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Experimental and statistical analysis of hybrid-fiber-reinforced recycled aggregate concrete

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Abstract. Although concrete is the most widely used construction material, its deficiency in shrinkage and low tensile resistance is undeniable. However, the aforementioned defects can be partially modified by addition of fibers. On the other hand, possibility of adding waste materials in concrete has provided a new ground for use of recycled concrete aggregates in the construction industry. In this study, a constant combination of recyclable coarse and fine concrete aggregates was used to replace the corresponding aggregates at 50% substitution percentage. Moreover, in order to investigate the effects of fibers on mechanical and durability properties of recycled aggregate concrete, the amounts of 0.5%, 1%, and 1.5% steel fibers (ST) and 0.05%, 0.1% and 0.15% polypropylene (PP) fibers by volumes were used individually and in hybrid forms. Compressive strength, tensile strength, flexural strength, ultrasonic pulse velocity (UPV), water absorption, toughness, elastic modulus and shrinkage of samples were investigated. The results of mechanical properties showed that PP fibers reduced the compressive strength while positive impact of steel fibers was evident both in single and hybrid forms. Tensile and flexural strength of samples were improved and the energy absorption of samples containing fibers increased substantially before and after crack presence. Growth in toughness especially in hybrid fiber-reinforced specimens retarded the propagation of cracks. Modulus of elasticity was decreased by the addition of PP fibers while the contrary trend was observed with the addition of steel fibers. PP fibers decreased the ultrasonic pulse velocity slightly and had undesirable effect on water absorption. However, steel fiber caused negligible decline in UPV and a small impact on water absorption. Steel fibers reduce the drying shrinkage by up to 35% when was applied solely. Using fibers also resulted in increasing the ductility of samples in failure. In addition, mechanical properties changes were also evaluated by statistical analysis of MATLAB software and smoothing spline interpolation on compressive, flexural, and indirect tensile strength. Using shell interpolation, the optimization process in areas without laboratory results led to determining optimal theoretical points in a two-parameter system including steel fibers and polypropylene.

Keywords: hybrid fiber reinforced concrete; recycled concrete aggregates; mechanical strength; toughness; shrinkage; spline interpolation

1. Introduction

Concrete has been used for many years as one of the most expensive building materials in the road and building industry. The use of cheaper and more economical materials, as well as materials which mitigate environmental pollution and improve flexibility, strength and durability of concrete are the reasons for the recognition of concrete as a privileged material (Neville 1995, Siempu and Pancharathi 2018)

Due to the limited lifecycle of any structure, destruction and construction of a new structure has become inevitable. Meanwhile the occurrence of various incidents such as earthquake, flood, storm and other destructive factors causes demolition of structures such as concrete structures. Due to such destructions, the amount of construction and demolition (C&D) waste is growing in the world every day that makes disposal of these materials a momentous concern among governments. In regard to damaging effects of C&D wastes on the environment and a rising demand for landfills needed to store them, reusing and recycling of such materials has become an important subject attracting the attention of many scientists and environmentalists. The study of various ways of recycling construction wastes has a positive impact on economics and energy industries as well as protecting the environmental, natural and mineral resources (Akça *et al*. 2015, Hendriks *et al*. 1998, Murali *et al*. 2018, Nagataki *et al*. 2004, Oikonomou 2005, Rao *et al*. 2007, Winter and Henderson 2003). The old concrete recycling mainly consists of a five-step process: 1. Old concrete crushing 2. Breaking concrete in the primary and secondary crusher, 3. Separating the rebar and other steel

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pieces buried in the concrete 4. Gradation and washing 5. Piling up coarse-grained and fine-grained aggregates. It should be noted that the final product should be free of other materials such as soil, chalk pieces, wood, etc., because the presence of such materials would reduce the strength and durability of the new mixture (Carneiro *et al*. 2014, Hosseini *et al*. 2009, Liang *et al*. 2018). In recycled concrete aggregate (RCA), the recycled grains can be used as an alternative to fine grains or coarse grains, or both. RCA absorbs higher amount of water and are less resistant compared to natural aggregates with regards to the higher strength and denser structure of natural aggregates (Belén *et al*. 2011). The strength of RCA is presented in various reports (Bentur and Mindess 2014, Hosseini *et al*. 2009, Thomas *et al*. 2016, Vytlačilová 2011, Xiao *et al*. 2012). According to recent studies, the strength of this type of concrete depends highly on some factors such as the strength of recycled aggregates, the percentage of aggregates replacement, the ratio of water to cement and the moisture of recycled aggregates. It has been (Zhang *et al*. 2015) reported that the high porosity of recycled aggregates can store water and provide internal curing.

Over the last years, reusing recycled aggregates in construction has attracted many researchers. Topcu *et al*. (1997) in 1997 were one of the first researchers who studied the probability of using waste concrete aggregated (WCA) in concrete. The results showed that WCA can be used in concrete after evaluation of capability of aggregates. Considerable experiments were also conducted in the following years to investigate different properties of RCA. Carneiro *et al*. (2014) examined compressive strength of concrete with 25% recycled aggregate as replacement of fine and coarse natural aggregates. The recycled C&D waste materials used in the experiment were composed of 55% mortar, 20% concrete and 25% bricks. According to the results, concrete with 25% recycled aggregates had higher resistance compared to the concrete with natural aggregates. A maximum 25% growth was observed in the compressive strength of the mixture containing both types of recycled aggregates. Wagih *et al*. (2013) investigated the effect of the substitution of natural aggregates with coarse-grained recycled aggregates. The results showed respective decrement of 4, 12, 22 and 27% in compressive strength of concrete containing 25%, 50%, 75% and 100% recycled aggregates. In a study by Lee *et al*. (2016), the mechanical behavior of the concrete containing large-size RCAs was compared to that of concrete with natural aggregate. The results revealed the slight difference of mechanical strength of concrete with natural and recycled aggregates in which only 14% decline was reported in samples with 40% recycled aggregate. Choi and Jan (2012) showed that the simultaneous use of coarse grained and fine-grained recycled aggregates increased the compressive strength of concrete. The reason for such growth was the high-adhesive property between sharp edges of large sized recycled aggregates and old mortar. In a study by Amjadi *et al*. (2017) waste concrete was pulverized in powder and used as cement replacement, and the results showed a decline in compressive strength with 3 different fractions of 5%, 10% and 15% by cement weight. To assess the durability properties of RCA, Thomas *et al*. (2013) reported the improper durability of the concretes made with recycled aggregate because of the intrinsic porosity of them, however the porosity was modified with decrease in water to cement (*w/c*) ratios. The permeability of concrete with fine recycled aggregates was similar to that of concrete with natural aggregates when the w/c ratio was relatively low.

On the other hand, the tensile and flexural strength of concrete is low due to the rapid development of capillary cracks under loads. The incorporation of fibers in concrete retards formation of cracks and prevents their extension and thus increases the tensile and flexural strength. Different types of fibers, both synthetic and natural, have been used as reinforcing elements in cementitious mixtures. Polypropylene (PP), glass, steel, nylon, poly ethylene erephthalate, carpet and widely varying different types of fibers with distinct properties are available for being incorporated in appropriate mixtures. The use of fibers also delays the onset of shrinkage cracks, and increases its stiffness, toughness, ductility and impact resistance of concrete, and also improves the post-crack behavior of concrete (Cao *et al*. 2014, Chen *et al*. 2014, Kandasamy and Akila 2015). Various natural or synthetic fibers in concrete containing RCAs has been evaluated by other researchers (Akça *et al*. 2015, Erdem *et al*. 2011, Marthong 2018, Prasad *et al*. 2007, Topcu 1997, Wagih *et al*. 2013, Xiao *et al*. 2012).

Incorporation of fibers has been investigated widely in recent years. The experimental outcomes on compressive strength is controversial and highly dependent on the types and physical characteristics of fibers. Many studies resulted in a decrement in compressive strength (Akça *et al*. 2015, El-Newihy *et al*. 2018, Hosseini *et al*. 2009, Islam and Gupta 2016, Ranjbar *et al*. 2016), while some others reported an increase in compression strength when fibers were added (Afroughsabet *et al*. 2016, Sun *et al*. 2001). EI-Newihy *et al*. (2018) studied the mechanical and self-healing effects of 0.6% macro and 0.3% micro PP fibers in concrete. They reported marginal decline in compressive strength of fiber reinforced samples compared to the plain concrete. Moreover, an increase in air content and a corresponding decrease in density of samples with micro and macro fibers was also observed. Ranjbar *et al*. (2016) studied the mechanical behavior of steel and PP fibers with 0.5-4% substitution percentage by volume. The results showed undesirable influence of PP fibers on mechanical properties, while steel fibers showed a reverse trend by enhancing the mechanical properties and energy absorption of concrete. Caggiano *et al*. (2016) investigated the fracture behavior of hybrid steel and PP fiber-reinforced concrete. Fiber-reinforced specimens showed a more ductile behavior than the control samples. The compressive strength of most samples increased and a maximum strength increase up to 15% was recorded by inclusion of steel fibers solely in concrete. Afroughsabet *et al*. (2016) reported that best results of mechanical properties were attained by a concrete mixture that contained 0.85% steel and 0.15% PP fiber. In addition, a couple of experiments have been assessed the shrinkage and crack propagation of concretes with the incorporation of fibers. Sun *et al*. (2001) reported an enhancement in shrinkage resistant and impermeability of hybrid reinforced concrete. According to the results, the size and the types of fibers (steel, polypropylene and polyvinyl alcohol fiber) can reduce the size and number of cracks at different scales. Banthia *et al*. (2006) investigated the influence of 4 different types of PP fibers with three volume fractions. The results showed a reduction in total crack area and confirmed the high influence of fibers when plastic shrinkage happened. They also reported that a finer and longer fiber is more effective in controlling shrinkage. Gupta *et al*. (2010) studied the cracking potential of hybrid polymeric fiber-reinforced concrete with the help of traditional and fiber optic sensors. They reported higher volume of fibers in concrete reduced the probability of cracking.

The main focus of this study is to investigate the effects of single and hybrid steel and polypropylene fibers in concrete containing recycled aggregates. As it was mentioned, many researchers have focused on the incorporation of steel and polypropylene fibers in concrete, however only a few investigations were performed on inclusion of fibers in green concrete. As a result, lack of sufficient resources on mechanical and durability properties of fiber-reinforced recycled concrete aggregate (FRRCA) is the main reason to conduct this research. Factors such as compressive strength, flexural strength, toughness, tensile strength, elastic modulus, shrinkage, ultrasonic pulse velocity and water absorption were evaluated.

As performing a large number of experiments to determine the optimal percentage of materials is difficult and unscientific, with the help of statistical analysis tools and the technical knowledge necessary to use these facilities properly, one can guess the optimal responses. Choosing the right tool to predict the optimal percentage and techniques for applying boundary conditions will determine the accuracy of prediction. Among such tools, the interpolation is the most helpful and popular approach to determine the optimal values between the existing results (Wang 2011). The smoothing spline interpolation is a powerful and flexible method which has been used in the current study to find the best possible response.

2. Experimental program

2.1 Materials

The cement used in this study is Portland Type 1-425, produced in accordance with ASTM C 150 (Zhang and Zhao 2017), supplied by the Khazar factory. The chemical composition of cement is presented in Table 1. The concrete pieces from a construction project containing 375 kg/m^3 cement, 1008 kg/m^3 coarse grain, 825 kg/m^3 fine grain were selected to be used as recycle aggregates. The 28-day compressive strength of the recycled concrete was 42 MPa. The procedure of application of RCA and the replacement of coarse and fine grained natural aggregates was complied with the limits set by ACI 555R.1 (Locher 2013) and ASTM C-33 (Heikal *et al*. 2006) for gradation. Concrete pieces were then sieved after being crushed by rock crusher jack, and graded as recycled fine and coarse aggregates. RCA

Table 1 Characteristics of Portland cement

Physical properties	Value	Chemical composition (%)	
density (gr/cm^3)	3.15	CaO	64.38
Specific area (cm^2/gr)	3100	SiO_2	21.08
Initial set time (min)	110	Al_2O_3	5.36
Final set time (min)	170	Fe_2O_3	3.64
Compressive strength at 28 days (MPa)	42	MgO	2
Average particle size (μm)	15	K_2O	0.82
		Na_2O	0.5
		SO_3	2.1

Fig. 1 The physical appearance of recycled aggregate

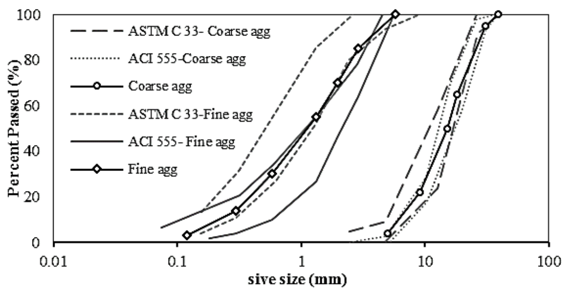

Fig. 2 The grading diagram of fine and coarse aggregates

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Fig. 1 river silica sand and crushed coarse aggregates were also used as normal fine and coarse aggregates respectively, in accordance with ASTM C-33. The grading diagram and the characteristics of aggregates are shown in Fig. 2 and Table 2, respectively. It should be noted that two different sizes of natural sand were used in the experiment. 0-3 mm and 6-3 mm sand kernels were used as fine aggregates with 80% and 20% by weight of the total required sand. The fibers used in this study include steel and polypropylene fibers. The physical appearance and their characteristics are shown in Fig. 3 and Table 3, respectively.

Table 2 Characteristics of natural and recycled aggregates

Properties	Fine aggregates		Coarse aggregates	
	natural	recycled	natural	recycled
Size (mm)	0-6	0-6	6-19	6-19
Specific gravity (gr/cm^3)	2.65	2.42	2.72	2.52
Bulk density (gr/cm^3)	1.43	1.33	1.5	1.18
Water absorption (%)	2.5	7.5	1.2	5.5
fineness modulus	2.5	3.01	-	-

Fig. 3 The physical appearance of polypropylene and steel fibers

Table 3 Characteristics of fibers

Fiber Type	Length (mm)	Diameter (mm)	Tensile Strength (MPa)	Density (gr/cm^3)	Elastic Modulus (GPa)	Melting point (^oC)	Shape
Steel	36	0.8	2100	7.8	160	1500	Hooked End
Polypropylene	12	0.1	500	0.91	5	164	Flat

2.2 Mixing and curing conditions

In this research, 50% of natural aggregates volume were replaced by recycled aggregate. In addition, steel fibers (0.5%, 1% and 1.5% by volume) and polypropylene fibers (0.05%, 0.1% and 0.15% by volume), were used in RAC mixtures individually and in hybrid forms. Concrete specimens made in accordance with ASTM C192 standard (Yamada *et al*. 2000). The samples were removed from the molds after 24 hours, and were immersed in lime-saturated water tanks at a temperature of 23±2℃. Table 4 shows the mix proportions of the mixtures. In Table 4, non-fiber mix abbreviated to Ctrl, Polypropylene fiber to *P* and the steel fiber to *S* and the opposite numbers represent the percent of the volume of polypropylene fiber×10-2 and steel fiber used in the specimen. For example, P15-S0.5 represents concrete mix containing 0.15% polypropylene fiber and 0.5% steel fiber.

Table 4 Mix design (Kg/m^3)

NO.	MIX ID	Cement	Water	Fiber		Fine agg		Coarse agg	
				PP	ST	Natural	Recycle	Natural	Recycle
1	Ctrl	375	169	0	0	412	405	524	495
2	P0-S0.5	375	169	0	39	412	405	524	495
3	P0-S1	375	169	0	78	412	405	524	495
4	P0-S1.5	375	169	0	117	412	405	524	495
5	P5-S0.5	375	169	0.455	39	412	405	524	495
6	P5-S1	375	169	0.455	78	412	405	524	495
7	P5-S1.5	375	169	0.455	117	412	405	524	495
8	P10-S0.5	375	169	0.91	39	412	405	524	495
9	P10-S1	375	169	0.91	78	412	405	524	495
10	P10-S1.5	375	169	0.91	117	412	405	524	495
11	P15-S0.5	375	169	1.365	39	412	405	524	495
12	P15-S1	375	169	1.365	78	412	405	524	495
13	P15-S1.5	375	169	1.365	117	412	405	524	495
14	P5-S0	375	169	0.455	0	412	405	524	495
15	P10-S0	375	169	0.91	0	412	405	524	495
16	P15-S0	375	169	1.365	0	412	405	524	495

2.3 Test procedure

A compressive strength test was performed on cube samples (150×150×150 mm) at 7, 28 and 90 days age in accordance with EN 12390-3 (Uchikawa *et al*. 1995). In addition, elastic modulus and indirect tensile strength test were performed according to ASTM C496 standard (Ransinchung and Kumar 2009) on a cylinder concrete block with a diameter of 150 mm and a height of 300 mm at 28 days of age. Prismatic samples with dimension (70×70×280 mm) were used to evaluate the three-point bending flexural strength and toughness according to ASTM C78 standard (Cardoso *et al*. 2009). Loading at a rate of 1 mm/min was performed by measuring the amount of displacement in the middle part of the sample. The amount of absorbed energy was determined by integrating the area under the load-displacement curve according to equation (1) (Khaloo *et al*. 2014, Mastali *et al*. 2016, Tonoli *et al*. 2010) In this study, the amount of flexural strength (energy: bending cross-sectional area) was calculated in two points: $\delta 1$ (the corresponding displacement of maximum load) and $\delta 2$ (corresponding displacement with 2.5 times as high as $\delta 1$) and evaluated compared to δco (corresponding displacement with maximum bending load of control sample).

$$\text{Absorbed energy} = \int_0^{\delta_f} P\, d\delta \qquad (1)$$

Where P is the force (N) and δ is the displacement (mm) in the middle of the flexural sample span.

The shrinkage test was performed according to ASTM C157 (Cardoso *et al*. 2009) standard on prismatic specimens with 70×70×280 of diameter. At both end of each sample, a stainless steel stud was installed. The specimens were removed from the mold after 24 hours and immersed in lime water and cured under laboratory conditions for 28 days. Subsequently, the samples were taken out of water and examined by strain gauge (with a precision of 1000 millimeter) for 90 days to monitor the shrinkage. The ultrasonic pulse velocity rate and water absorption test were also carried out at 28 days of age, according to ASTM C 597 (Banfill 1991) and ASTM C 642 (Van Tuan *et al*. 2011) respectively.

3. Software modeling based on the thin-plate spline concept

In the reciprocal analysis, the purpose of fitting on dispersed data is to estimate a function to build the smoothing curve with a certain range of random errors. Using such function, dependent or independent variables can be determined. Thin-plate spline refers to physical bending of a thin layer of metal. In the physical definition, the shape changes occur along *Z*, which is perpendicular to the page. In order to apply this idea on the transfer of coordinates, an interpretation can be the displacement of the coordinates *x* and *y* in a plate. Therefore, in general, two thin sheet of spline is required to determine the two-dimensional coordinates of the transition (De Boor 2005, Klasson 2008, Nguyen and Kim 2007, Wang 2011). In simple terms, the spline smoothing function of the thin plate *f* is a unique minimizer for the sum of the weight of Eq. (2), in which *p* is the smoothing coefficient, *E*(*f*) a requirement for Eq. (3), and *R*(*f*) represents Eq. (4):

The Eq. (2) is the error function and the Eq. (3) is the roughness function and *Dif* is the ith partial derivative of *f* and the value of *p* is the determinant of the degree of smoothness of the curve and its conformance to the data, which varies between zero and one (Wang 2011).

$$pE(f) + (1-p)R(f) \tag{2}$$

$$E(f) = \sum_j |y(:.j) - f(x(:.j))|^2 \tag{3}$$

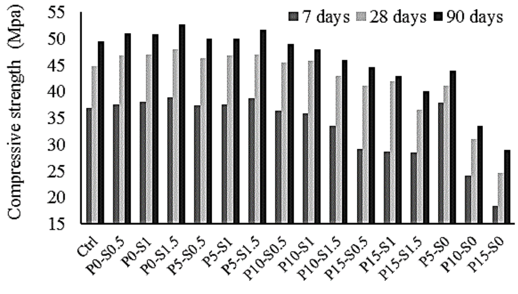
$$R(f) - \int |D_1D_1f|^2 + 2|D_1D_2f|^2 + |D_2D_2f|^2 \tag{4}$$

4. Results and discussion

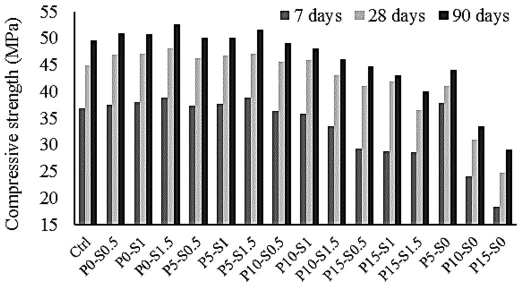
4.1 Compressive strength

Fig. 4 presents the results of compressive strength of samples at different ages. Fig. 4(a) illustrates that steel fibers boosted the strength by about 6% and by increasing the amount of the fiber, the strength has also an upward movement. While the compressive strength of the samples containing polypropylene fibers has a clear negative effect on compression strength. The degree of strength loss in samples containing 0.05%, 0.1% and 0.15% of polypropylene fibers was respectively (6.4% -11.1%), (30-34.5%) and (41.4% -50%) at different ages. It is noteworthy that despite the reduction in compressive strength, the test results after 28 days were categorized in structural reinforced concrete grade (>17 MPa). The positive effect of steel fibers on compressive strength is due to the confining ability of them in specimens.

In steel fiber reinforced RAC, a suitable amount of steel fiber can work as a confining factor reducing transversal deformation of specimen and results in an increase the compressive strength, In addition, steel fibers act as crack arresters by producing a great bond between concrete particles, and the compressive strength of concrete is highly dependent to the solidity of these bonds between particles. If the bonding within the concrete is improved by addition of additives, the strength will increases. Although longer fibers may cause several difficulties in placement and workability of concrete, they show positive impacts on strength of concrete by holding the concrete particles in transversal direction. This means that concrete samples with 36mm steel fibers will gain strength more than a similar concrete with 12 mm polypropylene fibers. In other words, the bridging effects of steel fibers on the wing cracks that propagate from pore-like and crack-like flaws help to improve compressive strength. However, longer fibers may inhibit the uniform distribution of fibers in cement matrix. This problem can be mostly tackled when larger aggregates are present to shear the bundles of fiber apart.



(a) Single fiber



(b) Hybrid fiber

Fig. 4 Compressive strength of specimens: (a) single fiber, (b) hybrid fiber

Fig. 4(b) compares compressive strength results of hybrid FRRAC. Samples containing 0.05% polypropylene fibers and various amounts of steel fibers indicated no significant influence on compressive strength. However, in samples containing 0.1% polypropylene fiber, an increment in the amount of steel fibers caused a downward trend in compression strength, and by adding more polypropylene fibers up to 0.15%, the fall in strength was even more considerable. Generally incorporating steel fibers increased the compressive strength of P5-S0, P10-S0, P15-S0 samples up to (12%- 66%), (11.45% - 69.5%) and (2% - 55.7%) respectively, but the compression strength of samples was still lower than that of CO sample, and Compressive strength loss varied at 7-22.5%. The decline in strength can be explained in such a way that 12mm polypropylene fibers

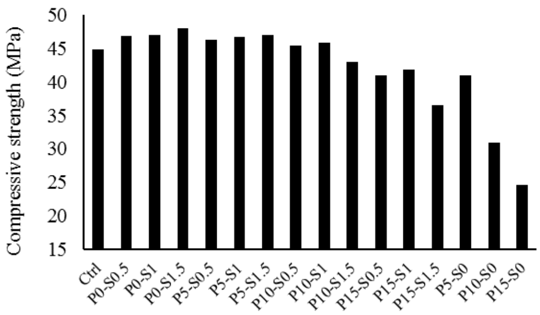


Fig. 5 Compressive strength of specimens at 28 days of curing

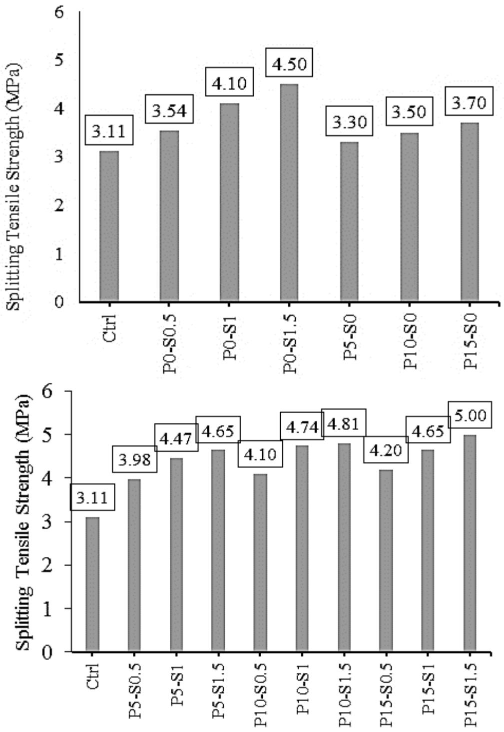
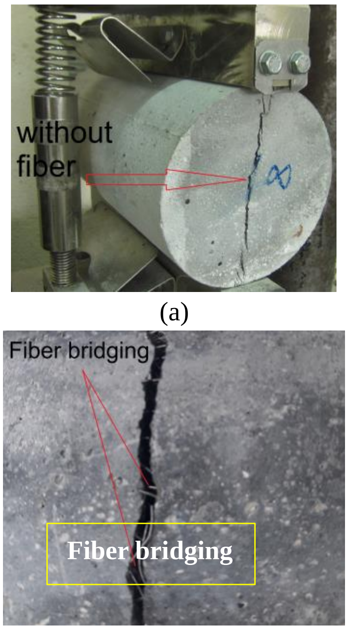


Fig. 6 Splitting tensile strength of specimens at 28 days: (a) single fiber, (b) hybrid fiber

are too short to work as confinements inhibiting or mitigating the crack propagation of concrete. On the other hand, with higher amount of fibers in concrete, the workability of concrete is reduced to such an extent that even admixtures cannot help. As a result, the concrete cannot be well compacted. In this case, excessive fiber content may have a detrimental effect on compressive strength, and reduce the strength of concrete due to the improper compaction. Overall, the negative effect of excessive amount of fibers ensures that there is a critical fiber volume fraction, beyond which the compressive strength will decrease.

Fig. 5 compares the compressive strength of all samples at 28 days of curing. It is notable that the reduced strength of the samples containing polypropylene fibers (P5-S0, P10-S0, and P15-S0) was partially compensated by the addition of 0.5%, 1% and 1.5% of the steel fibers, however the significant negative influence of polypropylene on compressive strength is incontestable.



(a)

(b)

Fig. 7 Cylinder failure mode under splitting tensile test: (a) ctrl, (b) fibrous specimen

4.2 Indirect tensile strength and elastic modulus

The results of the indirect tensile strength of the 28-day-age samples containing single and hybrid fibers are presented in Fig. 6(a) and 6(b), respectively. The results showed that in samples containing only steel or polypropylene fibers, tensile strength increased from 13-44% and 6-19% in steel and polypropylene reinforced RAC respectively. Meanwhile, the increase of tensile strength in hybrid reinforced RAC was varied between 28% and 61% (28% in P5-S0.5 and 61% in P15-S1.5). This is evident that the positive influence of incorporation of hybrid fibers is on the contrary with compressive strength, in which P15-S1.5 sample experienced a 19% tensile strength reduction. Moreover, the minimum and maximum strength gain for two subsequent fiber reinforced samples were varied between 10%-16% and 5%-6% for respective steel and polypropylene reinforcements, respectively.

It can be interpreted from Fig. 6(b) that despite the maximum reduction of 22.5% of the compressive strength in some samples with hybrid fibers, especially in samples with high amount of fibers, the tensile strength increased in all samples, indicating high performance of fibers against tensile stress. The presence of 3 different percentages of steel fibers (0.5%, 1% and 1.5%) in samples with fixed amounts of polypropylene fibers (0.05%, 0.15% and 0.1%) increased the strength from 28% to 50%, 32% to 55% and 35% to 61%, respectively. In addition, with 0.05% of increase in polypropylene fibers in steel fiber samples, the strength increased by 3% -18%.

Concrete behaves improperly against tensile strength. An internal small crack in concrete can be easily propagated due to the inability of concrete to endure tensile strength. However, if the crack remains locally by extending into another matrix adjacent to it, the extension of crack is

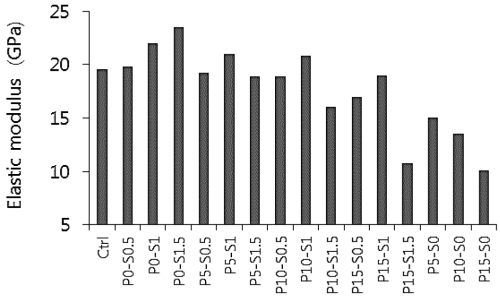


Fig. 8 Elastic modulus of specimens

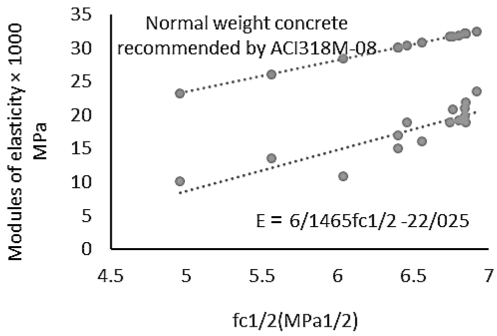
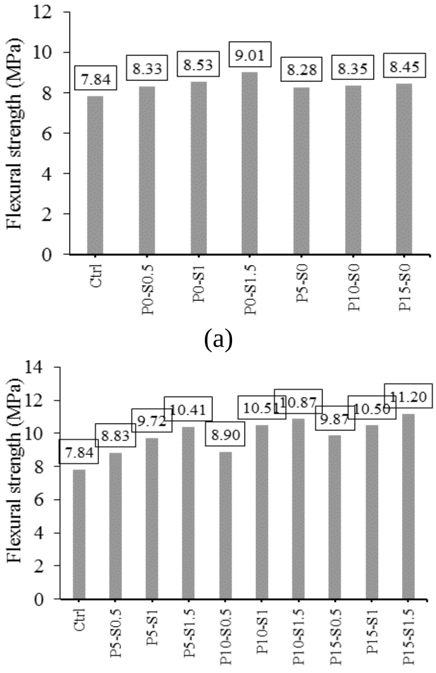


Fig. 9 Static Elasticity and Compressive Strength of FRRAC and normal concrete



(a)

(b)

Fig. 10 Flexural strength of specimens at 28 days: (a) single fiber, (b) hybrid fiber

retarded and results in higher tensile strength of concrete (Romualdi and Batson 1963). Addition of small length fibers can inhibit the propagation of cracks and leads to a better tensile strength. According to Fig. 7, experimental observations showed that the cylinders containing fiber, had a soft breakdown at the moment of crushing, under indirect tensile test. In the Fig. 7, presence of some fibers which are being pulled out is obvious. These fibers protected concrete from sudden collapse which happened in control sample.

Fibers can be classified in two distinct categories, hard intrusion and soft intrusion. Fibers with higher modulus of elasticity than cement mortar are called hard intrusion and those with lower modulus of elasticity than cement mortar are called soft intrusion (Parameswaran 1991). Polypropylene fibers are categorized in soft intrusion fibers, while steel fibers are hard intrusion fibers. Soft intrusion Fibers such as glass fibers are unlikely to improve strength but enhance the resistance against impact and shock due to elongation ability and hard intrusion fibers such as steel fibers make concrete strong and stiff (Parameswaran 1991).

The results of elastic modulus of samples are presented in Fig. 8. Concrete static elastic modulus containing recycled aggregates varied in regard to the type of fibers. As it was mentioned, polypropylene fibers are more responsible to enhance the ability of deformation of concrete while steel fibers can increase the stiffness of concrete. This trend was exactly demonstrated in elastic modules of samples in which steel reinforced samples had elastic modules near to or higher than control samples and in contrary with samples containing polypropylene the downward trend showed a decline in elastic module when the amount of soft intrusion fibers rose. For instance, the elasticity module of specimen containing 15% polypropylene and no steel fiber was halved in comparison with CO sample. However, the decrease in elastic module of polypropylene fiber reinforced samples was compensated considerably when steel fiber was added to the mixture.

Fig. 9 shows the static elastic module of normal concrete which is recommended by ACI308M-08 (Committee Institute and Standardization 2008) in comparison with elasticity modulus that was measured practically in the experiment. In ACI308M-08, elastic modules can be obtained from Eq. (5) in which $\acute{f}_c^{1/2}$is the compressive strength of normal concrete and E_c is the static elastic modulus. The equation shows a positive linear relation between modulus of elasticity and square root of the compressive strength. As can be seen, the best graph that suits the elastic modulus of fiber reinforced samples with waste aggregates is also a linear graph. The equation which determines the relation between the two factors is given in the Fig. 9. However, for the same compressive strength, much lower static elastic modulus was observed in fiber reinforced RAC in comparison to the normal concrete. Modulus of elasticity evaluate the resistance of a material to elastic deformation under load. The fiber reinforced specimens are more flexible than normal concrete because of a lower modulus of elasticity and can changes their shape slightly under loads which also means they are not as brittle as normal concrete.

$$E_c = 4700\sqrt{\acute{f}_c} \tag{5}$$

(MPa) Compressive strength of normal concrete: $\acute{f}$c
(×1000 MPa) Modulus of elasticity: E_c

On the other hand, the elastic modulus of concrete is closely related to the binding between their atoms, and binding energy is the magnitude of the attraction force between atoms. The elastic modulus of concrete will be increased with the increment in binding energy. Meanwhile, the elastic modulus of concrete is also dependent to its microstructure such as the structure of interfacial transition zone, porosity or grain structure. As it is obvious, all concrete samples containing waste fine and coarse concrete aggregates showed decline in the amount of elasticity module in comparison with the normal concrete. Investigating the module of elasticity of all samples gives us information about the weaker bind between cement and waste aggregates and also more porous structure of concrete with waste aggregates.

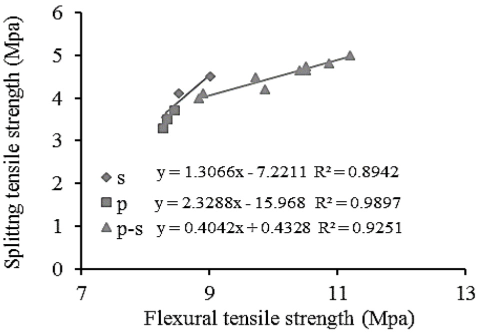
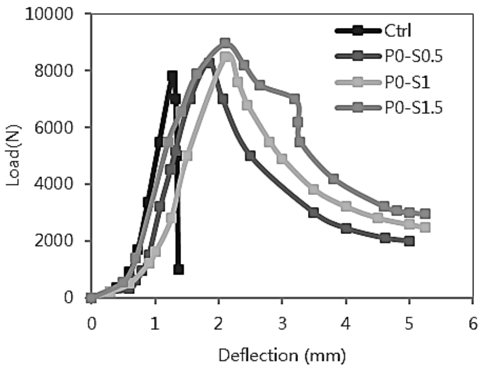


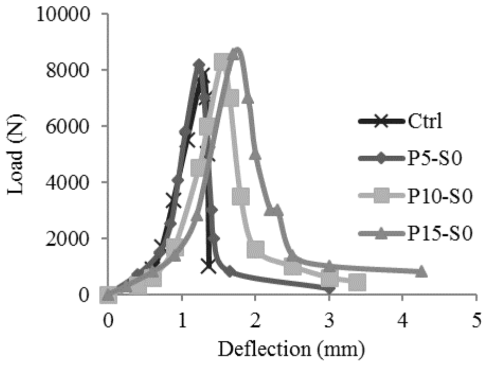
Fig. 11 Correlation of splitting and flexural tensile strength

4.3 Flexural strength

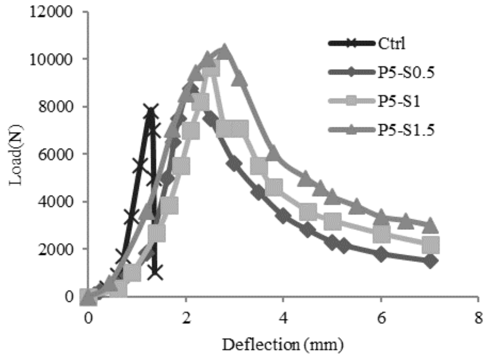
Flexural strength test measures the ability of concrete to resist deflection and cracking. Fig. 10 presents the results of flexural strength test. It can be seen that incorporation of sole steel or polypropylene fibers to samples increased the flexural strength slightly by 5.8% -14.5% and 4.8% -9.4%, respectively, while the percentage of growth was much



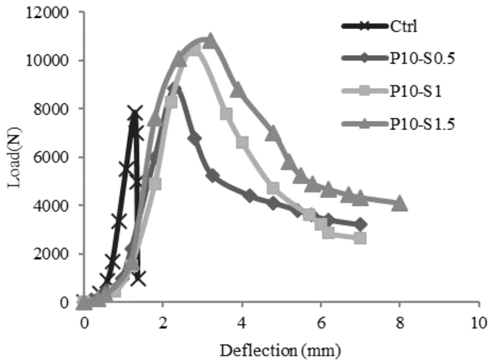
(a) P 0%- S (0.5%, 1%, 1.5%)



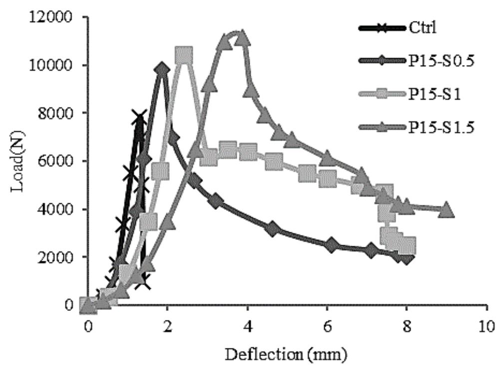
(b) P (0.05%, 0.1%, 0.15%) - S (0%)



(c) P (0.05%) - S (0.5%, 1%, 1.5%)



(d) P (0.1%) - S (0.5%, 1%, 1.5%)



(e) P (0.15%) - S (0.5%, 1%, 1.5%)

Fig. 12 Load-deflection curves of flexural specimens more considerable in hybrid samples. The addition of steel fibers with 0.05, 0.1 and 0.15% polypropylene fibers increased the flexural strength by 9.2 -32.2%, 13 -38% and 25.4% - 42%. The highest strength (11/20 MPa) was reported when 0.15 and 1.5% polypropylene and steel fibers were added to the RAC.

The reason for the efficacy of hybrid use of fibers can be explained in such a way that shorter fibers such as polypropylene fibers discrete cracks propagates into a slow controlled growth and longer fibers enhance the bonds in cement matrix. The two momentous factors can lead to a better flexural strength. There were also some previous studies illustrating the direct relationship between fiber volume and the maximum flexural load of samples (Banthia *et al*. 1993, Khaloo *et al*. 2014)

Fig. 11 shows the relationship between indirect tensile strength and bending strength. According to the results, the existence of parallel behavior between indirect tensile strength and flexural strength yielded a high correlation coefficient (R=0.89, R=0.98, R=0.92). Moreover, by increasing the amount of fiber, indirect and flexural tensile strength increased by a maximum of 50% and 43%, respectively.

Fig. 12 shows the load-displacement graph of control and fiber samples. According to the Fig. 12(b), in post-peak zone samples containing polypropylene fibers showed less ductility compared to those containing steel fibers (Fig. 12(a)). It seems that their strength decreased more than the steel fiber reinforced specimens; the reason is the lack of adequate friction and bonding of polypropylene fibers. This defect was solved by adding steel fibers as shown in Fig. 12(c), (d) and (e). Despite the increase in the amount of fiber in the RAC mixtures, the use of high amounts of polypropylene fibers does not seem to be very beneficial. The behavior of the samples in the post-peak part was strain-softening, and in some cases, the fibrous bridging (Fig. 12(a)) and hardening strain (Fig. 12(e)) were observed.

4.4 Flexural toughness

The post-peak point behavior is an important factor in evaluating the breakdown of concrete. Flexural toughness indicates the post-peak behavior (first crack) of fiber reinforced concrete. In Table 5, the amount of toughness is indicated for two points $\delta1$ (the corresponding displacement of maximum load) and $\delta2$ (corresponding displacement with 2.5 times as high as $\delta1$) in displaced span of bending specimens. At the moment of cracking, the toughness of all single-fiber samples except P5-S0 increased between 1.2 to 3 times as high as control sample. However, the growth rate was varied in regard to the type of fibers in which samples with polypropylene fibers saw a maximum augmentation of 1.4%, while the corresponding amount in steel reinforced concrete was more than doubled to nearly 3%. This result ensures the positive effect of steel fibers being solely incorporated in concrete. In addition, the toughness at $\delta2$, was 1.66 to 8.52 times as high as control sample.

The toughness of hybrid-fiber reinforced samples at the moment of cracking was between 1.2 and 3.5 KJ/m^2 and the increase percentage was 1.9% to 5.8% compared to that of control sample. At $\delta2$, where fibers can demonstrate their efficacy to inhibit the propagation of cracks, a considerable increase in toughness from 6.5 to 15.9% was observed, and the highest toughness was achieved in P15-S1.5 and P10-S1.5 with 9.6 and 9.7 J energy absorption respectively. Although addition of fibers may not result in a substantial rose in flexural strength, it can greatly contribute to the toughness of concrete. After the crack occurs, an essential factor for extension of the crack is to overcome the tensile strength of the fibers. Fibers can act like a bridge and hold concrete together and bear the load until they are pulled out (Mo *et al*. 2014; Yap *et al*. 2014). This means a significant amount of energy is absorbed by fibers in cementitious matrix. The superior behavior of FRRAC in post crack zone also confirmed the noticeable ability of concrete to confine crack extension, while this behavior was much more significant in steel fibers rather than polypropylene. Also in some cases, the synergistic effect of both fibers was noticeable (P15-S1.5), while in others, steel fibers also compensated the weakness of polypropylene fibers (P5-S0.5).

Table 5 Summary results of toughness, UPV, water absorption and modulus of elasticity (ES).

NO.	MIX ID	Toughness (KJ/m^2)			UPV (Km/s)	Water absorption (%)	Module elasticity (GPa)
		$T_{\delta1}$	$T_{\delta2}$	$T_{\delta2}$ / $T_{\delta co}$ [a]			
1	Ctrl	0.607	/	1	4.67	2.78	19.6
2	P0-S0.5	1.117	3.368	5.55	4.64	2.82	19.8
3	P0-S1	1.245	3.955	6.51	4.59	2.87	21.97
4	P0-S1.5	1.809	5.173	8.52	4.63	2.91	23.55
5	P5-S0	0.582	1.008	1.66	4.61	3.86	15.04
6	P10-S0	0.731	1.407	2.32	4.55	4.01	13.55
7	P15-S0	0.823	1.930	3.18	4.58	4.6	10.14
8	P5-S0.5	1.174	4.105	6.76	4.61	2.88	19.2
9	P5-S1	1.582	4.286	7.06	4.55	3.09	21.03
10	P5-S1.5	2.948	7.312	12.05	4.58	3.14	18.9
11	P10-S0.5	1.422	4.978	8.20	4.61	3.35	18.93
12	P10-S1	2.193	6.739	11.10	4.52	3.43	20.83
13	P10-S1.5	3.507	9.509	15.67	4.48	3.52	16.04
14	P15-S0.5	1.266	4.014	6.61	4.50	3.55	16.96
15	P15-S1	1.613	6.308	10.39	4.48	3.63	18.97
16	P15-S1.5	3.545	9.690	15.96	4.46	4.04	10.81

4.5 UPV and water absorption

Non-destructive ultrasonic pulse velocity (UPV) method is applicable to determine the presence of voids and cracks, and also to evaluate the effectiveness of crack (Banfill 1991). According to Table 5, it is observed that the ultrasonic pulse velocity of FRRAC samples has decreased slightly in comparison with control sample. The results are within the range of 4.46 and 4.67 Km/s, which indicates the sufficient resistance of the concrete (Güner 1999). The use of steel and polypropylene fibers didn’t exhibit a significant change on UPV and the maximum reduction percentage was only 6%. Furthermore, the main result of this decline is due to the micro pores produced in cement paste and especially in the contact zone of fibers and paste. Similar to

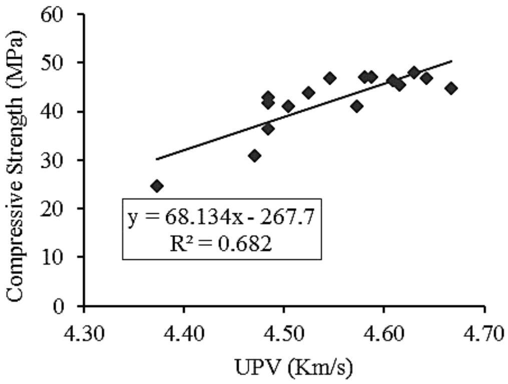


Fig. 13 Correlation of compressive strength and UPV

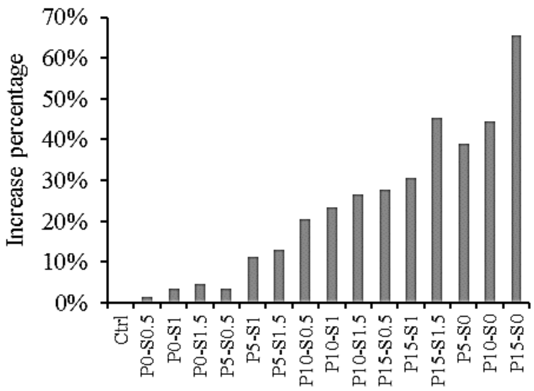


Fig. 14 Increase percentage of water absorption of specimens

the interfacial transition zone of concrete which is more porous due to the aggregate bleeding and bigger size and higher concentration of ettringate and Ca(OH)2 (Shetty 2005), the contact zone of fibers and cement paste contain more pores in comparison with other parts. The relationship plot between compressive strength and UPV is drawn in Fig. 13 to suggest an equation which predicts the compressive strength through non-destructive technique. The diagram also endorses their parallel behavior.

Water plays a momentous role in the transport processes of concrete because of its medium role for transformation of aggressive agents into the concrete which will result in corrosion of steel reinforcements. The experimentally obtained results of water absorption are given in Table 5 and the increase percentage of aforementioned with the addition of fibers is presented in Fig. 14. The results indicated that the inclusion of polypropylene fibers in specimens increased the absorption of water substantially, while samples containing steel fibers didn't reveal obvious changes in which the growth percentage was 4.7 when a maximum 1.5% of steel fibers were used. On the other hand, inclusion of a minimum amount of polypropylene fiber (0.15%) caused a 40-percent increase in water absorption and a maximum 65.6% increase was reported when 1.5% polypropylene was added solely to the specimens. However the substantial increase was mitigated when steel fibers were added to polypropylene containing samples. The relationship between water absorption and UPV is shown in Fig. 15, which indicates their indirect

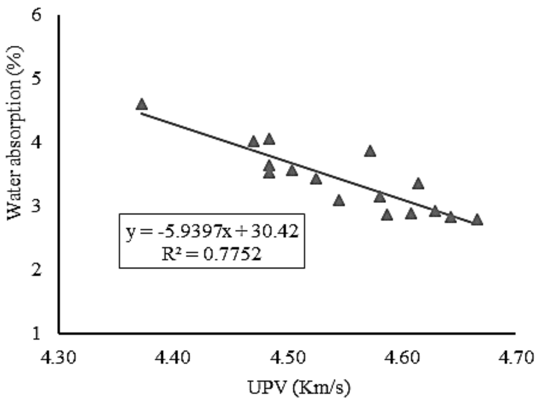


Fig. 15 Correlation of water absorption and UPV

relationship. Analyzing the figure confirms the unreliability results of water absorption test on durability of concrete. Water absorption estimates the total reachable pore volume of the concrete, but gives no information about concrete permeability, which is a much more important with regard to durability (De Schutter and Audenaert 2004). Concrete durability is highly dependent to the flow of a fluid into a porous structure which is defined as permeability property. In other words, micro or macro pores that possess a connection to the adjacent pore in which water with aggressive agents can pass through and deteriorate the concrete are the ones that specify the durability of concrete.

4.6 Drying shrinkage

Drying shrinkage or drying contraction is a situation in which concrete is contracted due to the loss of capillary water. Some factors such as the porosity of concrete structure, the presence of pores in cement paste matrix, the internal texture of the aggregates and the incorporation of fibers play an indispensable role in concrete contraction (Ransinchung and Kumar 2009). Fig. 16 shows the results of drying contraction over a period of three months. It can be seen that in most specimens the inclusion of fibers had a direct relationship with the reduction of drying shrinkage. The results of this study are similar to those of other researchers (Saje *et al*. 2010, Zhang and Li 2001).

By increasing the quantity of fibers in single-fiber concrete samples (except P15-S0 sample), the contraction reduction was tangible and the lowest contraction belongs to the sample containing 0% polypropylene fiber, and + 1% steel fiber. By analyzing the data, we can see that the addition of steel fibers up to 1.5%, reduced the contraction by at least 16.9% and a maximum of 35%. It is noteworthy that contraction was reduced with a growth in polypropylene fiber portion up to 1% and then started to soar.

In specimens containing both types of fiber, P5-S1 had the minimum contraction, while the highest contraction was for P15-S1.5. It can be derived that using more than 1% of polypropylene fiber in either single or hybrid form had a negative effect on drying shrinkage of samples. The results also confirmed the superior influence of steel fibers in reducing the contraction compared to polypropylene fibers.

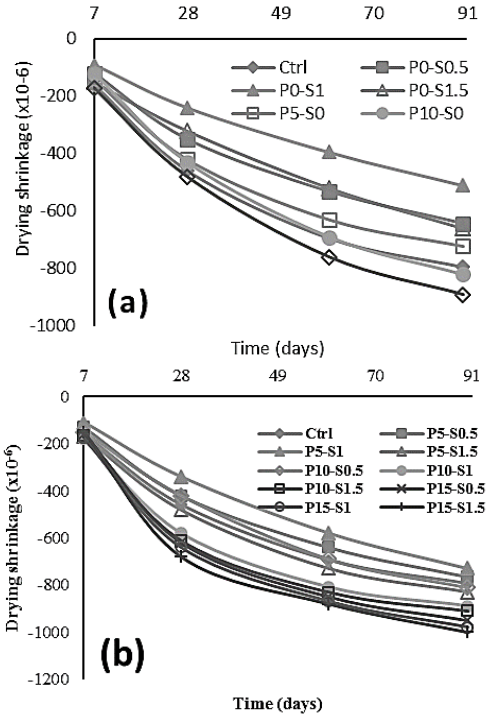
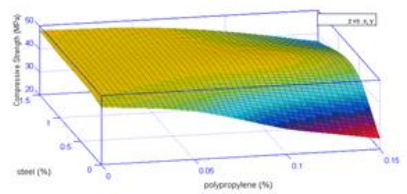
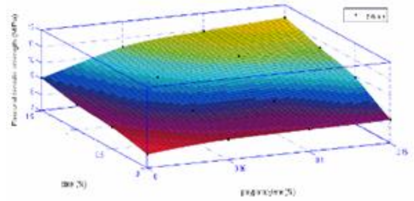


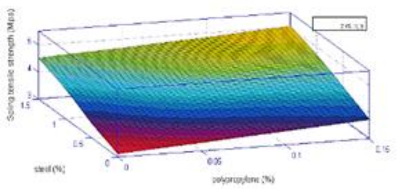
Fig. 16 Drying shrinkage of Prismatic specimens: (a) fiber single, (b) fiber hybrid



(a)



(b)



(c)

Fig. 17 Shell fitted (smoothed) on the results of (a) compressive, (b) flexural and (c) tensile strength

Several factors affect the shrinkage of concrete, first better bonding with the cementitious matrix in steel fiber reinforced samples is an important reason for the modification of shrinkage. Second, with the same fiber content, higher elasticity module results in a lower shrinkage and high elastic modulus fibers are more effective than those with a low elastic modulus regarding shrinkage reduction. Third, higher amount of fiber content leads to a more reduction in concrete shrinkage (Zhang and Li 2001).

4.7 Analysis and interpretation of modeling

The fitting of a thin-plate spline shows the behavioral complexity of the elements effective in a complex composite. In addition, it can help to find the maximum and minimum points. The optimum points using the available information on compressive, flexural and tensile strength at 28 days of age is presented in Fig. 17.

Fig. 17(a) shows a fairly smooth shell, on both points of which the minimum strength is observed. What is certain is the negative effect of polypropylene fibers in high percentages. The range from 0.5% to 1% is the optimum range, predicted by the software for steel fibers with different amounts of polypropylene fibers. Polypropylene fibers appear to decrease the strength. In addition, the changes in the strength of the polypropylene fiber is not significant with the increase of the steel fibers from 0% to 0.05%.

The maximum and minimum flexural strengths are clearly seen in the shell shown in Fig. 17(b). The optimized range for fiber was determined by software as follows: Polypropylene fiber from 0.0625% to 1.05% and steel fiber from 0.93% to 1.5%. An increment in strength was possible by increasing the amount of fibers, but with regard to the technical considerations, we consider 0.1% polypropylene fibers and 0.79% - 1.2% steel fibers, as optimum range.

The shell presented in Fig. 17(c) has a similar process to the shell of Fig. 17(b) (flexural strength). It seems they overlap in some parts. It seems that the maximum relative boundary can be found in the area with 1.5% of steel fibers and 0.017% - 0.05% of polypropylene fibers, which indicate an increase beyond the scope of forecasting (extrapolation). The optimum range in the inner area is 0.025% - 0.121% of polypropylene fiber and 0.75% - 1.5% of steel fiber. The optimal predicted point in the indirect tensile strength (strength range of 0.17±4.6 MPa) corresponds with to the optimum point for tensile strength.

5. Conclusions

In this study, the effects of various amounts of steel and polypropylene fibers were investigated on mechanical and durability properties of RAC. In addition, smoothing spline interpolator are used as a powerful and flexible method for statistical analysis of the modeling carried out in MATLAB software to find the best response to mechanical properties. The results are presented here.

- Steel fibers increased the compressive strength of specimens. By increasing the amount of steel fibers, the strength had also an upward trend. However, compressive strength of samples containing polypropylene fibers decreased by addition of more fibers. Strength gain in steel reinforced specimens is mainly due to its confining role to reduce the transversal deformation of specimen

• The tensile strength results showed that all fiber reinforced samples saw a growth in their strength. However, in samples containing only steel or polypropylene fibers, tensile strength increased from 13-44% and 6-19% in steel and polypropylene reinforced RAC respectively, while the increase percentage was between 28 and 61% in samples containing both types of fibers which confirms the efficacy of incorporation of hybrid fibers in tensile forces. Fibers work as crack arresters inhibiting the extension of cracks when concrete is applied to tensile load and the result is better endurance to tensile loads.
• Static elastic modulus of different samples varied in regard to the type of fibers. Steel reinforced samples had elastic modules near to or higher than control samples and samples containing polypropylene fibers showed a decline in elastic module.
• At the moment of cracking, the toughness of all single-fiber samples increased between 1.2 to 3 times as high as control sample. At δ2, a considerable increase in toughness from 6.5 to 15.9% was observed. The behavior of fiber reinforced concrete in post crack zone confirmed the noticeable ability of concrete to confine crack extension, while this behavior was much more significant in steel fibers rather than polypropylene fibers.
• Despite the decrement in compressive strength in some fiber reinforced samples, indirect flexural strength increased in all specimens, which indicated helpful performance of the fibers against the tensile stresses. The flexural strength increased between 6% and 60.7%. more suitable strength in flexural strength was achieved when both types of fibers were incorporated in samples in which polypropylene fibers discrete cracks propagates into a slow controlled growth and steel fibers enhance the bond in cement matrix.
• The ultrasonic pulse velocity of fiber reinforced RAC samples decreased slightly, however, the results are within the range of 4.46 and 4.67 Km/s, which is in the range of sufficient resistance of concrete mixtures. The maximum reduction percentage in UPV test was only 6%. The main result of the decline in UPV is due to pores produced in cement paste and especially in the contact zone of fibers and paste.
• The results of water absorption test indicated that the inclusion of polypropylene fibers in specimens boosted the absorption of water substantially up to 65.6%, while samples containing steel fibers didn’t reveal obvious changes in which the growth percentage was 4.7 when a maximum 1.5% steel fibers were used.
• In single fiber reinforced RAC samples containing steel fiber of up to 1.5%, the shrinkage was reduced by at least 16.9% and up to 35%. Polypropylene fibers decreased the contraction and then increase it up to 1%. In samples containing hybrid fibers, polypropylene fibers reduced contraction up to 0.05% and then they showed negative effect on contraction. The hybrid fibers reduced the shrinkage by a maximum of 8.1%.
• The fitting of a thin-plate spline can well represent the behavior of the elements affecting a complex composite. Optimum points were ranged from 0.5% to 1% according to the compressive strength results of steel fibers with different amounts of polypropylene fibers. Optimized range for fibers to increase flexural strength was recorded as follows: Polypropylene fiber from 0.0625% to 1.05%, and steel fibers from 0.93% to 1.5%. The optimized range for fibers to increase indirect tensile strength in the inner area was recorded as follows: polypropylene fibers from 0.025% to 0.121% and steel fibers from 0.75% to 1.5%. The optimal predicted point in the indirect tensile strength (strength range is 0.17±4.6 MPa) corresponded to the optimum point of tensile strength.

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