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Mechanical and Durability Properties of Different Types of Fiber Reinforced Concrete

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ABSTRACT

Concrete is a superior construction material due to its cost and excellent capability in the compression load bearing zone. However, concrete easily fractures under tensile loading. Therefore, reinforcement is installed in order to offset the tensile forces subjecting to concrete. So far, brittleness of concrete has been tailored to higher bending resistance behavior thanks to the utilization of fibers. Incorporating of fibers into concrete matrix not only enhances the bending properties but also affects other mechanical and durability properties. Although advantages of fiber inclusion have been proved, the effect of fiber type still remains to be further investigated for fiber reinforced concrete specimens. In this study, a total of 112 C20/25 concrete specimens (15x15x15 cm 56 cubic specimens, 15x30 cm cylinder specimens and 10x10x40 cm prismatic specimens) were produced and investigated taking into account of their compression, flexural, splitting strengths and water absorption rates. Experiments were carried out at the age of 7 and 28 days for each specimen group. All experiments were examined in detail and advantages/disadvantages of three fiber types were evaluated individually on the account of obtained data. Results indicate that length to diameter ratio and characteristic tensile strength of fibers have an influence on all mechanical properties irrespective of fiber volume.

Keywords: Fiber Reinforced Concrete, Fiber type, Mechanical properties, Water Absorption

INTRODUCTION

Discrete fibers are widely preferred to enhance the tensile and bending behavior of cement-based materials (Balaguru et al. 1992; Nawy, 2001). Mechanisms of fibers are generally attributed to bridging gaps to mitigate crack propagation so that additional energy is required to break the bonding between fiber and matrix (Johnston, 2001). Also, it is reported that fibers enable concrete mixtures to control shrinkage, to improve fracture toughness and impact resistance (Banthia et al., 1994; Qi et al., 2003; Banthia & Gupta, 2006; Sorelli et al., 2006)]. However, several studies put emphasis on increased permeability mortar/concrete due to weakened interface area of fiber and matrix (Yang & Zhu, 2005; Ramezanianpour et

al., 2013; Niu et al., 2013;). In addition to that, fiber addition may cause air-entrapped voids in concrete mixtures which are detrimental to mechanical properties. Therefore, the contribution of fibers in the crack development mechanism still remains to be understood exactly. The shapes, sizes and individual strength of fibers should be characterized for the most effective concrete performance.

Delaying of microcracks can be sustained until several processes occurs in the concrete matrix such as fiber pull-out, rupture or fiber yielding. In the end, increased number of microcracks tend to link each other to form wider cracks which trigger fracture mechanism. Several studies indicated that performance of the fibers is directly related to their dispersion in the mixture (Mobasber et al. 1990; Banthia et al. 1994) and size (Betterman et al., 1995). Different types and different sizes of fibers have been investigated to further improve the reinforcement contribution of fibers in concrete mixtures (Lawler et al., 2003; Sahmaran et al., 2005, 2007; Ganesan et al. 2014). Among these fiber types and sizes, the most commonly used ones are steel fibers, polymeric, glass fibers, and natural fibers. In view of above mentioned advantages, fiber reinforced composites have been considered as one of the potential candidates for structural applications which are expected to resist subjected loads without suffering an instant fracture during their service life.

To understand the mechanism of fracture process in fiber reinforced cement-based materials, experimental studies are implemented and efforts are undertaken to optimize mechanical and durability performance together with production cost. The presented study seeks to increase the knowledge of fiber reinforcement mechanism to adopt the utmost performance for fiber reinforced concrete composites. To that end, bulk properties such as compressive, flexural tensile and splitting tensile tests are investigated along with water absorption tests as an indicator of durability performance. Role of each individual fiber type is aimed to be discussed in detail in terms of their effect on basic mechanical and durability properties of conventional fiber reinforced concrete.

MATERIAL AND METHODS

Materials

Three different aggregate sizes were used at 0-5 mm, 5-12 mm and 12-22 mm. Percentage of used aggregate in the concrete mixtures were given in Table 1. Ordinary Portland cement (OPC), CEM 42.5 N, was used as a binder in conformity with TS EN 197-1 (TS EN 197-1, 2012). To make fresh mixtures adequately workable, high range super-plasticizing admixture (HRSA) was used at 1% of total mixture volume.

Table 1. Mix proportion of aggregates

Sieve (mm)	Upper limit (%)	Sublimit (%)	Gradation (%)
22.4	100.0	100.0	100.0
16	89.0	62.0	84.2
8	77.0	38.0	63.5
4	65.0	23.0	58.9
2	53.0	14.0	45.6
1	42.0	8.0	32.2
0.50	28.0	4.0	22.3
0.25	15.0	2.0	15.7

Steel fibers (SFs) and two polymeric fibers (PF1 and PF2) were added into fresh concrete mixtures at a single dosage of 1% by total mixture volume to improve the mechanical performance [Figure 1]. Characteristic properties of each fiber were given Table 2.



a) b) c)

Figure 1. SFs (a), PF1 (b) and PF2 (c) used in concrete mixtures.

Table 2. Properties of different fiber types used in the study

Fiber type	Length (mm)	Diameter (mm)	Slenderness ratio	Minimum tensile strength (MPa)
SFs	60	0.90	67	1050
PF1	54	0.55	98	900
PF2	54	0.9	60	585

Mix Proportions and Specimen Production

In the study, C20/25 concrete specimens, one of the most produced strength classes (Müller, 2009) in the world, were produced having 20 MPa characteristic compression strength at 28 days. A 108 L concrete mixer was used to produce four different mixtures. Initially, dry materials (aggr. and cement) were added into mixer and mixing was conducted for 2 mins.

Table 3. Specimens prepared for the tests

Exp.'s Mix. ID	Compressive Strength	Flexural Tensile Strength	Splitting Tensile Strength	Water Absorption
C-Ref.	7 cubic specimens with the dimensions of 15x15x15 cm	7 prismatic specimens with the dimensions of 10x10x40 cm	7 prismatic specimens with the dimensions of 15x30 cm	7 prismatic specimens with the dimensions of 15x15x15 cm
C-SFs	7 cubic specimens with the dimensions of 15x15x15 cm	7 prismatic specimens with the dimensions of 10x10x40 cm	7 prismatic specimens with the dimensions of 15x30 cm	7 prismatic specimens with the dimensions of 15x15x15 cm
C-PF1	7 cubic specimens with the dimensions of 15x15x15cm	7 prismatic specimens with the dimensions of 10x10x40 cm	7 prismatic specimens with the dimensions of 15x30 cm	7 prismatic specimens with the dimensions of 15x15x15 cm
C-PF2	7 cubic specimens with the dimensions of 15x15x15cm	7 prismatic specimens with the dimensions of 10x10x40 cm	7 prismatic specimens with the dimensions of 15x30 cm	7 prismatic specimens with the dimensions of 15x15x15cm

After that, potable water was fed into the mixer and mixing continued for another 2 minutes. HRSA gradually was poured into ongoing fresh mixture in 30 seconds and mixing proceeded for 1.5 minutes. After a total of 6 minutes mixing, fibers were gradually added into the mixer in 30 seconds and additional 2 minutes were sustained to distribute fibers homogenously in the fresh mixtures. Details of produced total 112 specimens for experimental tests were given in Table 3 and some specimens are presented in Figure 2.



Figure 2. Produced specimens for experiments

Experiments

All produced specimens were cast into relevant molds and cured for 24 hours at 50±5% RH, 23±2°C. After being removed from the molds, standard curing was applied to specimens in water at 20±2°C until the day of the experiment. Three C20/25 specimens from each mixture were tested for compressive strength, flexural tensile strength, splitting tensile strength and water absorption after 7 and 28 days of curing. Compression and splitting tensile tests were applied at 0.5 MPa/s while 3-point flexural tensile tests were applied at 0.2 MPa/s in accordance with TS EN 12390 (TS-EN 12390-3, 2003). For water absorption tests, cubic specimens were dried in an oven at 105 °C for 24 hours after curing and weighted in order to evaluate water absorption rates by using the equation below:

$$\text{Water absorption percent by weight} = \frac{W_S - W_K}{W_K}, \quad (1)$$

Where W_S and W_K stand for waterlogged weight and dry weight, respectively. In addition to mechanical and durability tests, fresh properties of each mixture were determined by slump tests. Experimental figures were given in Figure 3 and Figure 4.



a) b)

Figure 3. Compressive tests (a) and splitting tensile tests (b)



a) **b)**

Figure 3. 3-point flexural tensile tests (a) and dried specimens (b)

RESULTS AND DISCUSSION

In the presented investigation, experiments have been conducted to determine the effect of different fiber types on the fresh and mechanical properties of C20/25 concrete. To that end, slump tests were carried out to characterize mixtures' workability in the presence of three different fibers. The slump tests were made in accordance with TS EN 12350 (TS EN 12350-2, 2002). Compressive strength, flexural tensile strength, splitting tensile strength and water absorption tests of the samples were determined at the age of 7 and 28 days.

Workability

The rheology of fiber reinforced concrete is clearly different than that of mixtures without fibers. In this study, lower slump values of C-SFs, C-PF1, and C-PF2 were recorded compared to the plain mixtures. The maximum range was found between C-SFs and C-Ref mixtures. Average slump value of C-SFs mixtures was 8.3 cm whereas it was 13.2 cm for C-Ref mixtures that exhibits 37% disadvantageous consistency in the presence of steel fibers. Moreover, all fresh properties of fiber reinforced concrete were in a similar tendency although C-PF1 and CPF2 mixtures were more workable than the C-SFs mixtures. It can be easily stated that fiber inclusion decreased the workability irrespective of the fiber type preferred in the study. The reason can be explained by the characteristic stiffness and geometrical properties of the fibers. Steel fibers which have the higher stiffness than the other two of fibers may have led to reduce the slump values of mixtures. Another reason can be attributed to the increased surface area of the overall matrix. Fibers most probably caused more surface area thus leading to decrease the wettability of the particles. Although water reducing admixture was used at a constant level, i.e. 1% of the total mixture volume, experimental results indicated that water reducing admixture should be optimized in accordance with the specific properties of the fibers at given mixture parameters. Slump values of plain mixtures are within the limit values of the S3 category in TS-EN 12350 (TS EN 12350, 2002) that allows the adoption of mixtures in professional construction sites. However, all slump values of fiber reinforced concrete mixtures were within 50-90 cm all of which belongs to the S2 category that may significantly influence the uniformity unless vibrator is used.

Compressive Strength

The cube specimens with the dimensions of 15x15x15 cm were tested at 7 and 28 days under compression load and results were summarized in Figure 4.

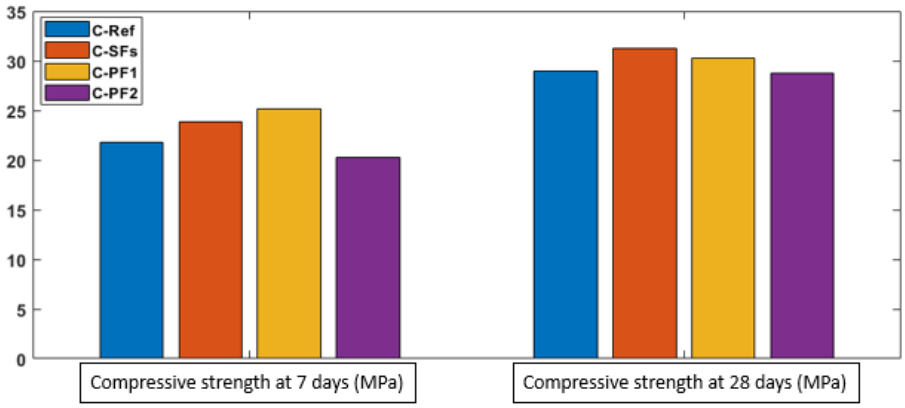


Figure 4. Compressive strength of the specimens at 7 and 28 days

As it can be inferred from the figure that compressive strength of the all specimens exhibited increase with the age regardless of fiber inclusion. Also, it can be seen that C-SFs and C-PF1 specimens yielded higher compressive strength than C-Ref and C-PF2 both in 7 and 28 days. Results demonstrate that inclusion of 1% fiber by volume of total mixture played considerable increase in compressive strength. The increase of compressive strength was more pronounced in C-PF1 and C-SFs specimens at 7 days and 28 days, respectively.

C-PF1 specimens were 14% higher than the plain specimens at 7 days while it was approximately 10% for the C-SFs compared to control specimens at 28 days. Results were also in line with the studies exist in the literature (Natajara et al., 1999; Lee et al., 2015). The main reason for this was because arrests of cracks due to fibers both in micro and macro levels increased the compressive strength of concrete. However, average of C-PF2 compressive strength was lower than the plain concrete at both 7 and 28 days. Although the lower compressive strength of C-PF2 specimens was negligible at 28 days, 11% decrease was obtained in C-PF2 specimens compared to reference specimens at 7 days. This result can be due to poor fiber dispersion and decreased uniformity of C-PF2 specimens. Agglomeration of PF2 fibers may cause weakened zone in the concrete matrix so that lower compression strength were obtained.

Flexural and Splitting Tensile Strength

Flexural and splitting tensile strength were determined after 7 and 28 days of curing. Results were given in Figure 5 and Figure 6. It is clear that flexural and splitting tensile strength of the C-SFs, C-PF1, and C-PF2 were higher than the reference specimens. The highest improvement can be seen in Figure 6 where C-SFs specimens possessed more than 25% higher splitting tensile strength than C-Ref specimens. This comparison was more pronounced for 7 days old C-SFs specimens that had approximately 40% higher splitting tensile strength. Similar behavior can be also recognized for the C-SFs specimens in flexural tensile strength both in 7 and 28 days.

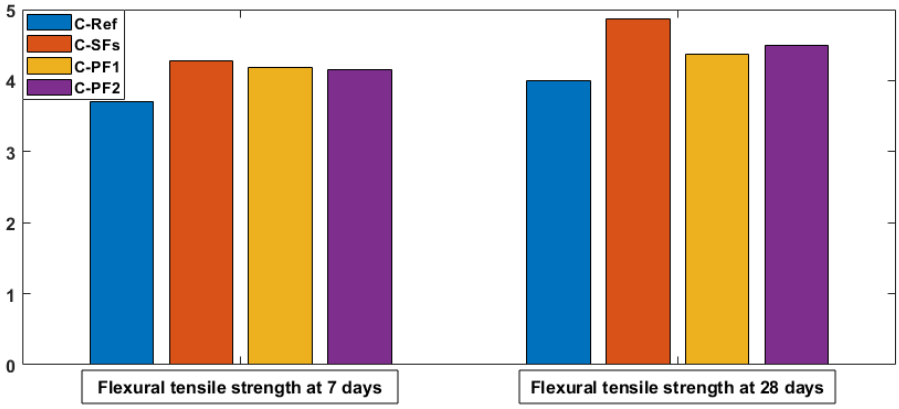


Figure 5. Flexural tensile strength of the specimens at 7 and 28 days

Flexural properties were evaluated 13% and 21% higher for the C-SFs specimens compared to references specimens at both test days. Although such an increase was not obtained in other prismatic specimens at 28 days, C-PF1 and C-PF2 exceeded the average of plain specimens at a rate of 8% and 10%, respectively. In the experiments, cracking instantly led to the failure of plain concrete specimens as expected. The increase of flexural strength of fiber reinforced concrete specimens can be explained by the crack arresting behavior of fibers that reduce the crack width by bridging smaller cracks initiated after loading.

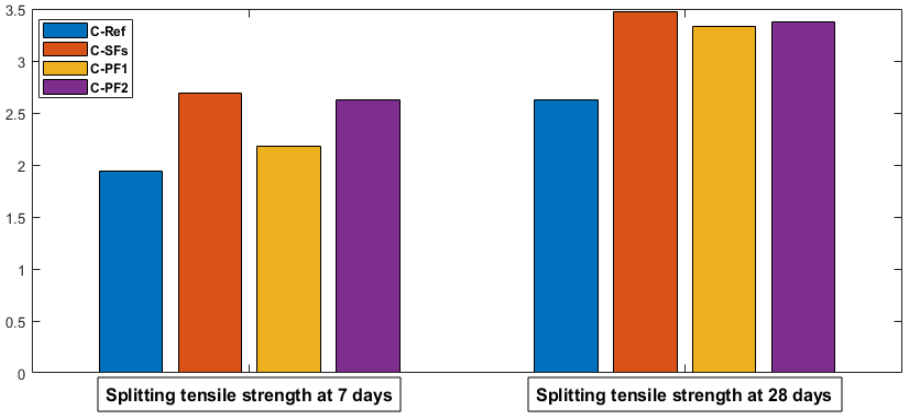


Figure 6. Splitting tensile strength of the specimens at 7 and 28 days

It is observed that fiber reinforcement played a significant role by improving the crack growth resistance in all tested specimens. Also, additional energy was required to proceed the cracks and deboned the fibers from the integrity of the matrix. This behavior enables fiber reinforced concrete to carry increasing loads after the first crack provided that the pull-out resistance of the fibers is higher than the load at crack initiation. In this study, improvement of strength was validated for most of the fiber reinforced specimens, more importantly it can be easily stated that fibers contributed the post-cracking ductility. The increased post-cracking behavior of the C-SFs fiber reinforced concrete can be seen in Figure 7. This behavior was more pronounced for the steel fiber reinforced concrete since hooked-end steel fibers improved the bonding between fiber and concrete matrix. Results of flexural and splitting tensile strength were also in line with the studies carried out on the different types of fiber reinforced concrete (Rizzuti et al., 2014).

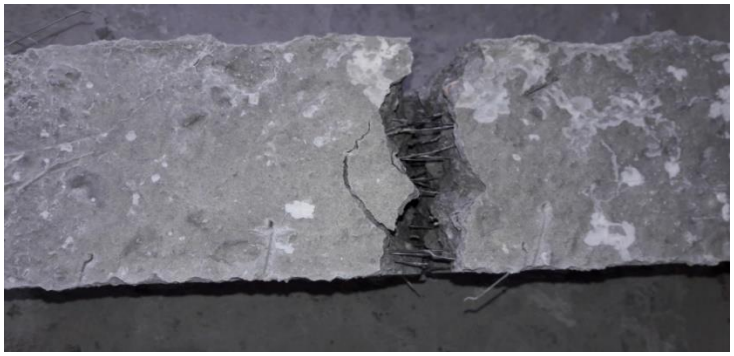


Figure 7. Steel fiber reinforced concrete specimens after tests

Water Absorption

Water absorption tests were carried out by submerging cubical specimens in water for 24 hours. Weight measurements were recorded on water-saturated specimens. After that, cubical specimens were put into an oven and kept drying at 105°C for 24 hours. Dried specimens were weighted and percentile weight change between water saturated specimens and dried specimens were determined as given in Figure 8.

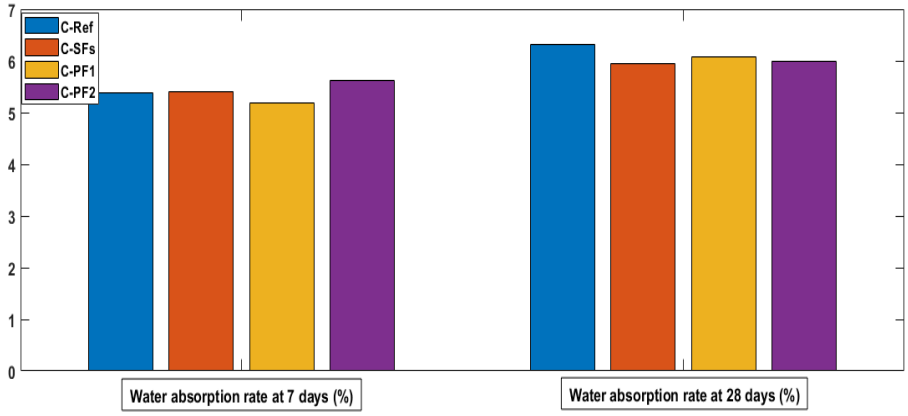


Figure 8. Water absorption rates of the specimens

In Figure 8, C-PF2 specimens resulted higher water absorption rate than the rest of all specimens at 7 days. If Figure 8 is compared with the Figure 4 where compressive strength of the specimens is presented, one can easily specify that higher water absorption rate of the specimens caused a decreased compressive strength. This result is more distinctive for the specimens at 7 days. The main reason could be associated with the high internal water that enables ongoing hydration influenced the weight after evaporation at 7 days compared to results conducted at 28 days. All types of fiber reinforced concrete exhibited similar water absorption rate at 28 days while water absorption rate of plain concrete was 6% higher than the C-SFs specimens. Since water absorption rates are highly dependent on the pore structure and network of the matrix, the increase of pore content may cause higher water absorption which is the indicator of poor durability. Fibers increase the surface area of the matrix during the mixing process of concrete so that potential existence of entrapped air also increases. However, it can be said that 1% fiber inclusion by volume of the total mixture is not detrimental to the probability of entrapped air that reduces the compressive strength of the specimens.

CONCLUSION

Based on the tests conducted to determine the compression strength, flexural tensile strength, splitting tensile strength and water absorption tests, the following conclusion can be made;

- Workability properties of fresh fiber reinforced concrete mixtures reduced, however, no detrimental effect was encountered for the mechanical properties. This concludes that 1% fiber addition into the matrix by volume of the total mixture is acceptable taking into account of the compressive strength. Moreover, steel fiber inclusion is worthy of recommendation since clear improvements were observed in C-SFs specimens thanks to arrests of cracks by steel fibers thus enhancing the compression load-bearing capacity.
- Although all fiber reinforced concrete specimens exhibited increased flexural strength and post-cracking ductility compared to plain concrete specimens, characteristic behavior of each fiber played a significant role both in flexural and splitting tensile strength. In conclusion, geometrical properties and individual tensile strength of the fibers are highly influential in mechanical properties. Obtained results indicate that hybridization of different fibers in one concrete mixture can be a better solution to tailor the brittle behavior of concrete.
- Water absorption rates of all fiber reinforced specimens were not different than the plain specimens. This finding also reveals that limited use of fiber reinforcement, i.e. 1% by total volume, does not pose a threat for durability since high water absorption rate of concrete is more susceptible to harmful ions along with water.

It can be summarized that use of different types of fibers in concrete requires special handling. Reduce of crack widths, resistance to deformation and improvement of ductility which are critical for the safety of the structures can be tailored much better by the combination of aforementioned fiber types. Nevertheless, the behavior of all single fiber reinforced concrete specimens were satisfying taking into account of mechanical and durability tests presented in this study.

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