could not be assessed with reference to EFNARC.

3.2.3 Influence of fiber type and content on the residual strength classification

ACI 544.1 R-96 aims to facilitate designers' job in selecting the required sprayed concrete, which can best fulfill deformation prerequisites of the lining under service conditions.

Figure 14: Residual classification of flexural strength in accordance with EFNARC

With this goal in mind, it proposes five classes at which toughness of a beam specimen through flexural test can be classified. Figure 14a-b demonstrates residual strength classes as per EFNARC; in order to assess the residual strength class of the tested beams with various fiber contents, relative bending load-deflection curves are also presented in Figure 14a-b. As can be observed, SFRC specimens endured higher flexural strength than PFRC specimens; though, in terms of residual strength they attained lower levels. In PFRC specimens an abrupt drop of strength preceded a fairly constant residual strength; whereas in SFRC specimens, the reduction of strength was gradual but continued to diminish with the advancement of deflection. Based on EFNARC, FRS are classified with regard to residual strength they obtain on or above a certain class boundary at deflections within the range of 0.5 and 2 mm. Therefore, the lowest class at which a specimen reaches between the deflections of 0.5 and 2 mm was chosen as their residual strength class. It evident from Figure 14a that with the increase of fiber content from 1.5% to 2.5% a change in strength class occurred, hence the prior was classified under class 1 while the latter was placed under class 2. Nonetheless, SFRC specimen containing 4% of reinforcing fibers gained considerably higher residual strength thus, acquired the higher class of 3 in EFNARC classification. A different trend appeared for PFRC specimens (Figure 14b) as by increasing fiber content from 1.5% to 2.5% a drop in class from class 1 to class 2 was obtained. However, by further increasing the fiber fraction from 2.5% to 4% another class change took place shifting from class 1 and settling in class 2. Yang *et al.* [19] and Bamonte *et al.* [2] reported SFRC at class 3, which is not contradictory to the

finding of this study. Difference in fiber content and mixing proportions might be possible causes for such distinction in specimens containing 1.5% and 2.5% of steel fiber. Once more it should be pointed out that in spite of significantly lower tensile strength and unit weight, polymer fibers proved themselves as a beneficial reinforcing material since PFRC specimens achieved the same residual strength class as SFRC specimen with identical amount of fiber did. Consequently it can be used in tunneling practices where a ductile, lightweight and corrosion resistant lining is demanded.

3.2.4 Influence of hybridization on the residual strength classification

Notwithstanding an adequate residual strength, PFRC specimens suffered relatively lower flexural strength in comparison with SFRC specimen which may prevent them from being used in strength demanding structures *e.g.* in deep tunnels and conduits. Therefore, hybridization of SFRC and PFRC seemed like a convenient solution for such drawback. Figure 15 demonstrates flexural load-deflection curves of hybrid fiber reinforced concrete (HFRC) beam specimens with different fiber content together with EFNARC residual strength class boundaries. HFRC specimens with 4% fiber content, from which 75 percent were steel and 25 percent were polymer fibers, showed the highest peak flexural strength together with decent ductility properties. Specimens containing lower amount of steel fiber attained lower peak and residual strength, though their difference was recognized to be less than 10%. Therefore,

Figure 15: Residual Classification of flexural strength for HFRC in accordance with EFNARC

specimens with higher steel fiber content were classified at class 2 whereas the ones with lowest steel fiber content were only classified as class 1. Another improvement on HFRC over other FRC specimens was noticed to be the considerable increase in the area under the flexural-deflection curve in comparison with PFRC specimens. This is an indicator of the further energy absorbed by the beams throughout the test [26]. In total, it should be reminded that hybridization of reinforcing fibers and their behavior should be studied more and a more thorough classification needs to be fabricated.

4 Conclusions

The present study investigated the influence of various reinforcing fiber parameters including fiber type, amount and hybridization on compressive, flexural and tensile strength of fiber reinforced concrete (FRC) specimens. Polymer fibers along with regular hooked steel fibers were chosen as the reinforcements. As fiber reinforced concrete is commonly employed in tunneling practices as the lining, strength and toughness classes of both polymer fiber reinforced concrete (PFRC) and steel fiber reinforced concrete (SFRC) were evaluated in accordance with EFNARC. Hybridization of the two fiber types was also investigated in three distinct mixing proportions in pursuance of determining a product with adequate strength and ductility characteristics. To conclude, the following findings were established based on the results obtained:

1. Compressive strength is drastically improved after addition of steel fibers to plain concrete (PC); albeit,

PFRC did not enjoy such improvement due to polymer fibers low shear modulus. Post-peak behavior of PFRC on the other hand was noticeably transcended that of the PC. Furthermore, SFRC attained greater peak stress displacements than PFRC, which indicates more permitted deformability before failure. Flexural strength of SFRC and PFRC was measured approximately similar, in contrast with results obtained in compressive strength. Greater number of polymer fibers in each PFRC specimen in comparison with those of steel fibers in a SFRC specimen was mainly held responsible of the similarity observed in the bending strength. Fantastic bond of polymer fibers due to their higher slenderness was also considered another influencing factor. SFRC endured higher tensile loads in the direct tensile test than PFRC. Strength difference however was not high and could be neglected.

2. Compressive, tensile and flexural performance of SFRC was improved as the result of an increase in fiber amount. PFRC although lost marginal values of compressive strength, as fiber content was risen but flexural and tensile strength experienced a boost as fiber content was elevated. Overall dependency of SFRC on fiber amount is mainly in compressive and tensile strength whilst that of PFRC is chiefly in flexural strength. Fiber orientation and bonding strength were discovered to be governing parameters in tensile strength of FRC.
3. Hybridization of PFRC and SFRC was found to be advantageous as higher strength steel fibers and corrosion resistant, lightweight and flexible polymer fibers tend to form a strong and ductile reinforced concrete, which will perform decently in harsh environment. It was understood that not more than 25% of polymer fiber in the total fiber fraction should improve the mechanical behavior of FRC.
4. Strength and residual class of PFRC and SFRC were determined as per EFNARC through compressive and flexural tests and the effects of fiber properties on the classification of the final product was evaluated. It was concluded that there was more than one compressive strength class difference between SFRC and PFRC. On the other hand, both FRC type were classified under the similar flexural class at the identical fiber content of 4%.

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