Computers and Concrete, *Vol. 21, No. 2 (2018) 167-179*
DOI: https://doi.org/10.12989/cac.2018.21.2.167

Mechanical behavior of hybrid steel-PVA fibers reinforced reactive powder concrete

Reza Poorhosein[a] and Mahdi Nematzadeh*

Department of Civil Engineering, University of Mazandaran, Babolsar, Iran

(Received July 20, 2017, Revised October 11, 2017, Accepted October 12, 2017)

Abstract. Reactive powder concrete (RPC) is a type of ultra-high strength cement-based material with a dense microstructure, which is made of ultra-fine powders. RPC demonstrate a very brittle behavior, thus adding fibers improves its mechanical properties. In this study, it was attempted to investigate the effect of using steel and polyvinyl alcohol (PVA) fibers as well as their combination on the properties of RPC. In this regard, hooked-end crimped steel fibers together with short PVA fibers were utilized. Steel and PVA fibers were used with the maximum volume fraction of 3% and 0.75%, respectively, and also different combinations of these fibers were used with the maximum volume fraction of 1% in the concrete mixes. In total, 107 concrete specimens were prepared, and the effect of fiber type and volume fraction on the physico-mechanical properties of RPC including compressive strength, tensile strength, modulus of elasticity, density, and failure mode was explored. In addition, the effect of the curing type on the properties of compressive strength, modulus of elasticity, and density of RPC was evaluated. Finally, coefficients for conversion of cubic compressive strength to cylindrical one for the RPC specimens were obtained under the two curing regimes of heat treatment and standard water curing.

Keywords: reactive powder concrete; physico-mechanical properties; hybrid fibers; heat treatment; failure mode

1. Introduction

In response to the increasing demand of the construction industry for materials with desired mechanical properties, concrete technology is continuously developing and trying to improve the compressive strength limit and enhance the performance of concrete. Along this development path, researchers have attempted to replace conventional concretes with a concrete with higher strength, called high-performance concrete (HPC), which does not demonstrate problems such as low strength or durability (Lee *et al*. 2007, Afroughsabet *et al*. 2016). Subsequently, ultra-high performance concrete (UHPC) with the compressive strength of 200 MPa or above was introduced, which demonstrates enhanced durability properties. Undertaking more research in this area, researchers subsequently produced reactive powder concrete (RPC) (Richard and Cheyrezy 1995, Cwirzen *et al*. 2008).

With the commercial name of DUCTAL (Russell and Graybeal 2013), RPC is a relatively new innovative type of cement-based material, which possesses ultra-high strength, low porosity, and high ductility, and is classified as ultra-high performance concrete (Zong *et al*. 2014, Ahmad *et al*. 2015). In this type of concrete, all the fine-grained powder and pozzolanic materials used are hydraulically active and chemically reactive, thus the name RPC (Lee and Chisholm 2005). The constituents of this concrete type are: Portland cement, silica fume, quartz sand, quartz powder, superplasticizer, water, and steel fibers (Bonneau *et al*. 1997, Williams *et al*. 2010).

RPC has been developed through an approach of microstructural engineering, which involves totally eliminating the coarse aggregates and replacing them with particles with the diameters of up to 600 μm, limiting the water-to-cement ratio to less than 0.2, lowering the CaO/SiO_2 ratio (lime/silica), and incorporating steel fibers. Eliminating the coarse aggregates leads to the elimination of the interfacial transition zone (ITZ) between the binder matrix and the aggregate, and CaO/SiO_2 ratio is reduced through introducing silica components. Also, similar to other types of concrete, incorporating steel fibers in the RPC mixture prevents brittle failure and increases strength and ductility of concrete (Nematzadeh and Hasan-Nattaj 2017, Arslan 2016). The significant improvement observed in many mechanical properties, e.g., a very high compressive strength in the range of 150-800 MPa (at least four times as high as conventional concrete), bending strength of above 40 MPa, tensile strength in the range of 6-13 MPa, and Young's modulus of above 50 GPa, is attributed to the homogeneous and dense microstructure of this concrete (Yazıcı *et al*. 2010, Tuan *et al*. 2014).

Although it is inferred that this concrete is expensive, it should be kept in mind that total construction costs would be reduced via dimension reduction of the concrete members due to the ultra-high strength of this concrete, which in turn leads to a considerably lower structural weight, less materials used, and also improved seismic performance of concrete through lowering inertial force (Tam *et al*. 2012). On the other hand, in order to construct high-rise buildings, strong and sustained reinforced

∗Corresponding author, Associate Professor
E-mail: m.nematzadeh@umz.ac.ir
[a]Graduate Student

http://www.techno-press.org/?journal=cac&subpage=8 ISSN: 1598-8198 (Print), 1598-818X (Online)

concrete structures, etc., it is essential that cementitious materials be designed with high strength and considerable durability and ductility. The first structure designed and built by RPC is a pedestrian bridge in Sherbrooke, Quebec, Canada, where using RPC led to a considerable reduction in the dimensions and weight of the concrete sections (Bonneau *et al*. 1997, Blais *et al*. 1999). By reviewing the literature, it is found that over 100 bridges were made with ultra-high performance concrete, in which this type of concrete was employed in some or all of their main members (Aitcin 1995).

Richard and Cheyrezy (1995) were among the first researchers in the field of RPC production who proposed four important principles for the production and development of this concrete as follows: improving material homogeneity by eliminating all coarse aggregates, increasing density by optimizing the grading and compacting, enhancing microstructure by applying a curing regime, and reaching the desired ductility by adding appropriate steel fibers. Other researchers such as Bonneau *et al.* showed in their studies that RPC strength is highly influenced by the type and duration of curing, with curing at the temperature of 90℃ leading to a concrete strength improvement of up to 200 MPa. Moreover, curing at 250℃ together with the application of pressure to specimens, leading to the extraction of the entrapped air and excess water, would raise the concrete strength above 800 MPa (Bonneau *et al*. 1997, Yazıcı *et al*. 2010, Yazıcı *et al*. 2013). Furthermore, in their work, Garas *et al.* (2012) showed that autoclaving is the best method for curing RPC. A study carried out by Ming-zhe *et al*. (2009) on the effect of specimen size on the compressive strength of RPC showed that, first, there is an inverse relationship between compressive strength and specimen size, and second, the standard specimen size must be around 100 mm.

The RPC without fibers is very brittle, thus introducing fibers leads to a higher strength and enhanced ductility. To date, there have been many studies investigating the effect of type, size, dosage in the mixture, and shape of fibers on the strength of RPC (Bian *et al.* 2016, Wu *et al.* 2016, Boughanem *et al.* 2015). Jia *et al.* (2014) explored the mechanical properties of RPC containing synthetic polypropylene fibers. Their results showed that these fibers positively affected the compressive strength, improved the toughness and energy absorption capacity of concrete, and changed the failure mode from brittle to ductile. Wile *et al* (2012) studied the effect of fibers and matrix properties on the tensile strength and ductility of ultra-high performance fiber-reinforced concrete (UHPFRC) using normal water curing at ambient temperature without the application of any special treatment. The obtained results indicated that using steel fibers, in particular twisted fibers as opposed to smooth steel fibers, is capable of providing strain-hardening behavior of UHPC in tension. Sanchayan and Foster (2016) investigated the effect of elevated temperatures on the RPC containing steel and polyvinyl alcohol (PVA) fibers, and found that replacing steel fibers with PVA fibers decreases the compressive strength, and adding PVA fibers prevents the explosive spalling of specimens at elevated temperatures. They also concluded that the mixtures containing hybrid fibers consisting of 1% steel fibers and 1% PVA fibers have better general results and a balanced performance at elevated temperatures.

Table 1 Physical, chemical and mechanical properties of cementitious materials

Component	Chemical composition (%)	
	Cement	Silica fume
SiO_2	20.6	90-95
Al_2O_3	4.86	0.6-1.2
Fe_2O_3	3.37	0.3-1.3
CaO	63.56	0.5-1.5
MgO	2.18	0.5-2
SO_3	2.3	-
Na_2O	0.33	0.3-0.5
K_2O	0.54	0.3-0.5
C	-	0.2-0.4
S	-	0.04-0.08
MnO	-	0.02-0.07
P_2O_5	-	0.04
PH value	-	6.8-8
	Physical properties	
	Cement	Silica fume
Specific gravity	3.07	1.9
Specific surface (m^2/kg)	312	20000-25000
Unit volume weight (g/cm^3)	-	0.3-0.5
	Compressive strength of cement (MPa)	
3 days	32.26	
7 days	39.03	
28 days	44.72	

By reviewing the relevant literature, it is found that sufficient information regarding the performance of RPC particularly in case of using combinations of different fibers is still lacking. In this study, the effect of using steel fibers and PVA fibers as well as the combination of these two fibers types on the properties of RPC was investigated. To do so, 10 different mix designs in 19 test groups, including various percentages of steel fibers, PVA fibers, and hybrid fibers were utilized for preparing the concrete specimens, and subsequently, the physico-mechanical properties of the RPC specimens such as compressive strength, tensile strength, modulus of elasticity, density, and failure mode were evaluated. Furthermore, the effect of curing type on the properties of RPC specimens was explored, and also the coefficients for conversion of cubic compressive strength to cylindrical one were determined.

2. Experimental study

2.1 Materials

2.1.1 Cement and silica fume

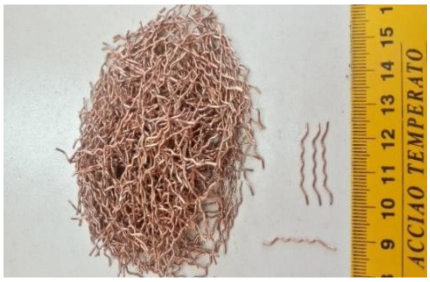
In RPC, cement and silica fume together act as a binder. The choice of cement is considered an important factor in the preparation process of RPC because of its high usage level in this concrete relative to conventional concrete, and the considerable effect of the cement type and quality on the

Table 2 Characteristics of silica sand and silica powder

Chemical composition	Silica Sand %	Silica Powder %
SiO_2	99.23	99.03
Al_2O_3	0.03	0.04
Fe_2O_3	0.5	0.07
CaO	0.03	0.48
MgO	-	0.15
Na_2O	0.06	0.005
K_2O	-	0.01
SO_2	-	0.007
TiO_2	0.01	-
P_2O_5	0.01	-
LOI (loss on ignition)	0.13	0.4

Table 3 Characteristics of fibers

Type of fiber	Length (mm)	Aspect ratio	Elastic modulus (GPa)	Tensile strength (MPa)	Specific gravity
Steel	25	35	200	1140	7.8
PVA	6	526	25.5	966	1.3



(a) Steel fibers


(b) PVA fibers

Fig. 1 Shape of different types of fibers used: (a) steel fibers; (b) PVA fibers

performance of RPC (Cwirzen *et al*. 2008). Here, type I Portland cement (CEM-I 42.5 N) in accordance with the ASTM C150 standard was used. Silica fume, a waste material of the manufacturing process of silicon or silicon-ferrous, was added as an admixture to the concrete mixture, serving as a secondary binder. The silica fume used in this work is a light gray undensified amorphous type with the purity and particle diameter of 90% and 0.2 µm, respectively, in compliance with the ASTM C1240 standard. The chemical, physical, and mechanical properties of the cementitious materials are listed in Table 1.

2.1.2 Silica sand and silica powder

Quartz minerals are very strong and tough relative to other minerals. Silica sand (quartz mineral) was provided with the particle size in the range of 0.2-0.6 mm and purity level of above 99%. In addition, with the aim of improving the packing density of the binder matrix and increasing pozzolanic reactions during heat treatment curing, additional quartz micro-fillers (silica powder) with the maximum nominal diameter of 20 μm and purity of above 99% were used. Table 2 presents the chemical characteristics of the silica sand and silica powder.

2.1.3 Fibers

Two fiber types, i.e., steel and PVA fibers, were used in this study. Crimped hooked-end steel fibers coated with a thin layer of copper to prevent corrosion were used. High-strength and high-modulus bunchy monofilament PVA fibers showing a good compatibility with cement and having a short length and small diameter was utilized here. Other characteristics of these two fibers and their shape are given in Table 3 and Fig. 1, respectively.

2.1.4 Superplasticizer

When mixing RPC, due to the low water-to-cementitious materials ratio, reaching the desired workability is feasible only through the use of superplasticizers. Therefore, in this research, the third generation of superplasticizers based on polycarboxylate ether having the solid content of 42 % and density of 1.1 g/cm^3, commercially available under the name of Carboxal HF5000 was used as a weight percentage of cement in all the mixtures. The physical properties of the used superplasticizer comply with ASTM C494 Type F.

2.2 Mix design and specimens

Here, due to the high sensitivity of RPC to any change in the chemical composition of the cementitious materials or the particle size distribution of its constituents, the RPC mixture was designed considering some of the proposed and published combinations, with the water-to-cementitious materials ratio of 0.18 (Shaheen *et al.* 2006, Zdeb 2013, Nematzadeh and Poorhosein 2017). The details of the mix design of the RPC specimens are given in Table 4, expressed as weight ratios relative to the weight of cement. In order to identify the specimens in Table 4, the first letter or letters after RPC represent the type of fibers used in concrete (N, ST, PVA, and HY indicate the absence of fibers, presence of steel fibers, PVA fibers, and hybrid fibers, respectively), and the number that follows denotes the volume fraction of fibers used. In the hybrid specimens, the number after HY shows the volume fraction of steel fibers in the total volume of fibers used, the rest of which is occupied by the PVA fibers (in all hybrid mixtures, the total fiber volume is 1% of the total volume). The second set of letters specifies the shape of the concrete specimens (Cy and Cu represent cylindrical and cubic specimens, respectively). The last letter in the name of the specimens represents the type of curing (S and H indicate standard and heat treatment curing, respectively). For example, RPC/ST2/Cy/H represents a cylindrical RPC specimen containing 2% steel fibers subjected to heat treatment, and

Table 4 Composition and details of RPC mixtures

Specimen ID	Mixture name	Number of specimens	Type of curing regime	Shape of specimen	Steel Fiber (V_f, %)	PVA fiber (V_f, %)
RPC/N/Cy/H	Plain	8	heat treatment	Cylindrical	-	-
RPC/N/Cy/S		3	STD	Cylindrical	-	-
RPC/N/Cu/H		3	heat treatment	Cubic	-	-
RPC/N/Cu/S		3	STD	Cubic	-	-
RPC/ST1/Cy/H	ST 1%	8	heat treatment	Cylindrical	1	-
RPC/ST2/Cy/H	ST 2%	8	heat treatment	Cylindrical	2	-
RPC/ST3/Cy/H	ST 3%	8	heat treatment	Cylindrical	3	-
RPC/ST3/Cy/S		3	STD	Cylindrical	3	-
RPC/ST3/Cu/H		3	heat treatment	Cubic	3	-
RPC/ST3/Cu/S		3	STD	Cubic	3	-
RPC/HY0.75/Cy/H	HY 0.75%	8	heat treatment	Cylindrical	0.75	0.25
RPC/HY0.5/Cy/H	HY 0.5%	8	heat treatment	Cylindrical	0.5	0.5
RPC/HY0.25/Cy/H	HY 0.25%	8	heat treatment	Cylindrical	0.25	0.75
RPC/PVA0.25/Cy/H	PVA 0.25%	8	heat treatment	Cylindrical	-	0.25
RPC/PVA0.5/Cy/H	PVA 0.5%	8	heat treatment	Cylindrical	-	0.5
RPC/PVA0.75/Cy/H	PVA 0.75%	8	heat treatment	Cylindrical	-	0.75
RPC/PVA0.75/Cy/S		3	STD	Cylindrical	-	0.75
RPC/PVA0.75/Cu/H		3	heat treatment	Cubic	-	0.75
RPC/PVA0.75/Cu/S		3	STD	Cubic	-	0.75
Total of specimen		107				

Mix design (by weight of cement=925 kg/m^3): Cement=1, Silica fume=0.24, Quartz sand=0.95, Quartz powder=0.084, Super Plasticizer=0.032, water=0.22

(a) Pan type mixer (b) Mortar flow test (c) Accessory apparatus for mortar flow testing

Fig. 2 Equipment used for mixing operation and determining rheological properties of RPC specimens

RPC/HY25/Cu/S represents a cubic RPC specimen containing hybrid fibers consisting of 0.25 and 0.75% steel and PVA fibers, respectively, subjected to standard curing.

In this study, 10 different mix designs in 19 experimental groups including 107 RPC specimens consisting of 89 cylindrical and 18 cubic specimens containing different volume fractions of steel and PVA fibers as well as their combinations were prepared. In order to reduce errors in reporting the results, for each mix design, the number of concrete specimens prepared was equal to the number mentioned in Table 4. In the 8-specimen mixtures, 4 specimens were used for compressive testing and the other 4 were used for tensile testing, while 3-specimen mixtures were all used for compressive testing. The concrete specimens prepared in this study included the cylindrical specimens with the diameter and height of 100 and 200 mm, respectively, together with the 100 mm cubic specimens.

Packing density (volume of solids in a unit volume), which is regarded as a fundamental principle for the mix design of ultra-high performance concrete was used in this study by the slightly modified method developed by Puntke (2002) for the mix design of RPC. The Puntke method approximates the packing density through determining the water demand of powder materials. In this method, dry materials are manually mixed in a steel vessel to achieve a uniform mix. Next, water together with the superplasticizer is added and mixed with the dry materials. In the next step, the vessel is dropped a couple of times from a 5 cm height to obtain a visible wetness on the surface of the materials. If such wetness is not observed, more water is added and the whole procedure is repeated.

2.3 Mixing sequence and flow test

Based on the literature review, the mixing method applied is an important factor in the preparation of this type of cementitious materials, and neglecting it could be a source of errors during the analysis of experimental results. Of the other factors affecting the properties of RPC are the duration and speed of the mixing. Since RPC is made of very fine materials, the conventional mixing method does not work well here, and special care and expertise are needed when mixing. Based on other studies (Ahmad *et al*. 2015, Tam *et al*. 2012, Schachinger *et al*. 2004) and using trial-and-error approaches, the mixing sequence of the RPC was selected as follows:

First, all dry constituents are mixed with each other for two minutes, and next, water and superplasticizer are added to the mixture gently during one minute. After 4 minutes, when the resulting mixture acquires a plastic consistency and becomes a flowable mixture, the fibers previously separated by hand are sprinkled into the mixture. Then, in order to ensure the homogeneous distribution of fibers throughout the mixture, the mixing is allowed to continue for 2 more minutes. The entire duration of the mixing procedure is about 11-13 minutes.

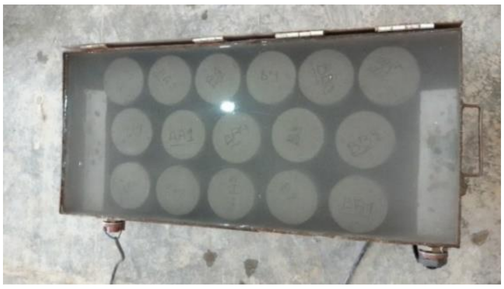
As observed here, the steel and PVA fibers were disappeared during the mixing procedure and were not clearly visible while casting concrete. Moreover, the addition of steel fibers to RPC mixtures did not influence the concrete finishability in the opposite of PVA fibers. The mixing was performed using a horizontal pan type mixer with the total volume of 0.02 m^3, as shown in Fig. 2(a).

Once the mixing completed, to determine the rheological properties of the fresh concrete in accordance with ASTM C1437 procedure, normally applied for the determination of the flow of mortars and known as the mini cone (mini flow table), the flow test was performed on the RPC mixture. In this test, a cone-shaped mold located at the center of a shaking table, as shown in Fig. 2(b), was filled with RPC mixture in two layers, each tamped 20 times with a tamping rod. Then, the mold was gently lifted away from the mortar, and immediately, the flow table was dropped 25 times in 15 seconds from a constant height, and the diameter resulted from the flow of the mixture on the flow table was recorded. The flow of mixture, which is resulted from the increase in the original diameter of the mortar, is calculated by averaging the maximum flow diameter and the diameter perpendicular to it (see Fig. 2(c)) and expressed as a percentage of the original diameter (100 mm). The conical mold for casting the flow specimen has a diameter of the bottom opening of 100.0 mm while the circular rigid table of the flow table apparatus is 255 mm. It should be kept in mind that the entire process from the completion of the mixing operation until lifting the mold away from the mortar should take only one minute.

2.4 Preparation and curing specimens

After completing the mixing and measuring the flow of the RPC, the fresh concrete was poured into the cylindrical molds previously sprayed with mold oil to reduce the interface friction between the molds and concrete mixes. In order to consolidate the concrete mixtures containing steel fibers, a hand-operated tamping rod with a square cross section was utilized. This hand operation was performed together with the vibrating table to consolidate the specimens containing PVA and hybrid fibers and to remove the air bubbles entrapped within them. The filled molds were then sealed with steel lids, as shown in Fig. 3(a), to prevent the release of moisture to the ambient air and provide a smooth surface to prevent stress concentration on the specimen surface during compressive testing. After demolding, a smooth surface was obtained for all the specimens, indicating the effectiveness of the lid method.

(a) Placement of steel lids on concrete specimens



(b) Curing box and specimens under heat treatment

Fig. 3 Molding and heat treatment of concrete specimens

The following two curing methods were applied to the specimens for at least 28 days. The first method, known as STD curing (standard water curing), involves demolding the specimens after 24 hours and placing them in a tank containing 20℃ lime water in accordance with the ASTM C192 standard. The second method, hot water curing, is conducted using the apparatus shown in Fig. 3(b). To prevent thermal shock that can lead to cracking, the temperature is raised up to the maximum temperature of 80-90℃ with the constant rate of 20℃ per hour. This curing regime begins 24 hours following the concreting and lasts for 72 hours. After completing the heat treatment, the specimens are kept in the tank for an additional three hours for gradual cooling, and are then placed under laboratory conditions until reaching the ambient temperature. The specimens treated with this method, as the ones treated with the first method, are kept submerged in the water tank until the testing day. This method of heat treatment was selected based on extensive studies whose results are described in the literature (Cwirzen 2007, Yazıcı *et al*. 2010).

2.5 Testing of specimens

2.5.1 Compressive strength specimens

Compressive strength is among the main and very helpful properties of concrete, with many other properties of concrete such as durability, shrinkage resistance, and modulus of elasticity depending on it.

After at least 28 days of curing, the compressive strength testing of the cylindrical and cubic concrete

Table 5 Test results of physical and mechanical properties of reactive powder concrete specimens

Specimen ID	Mixture name	Density	Compressive strength		Modulus of elasticity		Tensile strength		Flow*
		Ave (kg/m^3)	Ave (MPa)	COV (%)	Ave (GPa)	COV (%)	Ave (MPa)	COV (%)	(%)
RPC/N/Cy/H	Plain	2382	121.74	3.21	43.78	5.32	8.56	3.80	80
RPC/N/Cy/S		2309	115.32	3.4	46.21	2.21	-	-	80
RPC/N/Cu/H		2468	115.29	4.56	-	-	-	-	80
RPC/N/Cu/S		2377	95.25	4.36	-	-	-	-	80
RPC/ST1/Cy/H	ST 1%	2464	133.93	4.80	46.44	0.48	11.03	2.64	60
RPC/ST2/Cy/H	ST 2%	2491	130.49	5.20	49.23	1.31	12.49	4.64	70
RPC/ST3/Cy/H	ST 3%	2627	124.25	6.70	50.81	4.32	13.38	3.98	75
RPC/ST3/Cy/S		2567	109.86	5.7	50.03	2.45	-	-	75
RPC/ST3/Cu/H		2648	128.30	1.76	-	-	-	-	75
RPC/ST3/Cu/S		2571	93.44	2.58	-	-	-	-	75
RPC/HY0.75/Cy/H	HY 0.75%	2381	120.75	6.17	44.99	5.54	12.18	5.63	40
RPC/HY0.5/Cy/H	HY 0.5%	2371	118.01	5.92	43.18	6.91	11.47	5.12	30
RPC/HY0.25/Cy/H	HY 0.25%	2349	117.25	2.56	42.00	6.46	11.01	4.58	10
RPC/PVA0.25/Cy/H	PVA 0.25%	2262	113.00	4.5	45.07	7.24	8.67	3.91	50
RPC/PVA0.5/Cy/H	PVA 0.5%	2295	107.41	5.74	43.87	5.03	8.27	5.27	40
RPC/PVA0.75/Cy/H	PVA 0.75%	2315	105.59	6.26	42.28	8.17	8.00	2.24	20
RPC/PVA0.75/Cy/S		2259	104.02	3.72	43.41	6.72	-	-	20
RPC/PVA0.75/Cu/H		2404	101.50	2.56	-	-	-	-	20
RPC/PVA0.75/Cu/S		2334	88.54	1.43	-	-	-	-	20

*The original diameter of flow is 100 mm

specimens was carried out accordant to ASTM C39 and BS EN 12390-3 standards, respectively, using a digital compression testing machine with a maximum capacity of 2000 kN, and the obtained results were subsequently averaged and reported. According to the mentioned standards, the loading rate was considered in the range of 0.2 to 0.3 MPa/s for the concrete specimens. The loading rate for the compression test of the cylindrical and cubic concrete specimens was approximately 0.25 MPa/s, which is in the range of 0.2 to 0.3 MPa/s, in accordance with the requirements of the mentioned standards.

2.5.2 Tensile strength testing

The indirect tensile strength testing was conducted after at least 28 days of curing in compliance with ASTM C496 on the cylindrical specimens under a compressive load applied uniformly along the entire length of the specimen, and the average of the obtained results was reported for each of the groups. The loading rate in this test was selected as 60 kg/s, equivalent with 1.15 MPa/min, which is well within the permissible limit specified by the code (0.7-1.4 MPa/min).

2.5.3 Modulus of elasticity testing

As one of the most important elastic properties of concrete, modulus of elasticity affects the performance and serviceability of structures, and in regarded as a requirement for evaluating the deflection and cracking of structural members.

The secant modulus of elasticity of the cylindrical specimens was determined using the method recommended by the ASTM C469 standard. In this method, modulus of elasticity is determined as the ratio of a stress increment to strain increment between two points of compressive axial loading application; the first point corresponds to the longitudinal strain of 50 microns, and the second to 40% of the ultimate load. In order to determine axial strains, the displacement of the concrete specimens at mid-height was measured using two LVDTs placed symmetrically at two locations in front of each other, and their mean to the measuring distance (around 100 mm) ratio was reported as the results. The loading rate for determining the modulus of elasticity is similar to the value specified for the compressive testing. In order to determine the axial strains, the displacement of the mid-height of cylindrical specimens was measured by two linear variable differential transducers (LVDTs) mounted at two symmetrical locations on the specimen surfaces, and their average ratio to the initial measured distance (approximately 100mm) was reported as the results.

3. Results and discussion

3.1 Rheological properties

The flow values of the RPC mixtures, as presented in Table 5, are in the range of 10-80%. In this study, for plain concrete (RPC without fibers), the flow value of 80% (180 mm) was obtained. It was observed that by the addition of fibers to the mixtures the flow declined. Due to the consistency and cohesion that they provide in the concrete mixture, PVA fibers decrease the flow of fresh concrete, resulting in a stiff mixture, while higher contents of steel

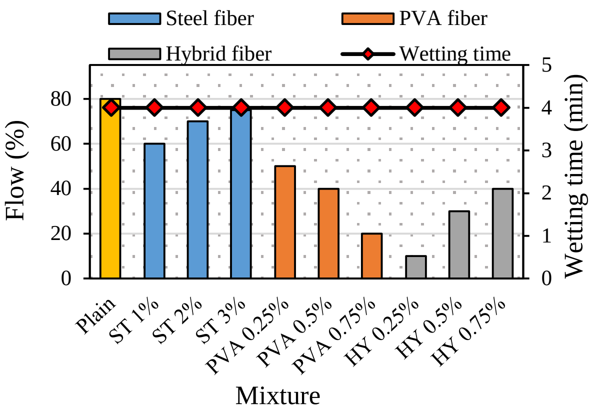


Fig. 4 Fresh concrete properties

fibers lead to higher workability (175 mm in the mixture containing 3% ST fibers). Increasing the volume fraction of steel fibers in fibrous RPC mixture increases the workability of fresh concrete, while the opposite trend is observed in RPC mixtures containing PVA fibers (a decrease in flow up to 120 mm in the mixture containing 0.75 PVA fiber). Here, the flow of the fresh concrete containing different volume fractions of steel fibers was obtained in the range of 60-75%. However, this value fell to the range of 20-50% for the fresh concrete containing PVA fibers. Furthermore, for the fresh concrete containing 1% volume fraction of hybrid fibers, the flow reached its lowest value in the range of 10-40%.

Wetting time defined as the time required for the change in mixture state from dry to wet following the addition of water and superplasticizer was the same for all the mixtures, due to the constant amount of dry constituents used and the constant speed of the mixer in this study.

3.2 Compressive strength

The compressive strength results of all the RPC specimens are given in Table 5. In Fig. 5, the average values of the compressive strength of the heat-treated cylindrical specimens vs. different mix designs of RPC are plotted. As can be seen, the steel fibers were able to improve the compressive strength of concrete, while the PVA fibers led to a reduction in compressive strength. The RPC specimens containing 1, 2, and 3% steel fibers demonstrated the compressive strength improvement of 10, 7.2, and 2.1%, respectively, with the highest effectiveness occurring at the volume content of 1% (RPC/ST1/Cy/H). The reason for the reduction observed in the compressive strength improvement at high amounts of fibers is attributed to an increase in concrete porosity and separation of the cement paste from aggregates. In the concrete containing PVA fibers, the highest compressive strength loss of 13.3% occurred for V_f=0.75%. The reason for this reduction is the short length of fibers, not being properly mixed in mixture and flow reduction, which results in a higher specimen porosity and weaker cohesion between the cement paste and fibers. It can also be observed in Fig. 5 that the RPC specimens containing hybrid fibers have a lower compressive strength in relation to the plain concrete

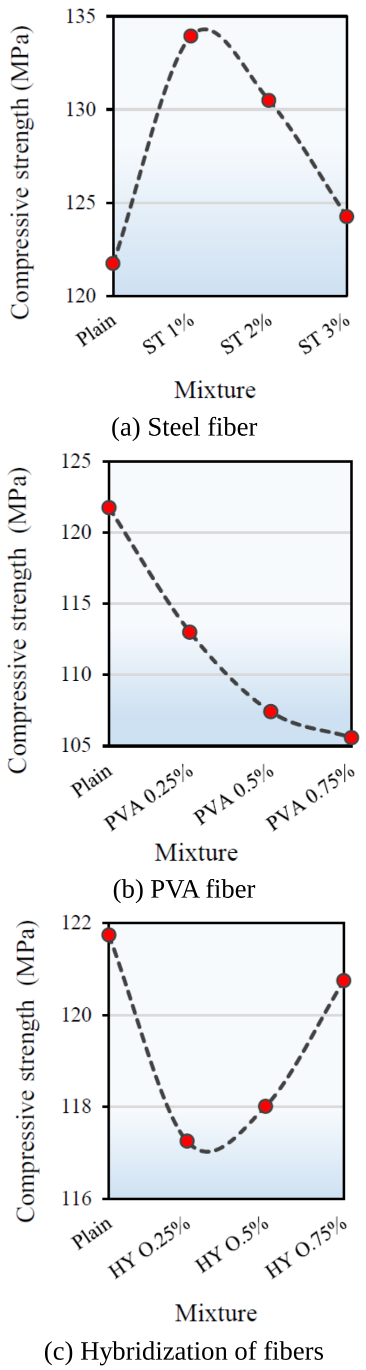


Fig. 5 Compressive strength at different mixtures of cylindrical heat-treated fiber reinforced and plain RPC specimens.

(reference RPC). As the volume fraction of PVA fibers increased and that of steel fibers decreased, the compressive strength of the hybrid fiber-reinforced concrete specimens declined. The maximum reduction in the compressive strength occurred in the concrete containing 0.25% steel and 0.75% PVA fibers (RPC/HY0.25/Cy/H) as 3.6%.

In this work, in order to investigate the effect of heat treatment on the compressive strength of RPC, and to obtain the specimens compressive strength conversion coefficient from cubic to cylindrical under the two curing regimes mentioned previously, the RPC specimen results including

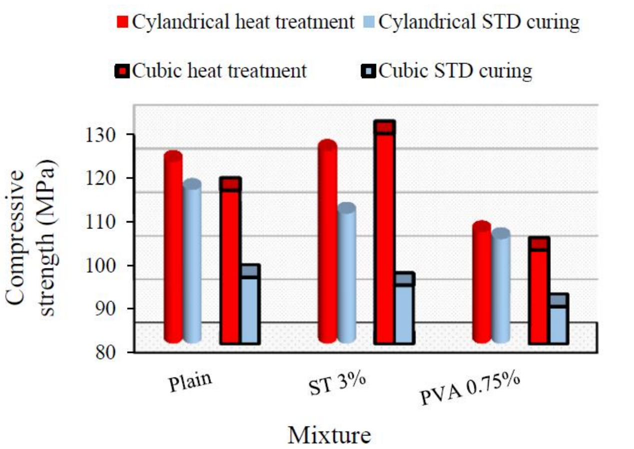


Fig. 6 Effect of curing type on compressive strength of RPC specimens

Table 6 Coefficients for conversion of compressive strength from cubic to cylindrical

Mixture	In STD Curing	In hot water curing
Plain	1.21	1.06
ST 3%	1.18	0.97
PVA0.75%	1.17	1.04

those of the plain concrete, the one containing 3% steel fibers, and the one with 0.75% PVA fibers are compared to each other in Fig. 6 and Table 6. As can be seen in the figure, heat treatment curing improved the compressive strength of RPC specimens. This is due to the acceleration of the hydration reaction of cementitious materials at high temperatures and formation of a dense matrix. The highest and lowest compressive strength improvement of 37.3 and 1.5%, respectively, due to the heat treatment occurred in the cubic specimens containing 3% steel fibers and the cylindrical specimens containing 0.75% PVA fibers, respectively.

With respect to Table 6, the coefficient for conversion of compressive strength from cubic to cylindrical for the specimens having experienced STD and heat treatment curing is on average 1 and 1.2, respectively, independent of the fiber type. In this regard, Graybeal and Davis (2008) obtained the conversion coefficient of 1 for the compressive strength of RPC.

3.3 Splitting tensile strength

Fig. 7 and Table 5 present the splitting tensile strength results for all the heat-treated RPC specimens. These results show that using fibers and in particular steel fibers, due to their presence in the brittle cement matrix, reduces the crack width and microcrack propagation, which leads to a higher splitting tensile strength. Considering Fig. 7 and Table 5, using steel fibers significantly increased the tensile strength of RPC specimens up to 56% at the volume fraction of 3%, whereas the PVA fibers led to an increase of 1 at the volume fraction of 0.25%, and the tensile strength decreased as the fiber content increased, with the strength reduction of 6.5% at the PVA fiber content of 0.75%.

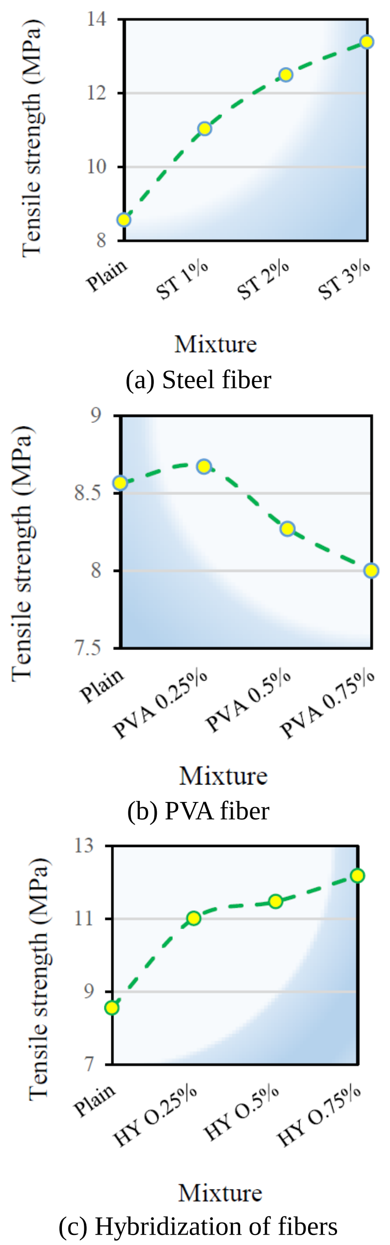
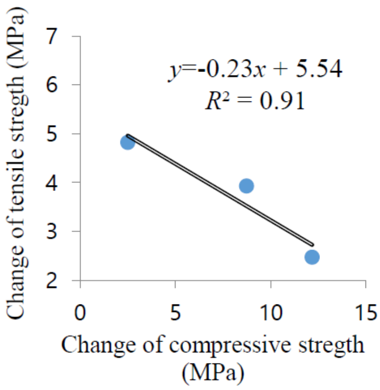


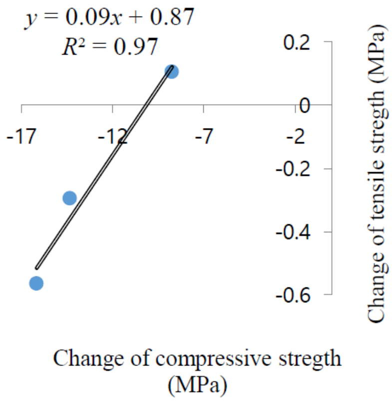
Fig. 7 Splitting tensile strength of heat-treated RPC specimens

Note that the steel fibers used in this study, due to their crimped shape and hooked ends, provide a strong firmness in the concrete under tensile stresses, and prevent the propagation of continuous cracks; therefore, a considerable increase was observed in the tensile strength. However, PVA fibers, considering their high aspect ratio (l/d), produce a significant cohesion and consistency within the concrete mixture, which efficiently prevent micro-crack propagation during the first stages of loading, but they are unable to bridge the micro-cracks, which leads to their partial action against tensile stresses; hence, their effect on the tensile strength is insignificant. Moreover, the short length of PVA fibers can be another reason for the lack of tensile strength improvement in RPC specimens.

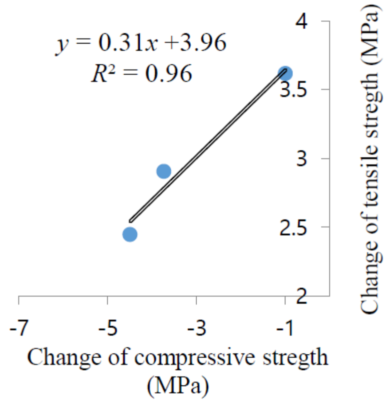
3.4 Compressive-tensile strength relationships



(a) Steel fiber

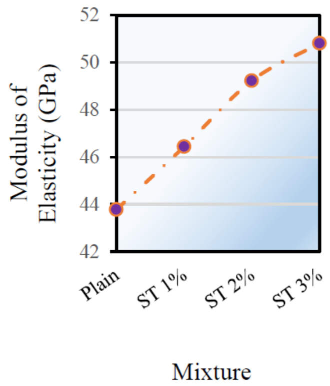


(b) PVA fiber

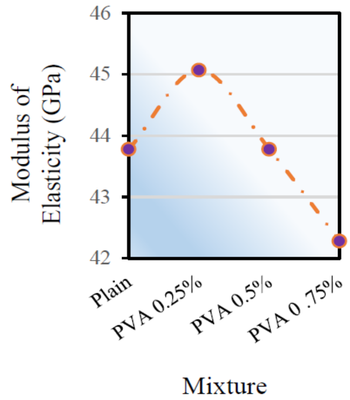


(c) Hybridization of fibers

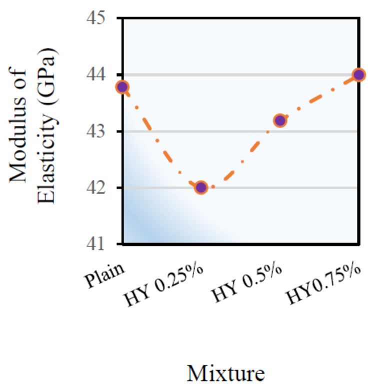
Fig. 8 Compressive strength vs. tensile strength for heat-treated cylindrical RPC specimens



(a) Steel fiber



(b) PVA fiber



(c) Hybridization of fibers

Fig. 9 Secant modulus of elasticity of cylindrical RPC specimens subjected to heat treatment

The linear relationships between the variations of the tensile strength and those of the compressive strength for the heat-treated cylindrical RPC specimens with different mixtures relative to the strength of plain concrete are presented in Fig. 8. It can be seen in the figure that for the RPC specimens containing PVA and hybrid fibers, the variations of the tensile and compressive strength are similar, and thus a direct relationship is obtained between the tensile and compressive strength. It is also found from Fig. 8 that for the RPC specimens containing steel fibers, a reverse relationship exists between the variations of the tensile and those of the compressive strength. In fact, by the addition of steel fibers, the tensile strength of RPC increased in comparison with the plain RPC, while its compressive strength declined. The curve slope of the hybrid fiber- reinforced RPC specimens is between the curve slopes of the PVA fiber-reinforced and steel fiber-reinforced concretes, as can be understood from Fig. 8.

3.5 Modulus of elasticity

The secant modulus of elasticity results of the RPC specimens are given in Table 5. The values of the modulus of elasticity of the heat-treated cylindrical specimens vs. different mixtures of RPC specimens are plotted in Fig. 9. Modulus of elasticity is affected by three phases of concrete: binder matrix, aggregates, and interfacial transition zone. According to Table 5, the modulus of

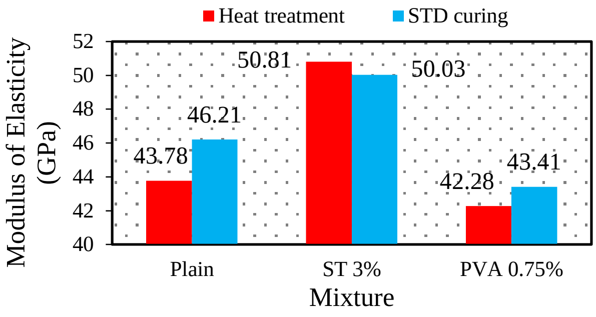


Fig. 10 Effect of curing type on secant modulus of elasticity of RPC specimens

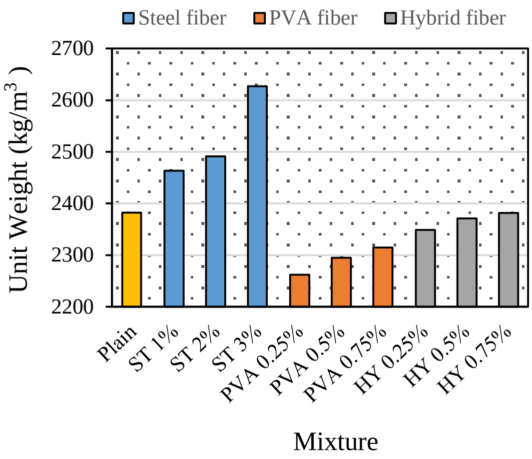


Fig. 11 Density of RPC specimens under heat treatment

elasticity of the steel-fiber reinforced RPC increases as the volume content of steel fibers increases, due to the crimped shape of fibers and the strong cohesion that they provide in concrete, with the maximum modulus of elasticity improvement of 16.1% at the fiber volume content of 3%. In the specimens containing PVA fibers, the highest modulus improvement relative to plain RPC occurred at the fiber volume fraction of 0.25% as 2.9%, and above that volume fraction, the modulus decreased, with a decrease of 3.4% in the modulus of elasticity at the fiber volume fraction of 0.75%.

This trend was also observed in the RPC specimens containing hybrid fibers, with the highest modulus of elasticity improvement of 0.48% at the hybrid fiber volume fraction consisting of 0.25% steel and 0.75% PVA fibers. This modulus reduction in the PVA fiber- and hybrid fiber-containing concretes is attributed to the decrease of concrete compressive strength with increasing content of PVA fibers (see Fig. 5).

Fig. 10 shows the effect of heat treatment on the modulus of elasticity of RPC specimens. It is seen that the heat treatment did not increase the modulus of elasticity of RPC specimens, with its reducing effect on plain RPC being more evident; however, in the steel fiber-reinforced concrete, a slight increase is observed in the modulus of elasticity. The values of modulus reduction in the plain and PVA fiber-containing RPC specimens was obtained as 5.7 and 2.7%, respectively.

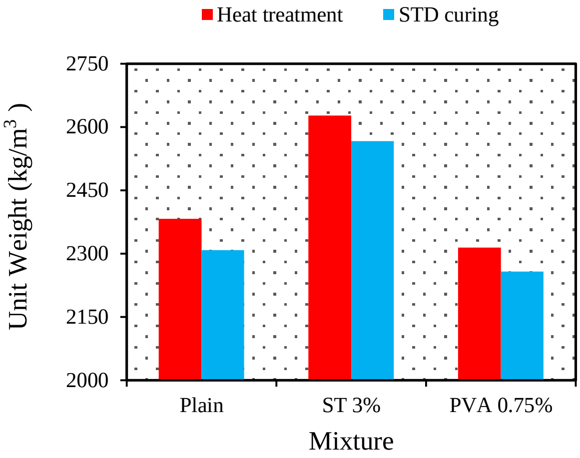


Fig. 12 Effect of curing type on density of RPC specimens

3.6 Hardened concrete density

Concrete density is an important factor in classifying concrete durability since there are fewer pores in a denser concrete for the penetration of harmful materials. The variations of concrete density depend on the amount of entrapped air, aggregate density, type and volume fraction of fibers and water-to-cement ratio (Fallah and Nematzadeh 2017, Hasan-Nattaj and Nematzadeh 2017).

The density of each group of specimens was measured prior to mechanical properties testing in f saturated-surface-dry (SSD) condition, and the average experimental results for different mixtures of RPC specimens are listed in Table 5. The variations of the RPC density with the type and percentage of fibers are shown in Fig. 11. As can be seen in the figure, the density of steel fiber-containing specimens is greater than that of plain RPC, due to the high density of these fibers, with the increase of 10.3% in the concrete density at 3% fiber volume content. Furthermore, the specimens containing PVA and hybrid fibers have a lower density compared to that of plain concrete. This can be due to the low density of PVA fibers, the reduction in the workability of PVA fiber-containing concretes, and the resulting porosity increase.

Fig. 12 demonstrates the effect of curing type on the density of RPC specimens. As can be seen, the specimens subjected to hot water curing have a higher density relative to the ones cured under standard (STD) conditions. The main reason for this is the fact that the conditions of hot water curing accelerate the hydration reactions of the cementitious materials in the form of speeding up the pozzolanic reactions of silica fume and silica powder with $Ca(OH)_2$, subsequently leading to the formation of a denser binder matrix, which in turn leads to a change in the microstructure of RPC and increase in its density. Considering that the mechanical properties of concrete are significantly affected by its density, and that an increasing trend was observed in the mechanical properties of the specimens subjected to hot water curing in relation to the ones subjected to standard curing, one could predict that the density of heat-treated specimens would be greater than that of the similar specimens under standard curing.

(a) Concrete containing PVA fibers (b) Concrete containing steel and hybrid fibers (c) Plain concrete

Fig. 13 Failure mode of RPC specimens

3.7 Failure mode

The failure mode is very sensitive to the boundary conditions of concrete specimens under compression. Although compressive testing is assumed as a form of pure compression of a specimen, the reality is not like that. In fact, the friction between the two ends of specimens and the steel platens of the loading machine create a very complicated system of stresses due to the development of tangential forces at their interface. The frictional forces are generated as a result of different modulus of elasticity and Poisson's ratio values of steel and concrete, which causes the lateral strain in the platens, in case they are free to move, to be much lower than the lateral expansion of the two ends of the specimen.

In the present study, a 3 mm medium density fiber (MDF) board plate with one side covered with melamine was placed at the both ends of the specimens to reduce the frictional forces at the end surfaces of the specimens, on one hand, and to reduce the roughness of the pouring surface of concrete specimens, which caused stress concentration during compressive loading, on the other. However, the steel lids placed on the fresh concrete largely smoothed the end surfaces of specimens.

The failure mode of the RPC specimens is shown in Fig. 13. It is seen from Fig. 13(a) that the failure mode of the specimens containing PVA fibers is shear failure. This type of failure normally occurs when there is an eccentricity between the testing machine and the specimen. In this regard, Neville (1995) reported that an eccentricity of up to 6 mm has no effect on the compressive strength and consequently on the failure mode of conventional concretes. Hence, it can be concluded that the high porosity and irregular distribution of fibers in this type of concrete led to different values of axial stiffness for the cross section elements of the concrete specimen, and thus, no overlapping occurred between the center of rigidity and center of force on the cross section. In addition, the addition of more PVA fibers to RPC results in further reduction of workability, more irregular distribution of fibers, and higher non-homogeneity of concrete, which affects the failure mode.

The failure mode of the RPC specimens containing steel fibers is demonstrated in Fig. 13(b). In these specimens, surface spalling considerably increased at the moment of failure. This is due to the presence of steel fibers, which reduces internal damages to the concrete and creates a crack-bridging mechanism (as described by Cwirzen and Penttala 2006). According to this mechanism, fibers form the structure of cracks and prevent further widening and propagation of them. This behavior and failure mode were also observed in the hybrid fiber-containing specimens.

In most of the plain specimens, a combination of conical and splitting failure modes was observed (see Fig. 13(c)). This failure type is symmetric, which occurred as a result of the absence of fibers and high level of concrete homogeneity.

4. Conclusions

In this study, the effect of adding steel fibers, PVA fibers, and their combination on the properties of RPC including compressive strength, tensile strength, modulus of elasticity, density, and failure mode was investigated. Furthermore, the effect of heat treatment on the properties of RPC was evaluated, and the coefficient for conversion of cubical compressive strength to cylindrical one was obtained under the two conditions of heat and non-heat (standard) treatment curing. Based on the experimental results obtained in this work, the following conclusions can be drawn:

1. The addition of PVA fibers to RPC mixture reduces the flow of fresh concrete, while the addition of steel fibers increases the workability of fresh concrete.
2. The addition of PVA fibers to the RPC subjected to heat treatment does not show a positive influence on the compressive strength, while the addition of 1% volume fraction of steel fibers demonstrates the highest positive effect on the compressive strength of RPC with 10% improvement relative to plain concrete.
3. The tensile strength of RPC increases with the addition of steel fibers, with a tensile strength improvement of 56% for the specimen containing 3% steel fibers, and a tensile strength improvement of 42% for the specimen containing hybrid fibers consisting of 0.75% steel and 0.25% PVA fibers. Furthermore, the effect of PVA fibers on the tensile strength of RPC was negligible, with the maximum tensile strength improvement of 1.3% occurring at the fiber volume fraction of 0.25% in this study.
4. The modulus of elasticity of RPC increases as the volume content of steel fibers increases, with a modulus increase of 16.1% at the volume fraction of 3%. However, the maximum increase in the modulus of elasticity of PVA fiber-containing concrete, similar to its tensile strength, occurred at the lowest volume fraction of fibers, with an increase of 2.9% at the volume fraction of 0.25%. Moreover, the highest modulus improvement in the concrete containing hybrid fibers occurred at the combination of 0.25% PVA and 0.75% steel fibers as 0.47%.
5. The addition of steel fibers to RPC increases its density, with an increase of 10.3% in concrete density at 3% volume content of fibers in this study. Furthermore, the specimens containing PVA and hybrid fibers had a lower density relative to plain concrete, with the concrete containing 0.25% PVA fibers demonstrating the greatest reduction in the concrete density among all the specimens.
6. In general, the failure of RPC specimens is a brittle one. Using steel fibers, PVA fibers, and hybrid fibers somewhat enhanced the type of failure and provided warning signs before the final failure of concrete. The failure mode in plain RPC is in the form of symmetric conical and splitting; in the concrete containing steel and hybrid fibers, it is in the form of surface spalling; and in the concrete containing PVA fibers, it is in the form of shear failure.
7. Heat treatment curing improves the compressive strength of RPC, especially in steel fiber-containing concrete. The highest compressive strength improvement due to heat treatment belonged to the cubic specimens containing 3% steel fibers and was 37.3%. Moreover, heat treatment had no effect on improving modulus of elasticity, and even led to the reduction of the concrete modulus of elasticity (even though to a small extent).
8. The coefficient for compressive strength conversion from cubic to cylindrical for the RPC specimens subjected to STD and heat treatment curing was independent of fiber type and on average equal to 1 and 1.2, respectively.

Compliance with ethical standards

The authors of this paper certify that they have NO affiliations with or involvement in any organization or entity with any financial interest, or non-financial interest in the subject matter or materials discussed in this manuscript.

References

Afroughsabet, V., Biolzi, L. and Ozbakkaloglu, T. (2016), "High-performance fiber-reinforced concrete: a review", *J. Mater. Sci.*, **51**(14), 6517-6551.

Ahmad, S., Zubair, A. and Maslehuddin, M. (2015), "Effect of key mixture parameters on flow and mechanical properties of reactive powder concrete", *Constr. Build. Mater.*, **99**, 73-81.

Aitcin, P.C. (1995), "Concrete the most widely used construction materials", *ACI SP*, **154**, 257-66.

An, M.Z., Zhang, L.J. and Yi, Q.X. (2008), "Size effect on compressive strength of reactive powder concrete", *J. China Univ. Min. Technol.*, **18**(2), 279-282.

Arslan, M.E. (2016), "Effect of basalt fibers on fracture energy and mechanical properties of HSC", *Comput. Concrete*, **17**(4), 553-566.

ASTM C1240 (2015), Standard Specification for Silica Fume Used in Cementitious Mixtures, ASTM International, West Conshohocken, PA, United States.

ASTM C1437 (2015), Standard Test Method for Flow of Hydraulic Cement Mortar, ASTM International, West Conshohocken, PA, United States.

ASTM C150 (2016), Standard Specification for Portland Cement, ASTM International, West Conshohocken, PA, United States.

ASTM C192 (2016), Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory, ASTM International, West Conshohocken, PA, United States.

ASTM C39 (2016), Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens, ASTM International, West Conshohocken, PA, United States.

ASTM C469 (2014), Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression, ASTM International, West Conshohocken, PA, United States.

ASTM C494 (2016), Standard Specification for Chemical Admixtures for Concrete, ASTM International, West Conshohocken, PA, United States.

ASTM C496 (2011), Standard Specification for Splitting Tensile Strength of Cylindrical Concrete Specimens, ASTM International, West Conshohocken, PA, United States.

Bian, H., Hannawi, K., Takarli, M., Molez, L. and Prince, W. (2016), "Effects of thermal damage on physical properties and cracking behavior of ultrahigh-performance fiber-reinforced concrete", *J. Mater. Sci.*, **51**(22), 10066-10076.

Blais, P.Y. and Couture, M. (1999), "Precast, prestressed pedestrian bridge: World's first reactive powder concrete structure", *PCI J.*, **44**(5), 60-71.

Bonneau, O., Lachemi, M., Dallaire, E., Dugat, J. and Aïtcin, P.C. (1997), "Mechanical properties and durability of two industrial reactive powder concretes", *ACI Mater. J.*, **94**(4), 286-290.

Boughanem, S., Jesson, D.A., Mulheron, M.J., Smith, P.A., Eddie, C., Psomas, S. and Rimes, M. (2015), "Tensile characterisation of thick sections of Engineered Cement Composite (ECC) materials", *J. Mater. Sci.*, **50**(2), 882-897.

Cwirzen, A. (2007), "The effect of the heat-treatment regime on the properties of reactive powder concrete", *Adv. Cement Res.*, **19**(1), 25-34.

Cwirzen, A. and Penttala, V. (2006), "Effect of increased aggregate size on the mechanical and rheological properties of RPC", *Proceedings of Second International Symposium on Advances in Concrete through Science and Engineering*, Quebec, Canada.

Cwirzen, A., Penttala, V. and Vornanen, C. (2008), "Reactive powder based concretes: Mechanical properties, durability and hybrid use with OPC", *Cement Concrete Res.*, **38**(10), 1217-1226.

EN, B. (2009), *Testing Hardened Concrete-Part 3: Compressive Strength of Test Specimens*, British Standard Institution, London.

Fallah, S. and Nematzadeh, M. (2017), "Mechanical properties and durability of high-strength concrete containing macro-polymeric and polypropylene fibers with nano-silica and silica fume", *Constr. Build. Mater.*, **132**, 170-187.

Garas, V.Y., Kurtis, K.E. and Kahn, L.F. (2012), "Creep of UHPC in tension and compression: effect of thermal treatment", *Cement Concrete Compos.*, **34**(4), 493-502.

Graybeal, B. and Davis, M. (2008), "Cylinder or cube: strength testing of 80 to 200 MPa (11.6 to 29 ksi) ultra-high-performance fiber-reinforced concrete", *Mater. J.*, **105**(6), 603-609.

Hasan-Nattaj, F. and Nematzadeh, M. (2017), "The effect of forta-ferro and steel fibers on mechanical properties of high-strength concrete with and without silica fume and nano-silica", *Constr. Build. Mater.*, **137**, 557-572.

He, K., Yang, H., Jia, F.F., Wang, E.P., Lu, Z.B., Liu, J.Y. ... and Dong, Q.X. (2014), "Experimental study on mechanical properties of synthetic macro-fiber reinforced reactive powder concrete", *Appl. Mech. Mater.*, **496**, 2402-2406.

Lee, M.G., Wang, Y.C. and Chiu, C.T. (2007), "A preliminary study of reactive powder concrete as a new repair material", *Constr. Build. Mater.*, **21**(1), 182-189.

Lee, N.P. and Chisholm, D.H. (2005), "Study report reactive powder concrete", *BRANZ*, **1**, 146.

Nematzadeh, M. and Hasan-Nattaj, F. (2017), "Compressive stress-strain model for high-strength concrete reinforced with Forta-Ferro and steel fibers", *J. Mater. Civil Eng.*, **29**(10), 04017152.

Nematzadeh, M. and Poorhosein, R. (2017), "Estimating properties of reactive powder concrete containing hybrid fibers using UPV", *Comput. Concrete*, **20**(4), 491-502.

Neville, A.M. (1995), *Properties of Concrete*, Vol. 4, Longman, London.

Puntke, W. (2002), "Wasseranspruch von feinen Kornhaufwerken", *Beton-Dusseldorf*, **52**(5), 242-249.

Richard, P. and Cheyrezy, M. (1995), "Composition of reactive powder concretes", *Cement Concrete Res.*, **25**(7), 1501-1511.

Russell, H.G. and Graybeal, B.A. (2013), "Ultra-high performance concrete: A state-of-the-art report for the bridge community", No. FHWA-HRT-13-060.

Sanchayan, S. and Foster, S.J. (2016), "High temperature behaviour of hybrid steel-PVA fibre reinforced reactive powder concrete", *Mater. Struct.*, **49**(3), 769-782.

Schachinger, I., Schubert, J. and Mazanec, O. (2004), "Effect of mixing and placement methods on fresh and hardened ultra high performance concrete (UHPC)", *Proceedings of the International Symposium on Ultra High Performance Concrete*, Kassel, Germany.

Shaheen, E. and Shrive, N.G. (2006), "Optimization of mechanical properties and durability of reactive powder concrete", *ACI Mater. J.*, **103**(6), 444-451.

Tam, C.M., Tam, V.W. and Ng, K.M. (2012), "Assessing drying shrinkage and water permeability of reactive powder concrete produced in Hong Kong", *Constr. Build. Mater.*, **26**(1), 79-89.

Tuan, B.L.A., Tesfamariam, M.G., Hwang, C.L., Chen, C.T., Chen, Y.Y. and Lin, K.L. (2014), "Effect of fiber type and content on properties of high-strength fiber reinforced self-consolidating concrete", *Comput. Concrete*, **14**(3), 299-313.

Wille, K., Naaman, A.E., El-Tawil, S. and Parra-Montesinos, G.J. (2012), "Ultra-high performance concrete and fiber reinforced concrete: achieving strength and ductility without heat curing", *Mater. Struct.*, **45**(3), 309-324.

Williams, E.M., Graham, S.S., Akers, S.A., Reed, P.A. and Rushing, T.S. (2010), "Constitutive property behavior of an ultra-high-performance concrete with and without steel fibers", *Comput. Concrete*, **7**(2), 191-202.

Wu, Z., Shi, C., He, W. and Wu, L. (2016), "Effects of steel fiber content and shape on mechanical properties of ultra high performance concrete", *Constr. Build. Mater.*, **103**, 8-14.

Yazıcı, H., Deniz, E. and Baradan, B. (2013), "The effect of autoclave pressure, temperature and duration time on mechanical properties of reactive powder concrete", *Constr. Build. Mater.*, **42**, 53-63.

Yazıcı, H., Yardımcı, M.Y., Yiğiter, H., Aydın, S. and Türkel, S. (2010), "Mechanical properties of reactive powder concrete containing high volumes of ground granulated blast furnace slag", *Cement Concrete Compos.*, **32**(8), 639-648.

Zdeb, T. (2013), "Ultra-high performance concrete–properties and technology", *Bull. Polish Acad. Sci., Tech. Sci.*, **61**(1), 183-193.

Zong-cai, D., Daud, J.R. and Chang-xing, Y. (2014), "Bonding between high strength rebar and reactive powder concrete", *Comput Concrete*, **13**(3), 411-421.

CC