An experimental investigation into the effect of polypropylene fibers on mechanical properties of concrete

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Abstract: In general, the behavior of most of materials is studied in terms of their mechanical properties like as compressive and tensile strengths; however, to study the behavior of fiber reinforced concrete, these properties is not enough and the flexural strength and the energy absorption capacity of the concrete should also be studied. The effect of polypropylene fibers of different lengths and diameters on the flexural strength of the concrete has been explored in this article. The variables of the experiments include three lengths for fine polypropylene fibers and two lengths for thick polypropylene fibers. Results indicate the flexural strength of the samples increased with increasing the fiber's length. But by addition fine polypropylene fibers, the flexural strength of the samples decreased with increasing the fiber's length. On the other hand, the addition of fibers polypropylene to the concrete can not be effective in enhancing the cracking load of the concrete, but thick polypropylene fibers can increases the ultimate load after cracking and the energy absorption capacity of the concrete.

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1.Introduction

The tensile strength and strain capacity of the non-reinforced concrete are small against fracture, which are traditionally compensated for with rods or pre-stressed steel. Though structural applications of fibers have not yet been introduced in guidelines, they are now used as excessive reinforcing materials in constructions and concrete parts.

Wide varieties of fibers are used to reinforce cement and other brittle materials. The fibers used in concrete can be generally divided into two categories of natural and synthetic fibers like carbon, nylon, polypropylene, etc (Tanyildizi, 2009). Polypropylene fibers are used for the purpose of controlling the cracks resulted from concrete shrinkage, and increasing the tensile strength and the energy absorption capacity (Mollaahmadi, 2010). Reportedly, these fibers were first used by Goldphin at the US Army in 1965 for making non-explosive concrete construction (Wong, 2004)

Polypropylene fibers are made in three different geometries including monofilament, fibrillated, and tape fibers, the first two of which are used for increasing mechanical properties of concrete and cement (Taklo, 2008). Monofilament fibers are better to be used in concrete, because in comparison with fibrillated fibers, they can be homogenously dispersed within the concrete with no air captured between them, making it possible to use high amounts of them. In contrast, fibrillated fibers can only be used up to 1 kg in each cubic meter concrete, as the air captured between the fibers prevents them from being homogenously dispersed, and reduces the strength of the concrete (Javadi , 1999).

Extensive experimental studies have been conducted into the effect of the polypropylene fibers addition on mechanical properties of concrete. Wu experimentally investigated the flexural strength and the behavior of polypropylene fiber reinforced concrete beams, and found that the flexural strength of the reinforced concrete was less than that of the non-reinforced concrete, but the toughness index of the flexural strength increased (Wu, 2002). Here, as shown in Fig. 1, the toughness index of the flexural strength is the ratio of the area amount enclosed under the load-deflection curve of the sample (e.g. ÓACD) to the area amount enclosed under the curve up to first crack (ÓAB). Noumowe studied mechanical properties and microstructure of high strength concrete containing polypropylene fibers at temperature 200 ^{o}C; he found that upon heating, the splitting tensile strength, compressive strength, and the modulus of elasticity of polypropylene fiber reinforced concrete reduced more than those of the non-reinforced concrete, which can be due to the melting of the fibers and the creation of small channels (Noumowe, 2005). Takloo and et al concluded that the addition of polypropylene fibers to concrete increases the energy absorption capacity of the concrete in proportion with the increase in the volume percentage of the fibers; moreover, the energy absorption capacity increases with increasing the strength of the concrete, which can be due to a better adhesion of the concrete and the fibers (Taklo, 2008). Banthia et al. proved that polypropylene fibers can effectively control plastic shrinkage cracking in concrete, and reduce the crack area, maximum crack width, and the number of cracks (Banthia, 2006). The amount of the effect of the fibers is in direct proportion with their volume percentage. Furthermore, the longer fibers of the same diameter have greater influence on the flexural capacity because, in view of the poor bond between the fibers and the cementitious matrix, a longer length is required for the efficient transfer of stress across cracks (Mollaahmadi, 2010). Khodaparaste-haghi et al reached the conclusion that the low modulus of elasticity of polypropylene fibers results in a low compressive strength of the fiber reinforced concrete as compared to the non-reinforced concrete (Khoda Parast, 2008).

In light of the fact that the fibers in fiber-reinforced concrete influence its behavior mostly after cracking, the study of the area amount enclosed under the load-deflection curve is more suitable for the purpose of investigating the concrete's behavior and its properties. To do flexural tests, American ASTM C1018 (ASTM, 2002) and Japanese JSCE (JSCE-SF4, 1984) standards can be utilized. In this study, flexural tests were carried out according to the ASTM C1018.

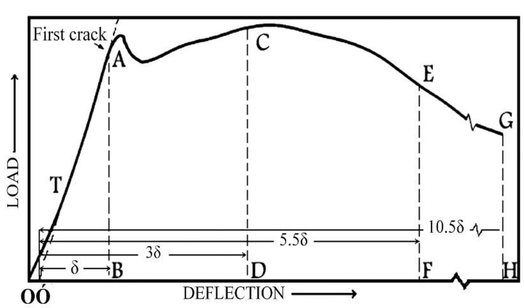

Fig. 1. The load-deflection curve according to the ASTM C1018

2.Materials and methods

In this study, The used Portland cement type II was chosen according to ASTM C150 (ASTM, 2005). The characteristics of polypropylene fibers have been presented in Table 1. To make polypropylene fiber reinforced concrete, and providing the necessary workability, The used superplasticizer as a commercial sulphonated melamine formaldehyd polymer (Vand chemie, Iran) has relative density of 1.15 produced by Vand Shimi Company with the industrial name of NSF, in accord with the ASTM C494 (ASTM, 2011). On the basis of the recommendation of the manufacturer, the allowed amount of the superplasticizer has been considered to be 1-3% of the weight of the cement.

Table 1. The characteristics of polypropylene fiber

Properties	Thick fiber	Fine fiber
Nominal diameter (mm)	0.98	0.022
Tensile strength (MPa)	240	400
Density (gr/cm^3)	0.88-0.92	0.91
Elastic modulus (MPa)	5100	8500
Elongation (%)	24.4	12
Shape	wavy	Flat

All the aggregate needed for this study were obtained from the minds around Yazd, Iran. Fine aggregate was fluvial sand with the fineness modulus of 2.4 and coarse aggregate was the crushed silica sand with maximum size of 9.5 mm. The aggregate was graded according to ASTM C33 standard (ASTM, 2007). The mixing ratios has been given in Table 2. The thick fibers of polypropylene were used with the lengths of 30 and 40 mm (samples T30 and T40), and the fine fibers were used with the lengths of 6, 12, and 19 mm (samples F6, F12, and F19). On the basis of the results of other researchers (Wong, 2004, Tanyildizi, 2009, Wu, 2002), the weight of the fibers per unit volume of the concrete were chosen to be 16.5 kg/m^3 for thick fibers, and 1.1 kg/m^3 for fine fibers (Table 3).

To fabricate plain concrete and the concrete containing PP fibers, superplasticizer was firstly dissolved in water. After cement, sand, coarse aggregate and PP fibers (if used) were mixed uniformly in a Concrete mixer, the mixture of water and superplasticizer was added gradually to in and mixed for several minutes. The fresh concrete was poured into the molds with dimensions of 10×10×50 cm in three layers. Each layer was compacted by 35 impacts of a steel rod.

Table 2. Mix proportion of the samples (kg/m^3)

Water (kg)	Cement (kg)	Sand (kg)	Coarse aggregate (kg)	Super plasticizer (kg)
178	450	1070	670	6.25

Table 3. The characteristics and weight of the fibers per unit volume of the concrete

Sample no	Fiber type	Nominal diameter (mm)	Length of fiber (mm)	Weight of fiber (kg/m^3)
PC (plain concrete)	-	-	-	-
F6	Fine	0.022	6	1.1
F12	Fine	0.022	12	1.1
F19	Fine	0.022	19	1.1
T30	Thick	0.98	30	16.5
T40	Thick	0.98	40	16.5

After pouring, a vibrator was used to facilitate compaction and decrease the amount of air bubbles. The moulded specimens were covered with a plastic layer for 24 hours and then the specimens were demolded and were cured at $(20 \pm 2)^o$ C up to end of the seventh day.

The variables of the experiments were the length and diameter of the fibers, while their volume and types were kept constant. The polypropylene fibers were of three different lengths and the thick fibers had two different lengths. According to the instructions given in ASTM C1018 (ASTM, 2002), the sample was turned to one side in the mould, and was put symmetrically on two supporting blocks. The distance between the centers of the supporting holders was 45 cm, and the centers of the two loading fixtures were at 15 cm distance from each other (Fig. 2). A gage with the accuracy of 0.01 mm is located at the midpoint of the flexural sample so that the deflection of the midpoint of the sample can be recorded at the same time as the load is applied to the sample. Taking into account the loading rate allowed by the ASTM C1018, and after doing many try and error tests, we chose the loading rate of 4 kg/sec to be suitable for simultaneous reading the gage and the load applied by the machine.

The area amount enclosed by the load-deflection curve has been calculated to be δ, 3δ, 5.5δ, and 10.5δ in four specified deflections (Fig. 1). The area amounts under the curves ÓAB, ÓACD, ÓAEF, and ÓAGH are respectively related to the toughness's in the deflections δ, 3δ, 5.5δ, and 10.5δ. The toughness obtained in the deflection δ is equivalent to the elastic toughness or the toughness first crack (the first-crack toughness). The other three deflections are related to the toughness after the first cracking point (Wu, 2002)

The indexes I_5, I_{10}, and I_{20} can be obtained through dividing the above-mentioned areas to the area amount enclosed under the load-deflection curve within the elastic limit (δ). Therefore, these primary indexes show the amount of the energy absorption at the primary and small deflections, while for comparing the behavior of the beam at larger deflections, higher indexes are required (Sukontasukkul, 2004).

(1) I_5=(area ÓACD)/(area ÓAB)
(2) I_{10}=(area ÓAEF)/(area ÓAB)
(3) I_{20}=(area ÓAGH)/(area ÓAB)

The indexes of the residual strength can be calculated from the following equations:

(4) $R_{5,10}=20(I_{10}-I_5)$
(5) $R_{10,20}=10(I_{20}-I_{10})$

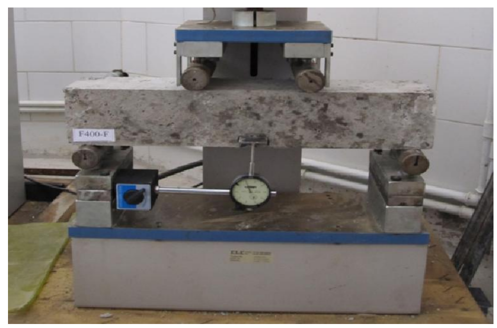

Fig. 2. The setup of the flexural test

3. Results and discussion

The force which is first cracking are respectively recorded as the cracking load (P_{cr}) and the ultimate load (P_u). The ultimate load is just obtained for the samples containing thick polypropylene fibers. because the samples containing fine fibers after reaching to the first crack, failure happens. The loading of the samples containing polypropylene fibers and the plain concrete have been shown in Table 4. It can be inferred from the table P_{cr} decreased by increasing fiber's length in the samples containing fine polypropylene fibers. It is caused by the micro cracks in the concrete that affects the flexural strength. Because by increasing fiber's length, the workability of concrete decreased, and the number of micro-cracks in concrete increases, which results in the decrease of flexural strength of concrete (Shuan-fa, 2001). But in the samples containing thick fibers, P_{cr} increased by increasing fiber's length. Because the thick fibers can bridge across the cracks due to higher long (fig.3) and its shapes that effecting of bridging of the fibers is more than increasing of number of micro cracks.

Table 4. Loading of the samples

Sample no	P_{cr} (kg)	P_u(kg)
PC	997.33	-
F6	965.33	-
F12	928	-
F19	806.33	-
T30	880	713
T40	1015	1030

Fig. 3. Bridging of the fibers between the cracks

The load-deflection curves of samples F40, F30, and PC (Plain concrete) have been illustrated in Fig. 4; the comparison of the curves shows that failure happens in plain concrete suddenly after reaching to the first cracking load, and the failure and cracking points overlap each others. But in the samples containing thick fibers after reaching to the cracking stage, through bridging of the fibers between the cracks, the concrete reinforced by thick fibers resist against the load (Fig. 3)

It can be seem by fig. 4 polypropylene fibers due to low strength and stiffness required a large deformation or crack opening before the fibers could respond to the load. As a result of this, the recovery of load was found late in first cracking load (Sukontasukkul, 2004).

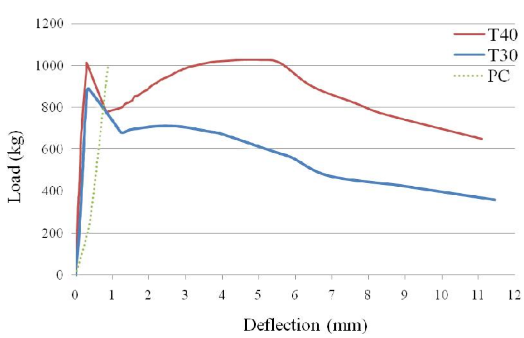

Fig. 4. Comparing the load-deflection curve of T40, T30 and PC

The flexural indexes were calculated with the use of the load-deflection curves of the samples, and the results have been shown in Table 5 and Fig. 5. The flexural indexes of sample T40 are more than those of sample T30; this increase is more for higher indexes. The main purpose of adding polypropylene fibers to the concrete is to increase its energy. The area amount enclosed under the load-deflection curve is equivalent to the energy absorption of the concrete. We calculated this under-curve area with a program written in EXCEL software, the results of which have been presented in Fig. 6. It can be seem from the table the addition of thick polypropylene fibers to the concrete increases the energy absorption. Also It has been shown in Fig. 6 that the energy absorption increases by the amount of 97.63% when the length of the fiber increases from 3 to 4 cm. This effect can be attributed to the fact that longer fibers of the same diameter can make more strength bonding with the concrete, and hence, can tolerate higher tension stresses.

Table 5. The average of the flexural indexes

Sample no	Average of the flexural indexes				
	I_5	I_{10}	I_{20}	$R_{5,0}$	$R_{10,20}$
T30	4.07	6.65	11.81	51.6	51.6
T40	4.36	8.27	17.3	78.2	90.3
Enhanced extent(%)	7.12	24.36	45.62	344.8	212.6

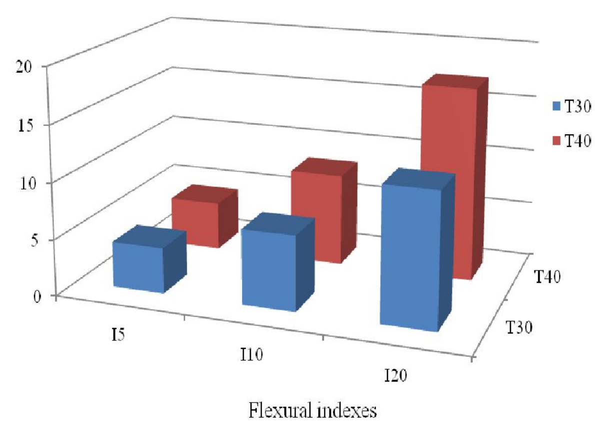

Fig. 5. Flexural indexes

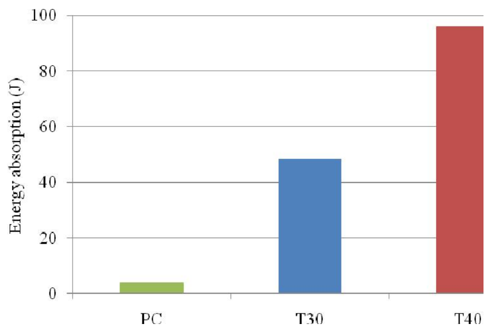

Fig. 6. The energy absorption of the samples

Through recording the deflection of the concrete sample at the time of first cracking, the equivalent deflection of the first cracking has been obtained as first-crack deflection, and the results have been shown in Table 6. It can be inferred From the table that the deflection equivalent to the first cracking has been reduced by 139% through making use of thick polypropylene fibers. This is due to the increase in hardness through transferring the stress across the cross section of a crack.

Table 6. The deflection of the samples

Sample no	Average of first-crack deflection (mm)
PC	0.91
T30	0.59
T40	0.38

conclusions:

1- The addition of thick polypropylene fibers to the concrete has no substantial effects in increasing the cracking load of the concrete, and can mostly bring an increase in the amount of the ultimate load after cracking and in the energy absorption of the concrete.

2- The comparison between the load-deflection curves of the plain concrete and polypropylene fiber reinforced concretes indicates that the behavioral differences can appear after elastic stage and the first cracking load. The plain concrete acts as a brittle material, and often a high amount of energy is released suddenly after the concrete reaches its the first cracking, and the first cracking and failure points are the same. But the concrete containing thick polypropylene fibers can still tolerate extra loading after it reach to its first cracking point, due to the fibers makes bridges between the cracks.

3- The deflection equivalent to the first cracking has been reduced by 139% through making use of thick polypropylene fibers. This is due to the increase in hardness through transferring the stress across the cross section of a crack. This result can have application in structures demanding some special services during their usage.

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