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Estimating properties of reactive powder concrete containing hybrid fibers using UPV

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Abstract. In this research, the application of ultrasonic pulse velocity (UPV) test as a nondestructive method for estimating some of the mechanical and dynamic properties of reactive powder concrete (RPC) containing steel and polyvinyl alcohol (PVA) fibers, as well as their combination was explored. In doing so, ten different mix designs were prepared in 19 experimental groups of specimens containing three different volume contents of steel fibers (i.e., 1, 2, and 3 %) and PVA fibers (i.e., 0.25, 0.5, and 0.75 %), as well as hybrid fibers (i.e., 0.25-0.75, 0.5-0.5, and 0.75-0.25 %). The specimens in these groups were prepared under the two curing regimes of normal and heat treatment. Moreover, the UPV test results were employed to estimate the compressive strength, dynamic modulus, shear modulus, and Poisson's ratio of the RPC concrete and to investigate the quality level of the used concrete. At the end, the effect of the specimen shape and in fact the measuring distance length on the UPV results was explored. The results of this research suggest that the steel fiber-containing RPC specimens demonstrate the highest level of ultrasonic pulse velocity as well as the highest values of the mechanical and dynamic properties. Moreover, heat treatment has a positive effect on the density, UPV, dynamic modulus, Poisson's ratio, and compressive strength of the RPC specimens, whereas it leads to a negligible increase or decrease in the shear modulus and static modulus of elasticity. Furthermore, the specimen shape affects the UPV of fiber-lacking specimens while negligibly affecting that of fiber-reinforced specimens.

Keywords: reactive powder concrete; nondestructive test; ultrasonic pulse velocity; compressive strength; dynamic modulus; hybrid fibers; heat treatment

1. Introduction

Reactive powder concrete (RPC) is a new type of cementitious material possessing ultra-high strength and low porosity and having been developed in the mid-1990s (Zong *et al*. 2014). The constituents of this concrete type are Portland cement, silica fume, silica sand, silica powder, superplasticizer, water, and steel fibers (Williams *et al*. 2010). To improve consistency in the production of RPC, coarse aggregate was eliminated entirely, and particles of up to 600 μm in diameter replaced them in the concrete mixture. Moreover, to obtain an ultra-dense mix, the grading of its constituents can be optimized. Heat treatment together with the application of pressure to RPC during its early age has a considerable effect on the concrete compressive strength and modulus of elasticity improvement through enhancing its microstructure. By applying the general principles outlined here, RPC with a high compressive strength can be produced; however, its ductility is still unimproved relative to ordinary concretes, and adding steel fibers with an appropriate length and diameter can increase the ductility and energy absorption of this concrete and prevent its brittle failure, as in high-strength concrete (Rahdar *et al*. 2016, Nematzadeh and Hasan-Nattaj 2017).

Today, due to issues such as uncertainty regarding the strength of concrete specimens, local damages induced by weathering, fire, and chemical effects, civil engineers require reliable and advanced methods for evaluating and controlling concrete quality. Among these various methods, the nondestructive ones has received greater interest due to their rapidity in use and simplicity, and being cheaper in comparison with the destructive ones, as well as having been established as being useful in the inspection and evaluation of the quality of old concrete structures. Nondestructive testing methods are employed for evaluating the quality and measuring the mechanical properties of structures without the need of test specimens. There are several well-known nondestructive methods for cement-containing mixtures such as ultrasonic pulse velocity (UPV), impact-echo, ultrasonic pulse echo, and resonant frequency for concrete structures. Ultrasonic wave-based methods employed for determining the properties of the hardening and hardened cementitious materials are preferred over other conventional methods due to the close relevance of the transition time, damping, and frequency content of the ultrasonic waves emitted into the material with the elastic properties of concrete or mortar (Wang *et al*. 2010). At the moment, one of the preferred nondestructive methods capable of being applied to assess the quality and consistency of concrete as well as to estimate the compressive strength and elastic properties of concrete is

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Table 1 Physical and chemical properties of cement and silica fume

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
	Compounds	
C_3S	56.9	-
C_2S	15.83	-
C_3A	4.19	-
C_4AF	9.58	-
	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

Table 2 Characteristics of silica mineral

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	0.13	0.4

the ultrasonic pulse velocity (UPV) test (Krautkramer *et al*. 2013); a part of some existing national standards is devoted to experimenting and investigating the application of this method to concrete. However, only a handful of international standards and codes of practice have addressed the prediction of concrete mechanical properties using the ultrasonic pulse velocity, among which the BS EN 13791 can be mentioned that investigates the in-situ compressive strength using UPV with the help of calibrated curves achieved from core tests. Moreover, ACI 228.1R estimates the concrete compressive strength based on in-situ tests by employing statistical methods or regression analysis and the standard deviation of the experimental values, whereas ASTM C597 and DIN/ISO 8047 lack a detailed procedure to evaluate concrete strength. This is due to the fact that there is not a standard correlation between the concrete mechanical properties including compressive strength and UPV as a result of the concrete nonhomogeneity as well as the nonlinear stress-strain relationships of the materials; hence, this correlation must be calibrated for every specific concrete mix (BS EN 13791, Popovics *et al*. 1997). By reviewing the associated literature (Washer *et al*. 2004, Malhotra and Carino 2003, Lia and Sun 2010), it can be found out that numerous studies have been conducted on the correlation of the ultrasonic pulse velocity and mechanical properties such as modulus of elasticity and compressive strength in a variety of existing concrete types, and equations have also been proposed. Furthermore, the limitations related to this method are described in detail in the literature (Malhotra and Carino 2003, BS. Part 203).

The basic theory of ultrasonic wave distribution in concrete is described in detail by Jones (1962), who identified the concrete elastic stiffness and mechanical properties as the factors affecting the velocity of ultrasonic pulses in concrete. Therefore, the physical properties of cement paste, concrete age, water-to-cement ratio, aggregate type used in concrete, curing regime, measuring distance length, mixture composition, moisture level, and the temperature of the measurement region are some of the factors capable of affecting the velocity of ultrasonic pulse in concrete (Lin *et al*. 2007, Neville 1995). Hassan and Jones (2012) employed two nondestructive methods of UPV and resonant frequency in their research to determine the Poisson's ratio and modulus of elasticity of UHPFRC (ultra-high performance fiber-reinforced concrete) containing 2% steel fibers. Comparing the dynamic results of the resonant frequency test with the static results of the ultrasonic pulse velocity test, obtaining a close agreement between the two results and applying the empirical equations proposed in the works of others, they found that the ultrasonic wave propagation to determine the elastic properties of ultra-high performance fiber-reinforced concrete is a very simple, reliable and cost-effective method. Through investigating the experimental results of the velocity of longitudinal and shear waves of cylindrical and cubic RPC specimens, Washer *et al*. (2004) reached the conclusion that the wave velocity depends on the presence of fibers, curing regime, modulus of elasticity, and density of concrete. They also suggested that the propagation of ultrasonic waves at high frequencies such as 1 MHz or above can be launched and received, and that increasing the testing frequency leads to a slight increase of both the longitudinal and shear velocity of ultrasonic waves. Furthermore, ACI 228.1R states that this test demonstrates a good performance relative to other in-situ tests such as rebound number (ASTM C805) and penetration resistance (ASTM C803) tests, and that its results provide much more accurate estimations particularly for new constructions. On the other hand, unlike maturity test (ASTM C1074), this test does not require verification by other tests.

Given the scarcity of published resources in the literature regarding the application of UPV test specially to determine the elastic and dynamic properties of RPC, in this study, the ultrasonic pulse velocity test was employed as a qualitative method in order to explore the homogeneity and integration of RPC specimens and to predict the dynamic modulus, shear modulus, and static Poisson's ratio, as well as to present a relationship between that and the compressive strength of RPC specimens. To do so, ten RPC mix designs in 19 experimental groups containing different contents of steel and polyvinyl alcohol (PVA) fibers as well as their hybridization were prepared under the two normal and heat curing regimes. Moreover, the effect of specimen shape on the ultrasonic pulse velocity of RPC is investigated in this paper.

2. Experimental study

2.1 Materials

2.1.1 Cement and silica fume

Since the best results so far in terms of technological parameters and mechanical properties of matured materials have been obtained by using Type I Portland cement (Cwirzen *et al*. 2008), in this study, Type I Portland cement (CEM-I 42.5 N) in accordance with the ASTM C150 standard was also used. Silica fume being a pozzolanic mineral admixture consisting of ultrafine spherical particles and containing high content of amorphous silicon dioxide was added to the concrete mix as a secondary cementitious material. The silica fume used is a light-gray amorphous type with the purity and particle diameter of 90% and 0.2 µm, respectively, complying with the ASTM C1240 standard. The chemical and physical properties of the cement and silica fume are listed in Table 1.

2.1.2 Silica sand and silica powder

The biggest particle size of powder materials in the RPC belongs the silica sand, possessing the maximum particle size and purity of 600 μm and >99%, respectively, in this study.

Furthermore, in order to enhance the packing density of the binder matrix and activate the reactivity of the RPC during the hydration process of the cement under heat treatment, silica powder as micro-fillers with the maximum and mean nominal particles size of 20 and 5 μm, respectively, with the purity of >99 % were used. Table 2 presents the chemical properties of the silica sand and silica powder.

2.1.3 Fibers

Two types of fibers including steel and PVA fibers were used here. The steel fibers used were 25×0.7 mm hooked-end sinusoidal fibers coated with a thin layer of copper with the maximum tensile strength, modulus of elasticity, and specific gravity of 1140 MPa, 200 GPa, and 7.85, respectively. 6×0.011 mm bunchy monofilament type synthetic polyvinyl alcohol fibers with the maximum tensile strength, modules of elasticity, and specific gravity of 966 MPa, 25.5 GPa, and 1.3, respectively, were utilized. The shape of the fibers is shown in Fig. 1.

(a) Steel fiber (b) Polyvinyl alcohol fiber

Fig. 1 The shape of fibers

Table 3 Information of RPC specimens

Series	Specimen ID	Type of curing regime	Shape of specimen	Steel Fiber (%)	PVA fiber (%)
RPC1	CTRL-HWC-Cy	Hot water curing	Cylindrical	-	-
RPC2	CTRL-NC-Cy	Normal curing	Cylindrical	-	-
RPC3	CTRL-HWC-Cu	Hot water curing	Cubic	-	-
RPC4	CTRL-NC-Cu	Normal curing	Cubic	-	-
RPC5	ST1-HWC-Cy	Hot water curing	Cylindrical	1	-
RPC6	ST2-HWC-Cy	Hot water curing	Cylindrical	2	-
RPC7	ST3-HWC-Cy	Hot water curing	Cylindrical	3	-
RPC8	ST3-NC-Cy	Normal curing	Cylindrical	3	-
RPC9	ST3-HWC-Cu	Hot water curing	Cubic	3	-
RPC10	ST3-NC-Cu	Normal curing	Cubic	3	-
RPC11	P.S0.75-HWC-Cy	Hot water curing	Cylindrical	0.75	0.25
RPC12	P.S0.5-HWC-Cy	Hot water curing	Cylindrical	0.5	0.5
RPC13	P.S0.25-HWC-Cy	Hot water curing	Cylindrical	0.25	0.75
RPC14	PVA0.25-HWC-Cy	Hot water curing	Cylindrical	-	0.25
RPC15	PVA0.5-HWC-Cy	Hot water curing	Cylindrical	-	0.5
RPC16	PVA0.75-HWC-Cy	Hot water curing	Cylindrical	-	0.75
RPC17	PVA0.75-NC-Cy	Normal curing	Cylindrical	-	0.75
RPC18	PVA0.75-HWC-Cu	Hot water curing	Cubic	-	0.75
RPC19	PVA0.75-NC-Cu	Normal curing	Cubic	-	0.75

*Mix design: Cement=1, Silica fume=0.24, Quartz sand=0.95, Quartz powder=0.084, Super Plasticizer=0.032, water=0.22

2.1.4 Superplasticizer

Producing RPC with a very low water-to-cement ratio and desired workability is only feasible by using superplastcizers. Hence, in this study the third generation superplasticizers based on polycarboxylate ether having the solid content of 42% and density of 1.1 g/cm^3 in the PH

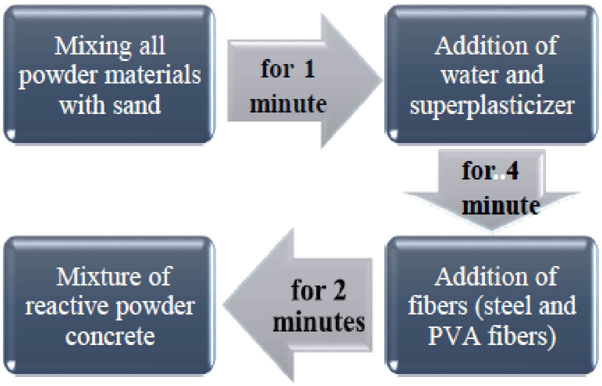


Fig. 2 Mixing procedure of reactive powder concrete

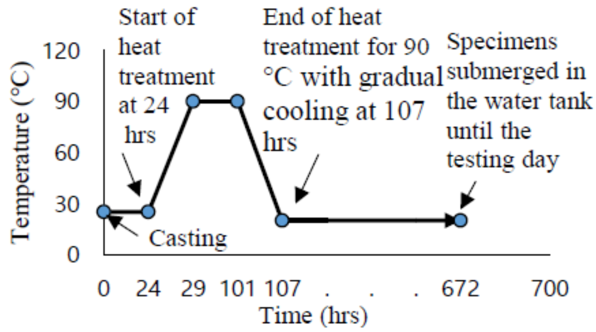


Fig. 3 Heat regime employed for curing of RPC specimens

range of 6-8 were added to all the mixtures as a cement weight percentage. Based on the ASTM C494 standard, this superplastcizer is an F-type.

2.2 Mix design

The mix design of RPC proves to be very challenging; thus in this study, a mixture of reactive powder concrete was designed with trial and error considering some of the proposed proportions published in the literature (Shaheen and Shirve 2006, Tam *et al*. 2010). The details of the reactive powder concrete mix design are given in Table 3 as weight-to-cement weight ratios. The water-to-cementitious materials ratio was considered 0.18 in all the mixes. As can be seen in Table 3, 19 series of reactive powder concrete mixtures including the total of 67 concrete specimens consisting of 49 cylindrical and 18 cubic specimens were prepared using different volume fractions of steel fibers (1, 2, and 3 %) and PVA fibers (0.25, 0.5, and 0.75 %), as well as their hybridization (total fiber volume fraction of 1 %) under the two curing regimes of normal and hot water curing to investigate the effect of factors such as the type and volume fraction of fibers, curing regime, and specimen shape on the mechanical properties and ultrasonic pulse velocity of RPC specimens. To reduce error in reporting the results, 4 cylindrical and 3 cubic concrete specimens were produced for each mix design.

For a better and faster understanding of the apparent characteristics of the specimens and the curing regime employed, the identification codes of specimens are provided in Table 3, in which the letters of the first part denote the type of fibers used in RPC concrete (CTRL, ST, PVA, and P.S represents the fiber-lacking and steel fiber, PVA fiber, and hybrid fiber-containing specimens, respectively), and the number following indicate the volume fraction of fibers used in concrete. In the specimens with hybrid fibers, the number following P.S indicates the volume fraction of steel fibers in the total fiber volume fraction of 1% used, with the remaining volume being occupied by the PVA fibers. The second group of letters represents the curing regime applied to the specimens (NC and HWC indicate the normal curing and hot water curing, respectively), and the final letters specify the shape of concrete specimens (Cy and Cu denote cylindrical and cubic specimens, respectively).

2.3 Mixing and production of specimens and curing

Since reactive powder concrete is composed of ultrafine aggregates, the conventional mixing procedure does not apply here. The mixing sequence used for the RPC concrete is shown in Fig. 2. This mixing sequence was performed in order to homogenize the cementitious materials and obtain a better scattering of fibers in accordance with the studies of (Tam *et al*. 2010, Yazıcı *et al*. 2010). As can be seen in Fig. 2, first the cement, silica fume, silica powder, and fine silica sand were mixed with each other for about 1 min, then the water-superplasticizer mixture was added to the previous mix and the blending continued for 4 min, and when the mixture becomes flowable, fiber(s) were scattered randomly throughout the cementitious materials and the mixing procedure continued for 2 more minutes. The mixing procedure was performed by a pan-type mixer with the capacity of 0.02 m^2 for about 12 min for each mixture (including the duration of pouring the materials into the mixer). After the mixing completed, the workability of the fresh concrete was measured using the mini-flow table test according to the ASTM C1437 standard.

The fresh reactive powder concrete mixture was poured in two layers into oil-covered metal molds, and then, in order to compact the steel fiber-containing specimens, a hand-operated square-section tamping rod was utilized, and to compact the PVA fiber- and hybrid fiber-containing specimens, hand operations together with a vibrating table was employed. At the end, in order to prevent the release of concrete moisture to the ambient air and also to prevent the grinding of the specimen surface for providing a smooth surface for conducting ultrasonic pulse velocity and preventing stress concentration at the specimen surface during compressive testing, the filled molds were sealed with thick circular steel covers.

The curing procedure was performed by two different methods on the RPC specimens for at least 28 days. The first method known as normal curing involves demolding specimens 24 hours after casting and submerging them in a tank filled with lime water with the temperature level of 20ºC, complying with the ASTM C192 standard. The second method is known as hot water curing which involves heat treatment at the temperature of 90ºC for 72 hours. The heat treatment used in the second curing method is presented in Fig. 3.

The water surrounding the specimens was warmed with the temperature increase rate of 20ºC/h up to the maximum

Fig. 4 Ultrasonic pulse velocity testing device and location of transducer placement on RPC specimen

temperature of 80-90ºC, as can be seen in Fig. 3. Subsequently, the specimens were left for 3 h in the hot water tank to be gradually cooled after the end of curing, and then they were placed in the laboratory environment for another 3 h to reach the ambient temperature. Finally, like the specimens cured by the first method, those cured by this method are kept submerged in a tank filled with 20ºC water until the testing day. This heat curing procedure was selected based on extensive research whose results are reported in the literature (Yazıcı *et al*. 2010, Cwirzen 2007).

2.4 Testing procedure

First, the nondestructive ultrasonic pulse velocity test was carried out after at least 28 days of curing prior to the compressive testing on the cylindrical and cubic concrete specimens in compliance with the ASTM C597 standard to determine the ultrasonic pulse velocity using the direct transmission method being the most precise method of the three described in the ACI 228.2R. This test was conducted by employing a Portable Ultrasonic Nondestructive Digital Indicating Tester (PUNDIT, Model PC 1012), shown in Fig. 4, and the reported results were the average of the obtained results. In this method, electrical impulses are generated from a specific center frequency by a pulse generator, and an electro-acoustical transducer located at one side and in contact with the specimen surface converts them to elastic waves propagating throughout the entire specimen. The receiver placed at the other side of the specimen receives the mechanical energies of the propagated waves and converts them to electrical energy of the same frequency. The time it takes for the ultrasonic waves to pass through the whole length of specimen is measured electrically. The read transmission time displayed on the digital screen of the oscillo-scope device is in microseconds with the precision of 0.1 microsecond (see Fig. 4). The pulse transmission velocity was calculated considering the distance between the transducer faces (L) in mm and the transmission time reading of ultrasonic pulses (t) in the concrete specimen via the mentioned device in terms of microseconds, and then, using $V=L/T$ formula, the velocity was expressed in km/s. The frequency of the longitudinal pulses selected for all the specimens is 54 kHz, and considering the results reported by other researchers, the 40-80 kHz range of ultrasonic pulses seems like an appropriate one to evaluate concrete (Bungey *et al*. 2006, Solis-Carcaño and Moreno 2008).

In all the tests, to ensure the proper connection of the transducers to the specimen surface and to facilitate the ultrasonic energy transfer from the transducer to specimen, a thin layer of couplant (solid Vaseline) was used. Prior to any measurements, the device was calibrated with a cylindrical Perspex bar with a specific pulse transfer time (t_{us}). It is seen in Fig. 4 that the location of the transducers with 50 mm diameter was selected at the surface center of both the specimen ends. For every test on the concrete specimens, three measurements were performed by switching the location of transducers between the two opposite ends (faces).

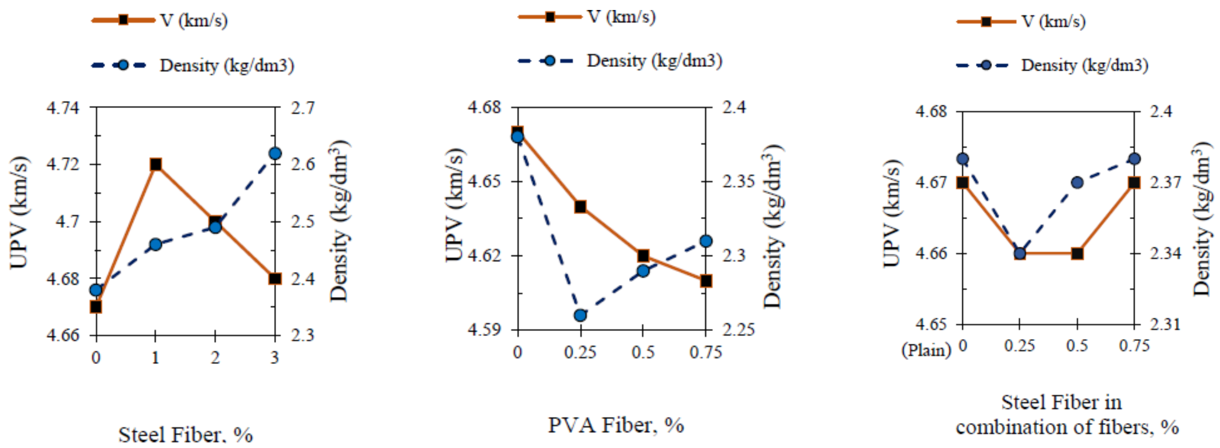
On the same day the nondestructive UPV test was conducted, the compressive strength and elastic modulus tests were also performed as described below.

The compressive strength test was conducted on the cylindrical and cubic reactive powder concrete specimens after a minimum 28-day curing period with the loading rates of 1.96 and 2.5 kN/s, respectively, within the allowable ranges specified by the ASTM C39 and BS EN 12390-3 standards. This test was performed using a 2000-kN digital compressive testing machine on the groups of specimens consisting of four and three specimens for the cylindrical and cubic specimens, respectively. The secant modulus of elasticity of the cylindrical concrete specimens was determined according to the method specified by the ASTM C469 standard. The loading rate for the elastic modulus test was set the same as the one selected for the compressive strength test. In order to obtain equal testing conditions, all the tests on the specimens under study were carried out in the saturated surface dry (SSD) condition.

3. Results and discussion

3.1 Effect of type and amount of fibers on UPV, density, and flow ability

Table 4 and Fig. 5 present the density and UPV of the hot water-cured RPC specimens containing steel and PVA fibers as well as their hybrid form at different fiber volume fractions. Concrete density depends on the type and volume fraction of the fibers used, and variations of the wave velocity represent the variations of the modulus of elasticity and density of materials (ACI 228.2R 2004, Fallah and Nematzadeh 2017, Hasan-Nattaj and Nematzadeh 2017). It is evident from Fig. 5 that the density of steel fiber-containing specimens demonstrates an ascending trend as the volume fraction of fibers increases, with an increase of 10.3 % in the density relative to the ordinary (without fiber) specimen for the fiber volume fraction of 3%. This increased density is due to the higher density of these fibers relative to that of concrete material. Furthermore, the ultrasonic pulse velocity demonstrates an ascending trend up to the fiber volume content of 1%; above which, however, a descending trend is seen suggesting that at high volume fractions of steel fibers, the concrete porosity increases. Since UPV is a function of the volumetric concentration of the concrete constituents (Albano *et al*. 2009), smaller velocity values may represent the lower solid phase and volume of hydration products as well as higher volume of voids in the fiber-containing specimen due to



(a) Steel fiber (b) PVA fiber (c) Hybridization of fibers

Fig. 5 Ultrasonic pulse velocity and density of cylindrical RPC specimens cured in hot water vs. volume fraction of fibers

Table 4 Results of mechanical properties and ultrasonic pulse velocity of RPC specimens

Series	Specimen ID	Compressive strength		Ultrasonic pulse velocity		Modulus of elasticity		Density	Flow
		Ave (MPa)	COV (%)	(km/s)	COV (%)	Ave (GPa)	COV (%)	Ave (kg/m^3)	Ave (mm)
RPC1	CTRL-HWC-Cy	121.74	3.21	4.67	2.77	43.78	5.32	2382	180
RPC2	CTRL-NC-Cy	115.32	3.4	4.65	1.27	46.21	2.21	2309	180
RPC3	CTRL-HWC-Cu	115.29	4.56	4.71	2.8	-	-	2468	180
RPC4	CTRL-NC-Cu	95.25	4.36	4.69	1.7	-	-	2377	180
RPC5	ST1-HWC-Cy	133.93	4.80	4.72	3.16	46.44	0.48	2464	160
RPC6	ST2-HWC-Cy	130.49	5.20	4.70	2.84	49.23	1.31	2491	170
RPC7	ST3-HWC-Cy	124.25	6.70	4.68	2.87	50.81	4.32	2627	175
RPC8	ST3-NC-Cy	109.86	5.7	4.66	2.29	50.03	2.45	2567	175
RPC9	ST3-HWC-Cu	128.30	1.76	4.70	2.57	-	-	2648	175
RPC10	ST3-NC-Cu	93.44	2.58	4.67	2.41	-	-	2571	175
RPC11	P.S0.75-HWC-Cy	120.75	6.17	4.47	2.84	44.99	5.54	2381	140
RPC12	P.S0.5-HWC-Cy	118.01	5.92	4.66	3.9	43.18	6.91	2371	130
RPC13	P.S0.25-HWC-Cy	117.25	2.56	4.66	3.4	42.00	6.46	2349	110
RPC14	PVA0.25-HWC-Cy	113.00	4.5	4.64	3.74	45.07	7.24	2262	150
RPC15	PVA0.5-HWC-Cy	107.41	5.74	4.62	4.6	43.87	5.03	2295	140
RPC16	PVA0.75-HWC-Cy	105.59	6.26	4.61	3.35	42.28	8.17	2315	120
RPC17	PVA0.75-NC-Cy	104.02	3.72	4.60	3.15	43.41	6.72	2259	120
RPC18	PVA0.75-HWC-Cu	101.50	2.56	4.63	3.47	-	-	2404	120
RPC19	PVA0.75-NC-Cu	88.54	1.43	4.61	2.96	-	-	2334	120

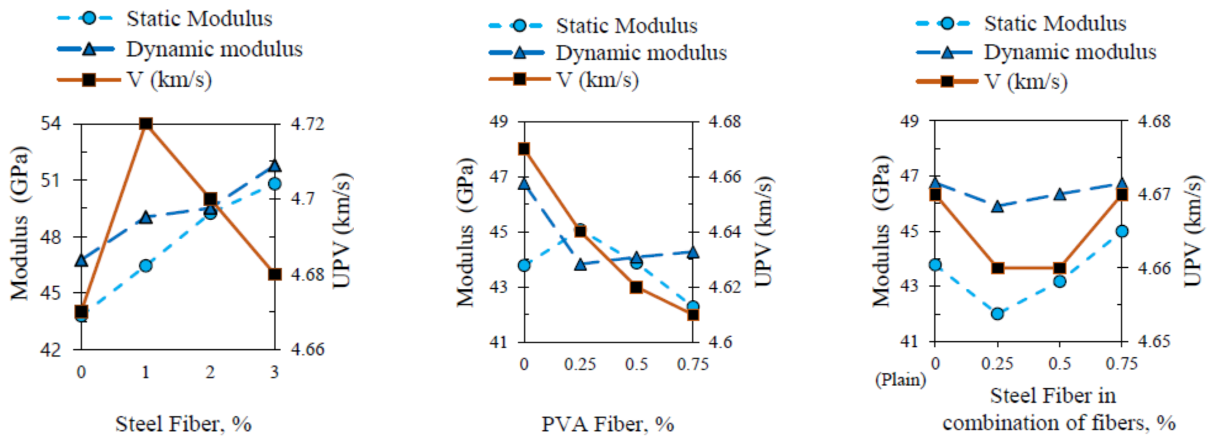
incomplete mixing or long length of steel fibers being one of the factors underlying these voids. The highest velocity value of 4.72 km/s was obtained for the specimen containing 1% fibers.

With respect to Fig. 5, the PVA fiber-containing specimens possess a lower density relative to the ordinary concrete, which can be attributed to the low specific gravity of PVA fibers. Moreover, as the volume fraction of PVA fibers increases, the ultrasonic pulse velocity decreases, with the minimum velocity of 4.61 km/s belonging to the specimen containing 0.75% PVA fibers, while for the ordinary RPC specimen, this velocity is 4.67 km/s. The reasons for this trend in the UPV values are the ones discussed above. The results presented in Table 4 demonstrate that the PVA fiber-containing specimens have the lowest ultrasonic pulse velocity values among all the RPC specimens, with the cylindrical specimen reinforced with 0.75% PVA fibers under normal curing showing the lowest UPV value of 4.60 km/s.

It is also found from the results presented in Table 4 that the range of ultrasonic pulse velocity in the hybrid fiber-containing specimens varies between the UPV of the steel fiber-reinforced and that of the PVA fiber-reinforced specimens, and increasing the volume content of steel fibers does not show a noticeable effect on the UPV, contrary to what is seen for density. The coefficient of variation (COV) of UPV for all the RPC specimens is provided in Table 4, where it is seen that the COV obtained from the specimens tested from each mix design is less than 5% in generally, indicating the relatively small variations of the UPV method and the relatively appropriate homogeneity of the produced concrete specimens.

To evaluate the quality of reactive powder concrete through UPV method, the ranges presented by different codes or other researchers can be employed. Table 5 provides the range given in IS 13311-1 together with the ranges proposed by Neville (1995) and Whitehurst (1951). Regarding the results reported in Table 4, the ultrasonic pulse velocity of the RPC concretes containing different types and contents of fibers varies in the range 4.60-4.72 km/s, indicating an excellent class in terms of quality and physical conditions for the RPC specimens based on the presented classification ranges. In addition, as suggested by Malhorta (1976), concrete with good durability is obtained for a pulse velocity in the range of 3660-4575 m/s, thus the RPC mixtures can be regarded as durable mortars (Mohseni *et al*. 2015). Note that all the tested specimens were in the saturated condition, in which it is likely to obtain the ultrasonic pulse velocity values of up to 5% above those of the dry condition.

It is found from the results given in Table 4 that the specimens cured in hot water exhibit higher density and ultrasonic pulse velocity relative to those of the specimens



(a) Steel fiber (b) PVA fiber (c) Hybridization of fibers

Fig. 6 Static and dynamic modulus of elasticity of hot water-cured cylindrical RPC specimens

Table 5 Classification of concrete quality considering the UPV values adopted from the literature

IS and Neville		Whitehurst	
UPV (km/s)	Class	UPV (km/s)	Class
Above 4.5	Excellent	Above 4.5	Excellent
3.5 to 4.5	Good	3.5 to 4.5	Good
3.0 to 3.5	Medium	3.0 to 3.5	Doubtful
Below 3.0	Poor	2.0 to 3.0	Poor
		Below 2.0	Very Poor

cured under standard conditions. The main reason for this is the fast hydration processes of the cementitious materials in the form of the pozzolanic reaction of silica fume and silica powder with $Ca(OH)_2$, and subsequently the formation of a denser binder matrix and the increase of the solid phase in RPC, which in turn increases the density up to the maximum value of 3.8% in the fiber-lacking cubic specimen and the UPV up to 0.65% in the cubic specimen containing 3% steel fibers. By comparing the results of cubic and cylindrical specimens presented in Table 4 with each other, it can be concluded that the specimen shape and in fact the measuring distance length affect the UPV of fiber-lacking RPC specimens, while it has a negligible effect on the UPV of the fiber-containing RPC specimens. In this regard, ASTM C597 considers UPV as being independent from the specimen dimensions, while ACI 228.1R considers the geometry of the test specimens as contributing to the ultrasonic pulse velocity. However, the minimum dimension of test specimens must be greater that the wavelength of ultrasonic velocities (ASTM C 597), and given the results of ultrasonic velocities being in the range 4.60-4.72 km/s as well as the frequency of the used pulses being equal to 54 kHz, the wavelength of ultrasonic velocities, determined as the ratio of the pulse velocity to the velocities frequency, is obtained in the range 8.52-8.74 cm; therefore, the dimensions of the specimens under study are well within the allowable range.

The workability results of the reactive powder concrete determined by the mini-cone table test vary in the range 110-180 mm, with the lowest flowability value belonging to the mixture containing the combination of the PVA and steel fibers with the volume contents of 0.75 and 0.25 % (RPC13), respectively, and the highest value belonging to the fiber-lacking mixture. In fact, addition of fibers in all the mixtures reduces the fresh concrete workability.

3.2 Static and dynamic modulus of elasticity

In the UPV method, strength and other mechanical properties of concrete have influence upon the velocity of longitudinal compression waves. Hence, UPV can be useful in estimating the static and dynamic modulus of elasticity of concrete as well as measuring time-dependent behaviors (Bin Ibrahim *et al*. 2002).

Table 4 lists the static modulus of elasticity of the RPC specimens, which are between 42 and 50.8 GPa. The dynamic modulus of elasticity was also obtained by employing the UPV values and Eq. (1) which is based on the elastic theory and applies to a homogeneous isotropic environment (Nazarian *et al*. 1997). The associated results are given in Table 6 for the cylindrical RPC specimens.

$$E_d = \rho V_P{}^2 \frac{(1+\nu_d)(1-2\nu_d)}{(1-\nu_d)} \quad (1)$$

In the above equation, E_d is the dynamic modulus of elasticity (Pa), ρ is the concrete density (kg/m^3), V_p is the measured UPV (m/s), and ν_d is the dynamic Poisson's ratio. In their research on UHPFRC and regarding the results of the resonant frequency test, Hassan and Jones (2012) reported that the dynamic Poisson's ratio of a 28-day concrete is equal to 0.2. Here, the dynamic Poisson's ratio was also considered constant and equal to 0.2 to calculate the dynamic modulus of elasticity.

It should be kept in mind that Eq. (1) holds for homogeneous and isotropic solids, while concrete is essentially a nonhomogeneous material to which these assumptions surely do not apply. However, compressional waves do not relate and interact with most of concrete nonhomogeneity (Anugonda *et al*. 2001), and thus, concrete can be reasonably considered as a homogenous material (Sansalone *et al*. 1997). With similar arguments, concrete is

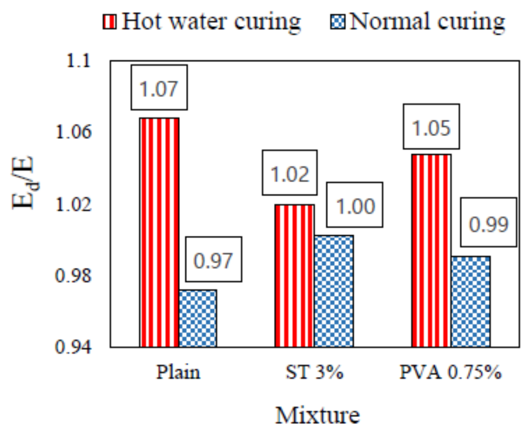
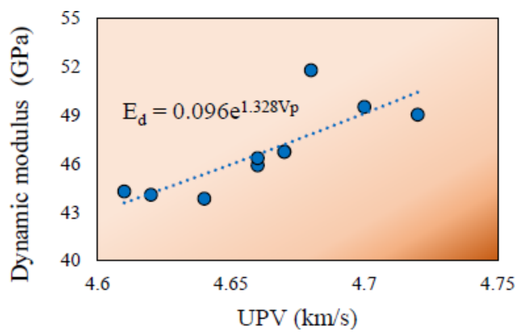
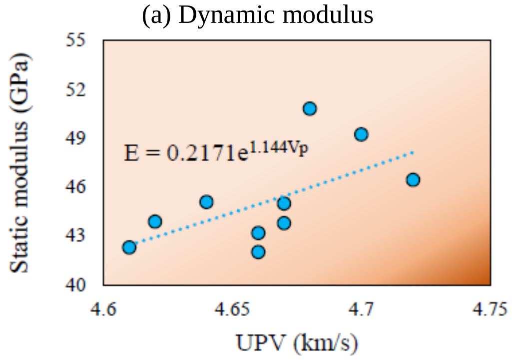


Fig. 7 The effect of curing type on dynamic-to-static elastic modulus ratio



(a) Dynamic modulus



(b) Static modulus

Fig. 8 Relationship of static and dynamic modulus of elasticity with UPV for RPC specimens cured in hot water

considered as homogeneous in other nondestructive methods (Krautkrämer and Krautkrämer 2013). In this regard, Washer *et al*. (2004, 2005) in their studies on the distribution of ultrasonic waves within UHPFRC in the direct method reported that the materials demonstrated the isotropic elastic properties within normal operating stress limits at the frequencies of up to 2.25 MHz of launching and receiving the pulses.

In Fig. 6, the static and dynamic modulus of elasticity results of the hot water-cured cylindrical RPC specimens vs. the type and volume fraction of fibers are shown. As can be seen in the figure, the dynamic modulus of elasticity values of the specimens (except RPC14) are greater than the corresponding static modulus of elasticity values. In the steel fiber-containing specimens, as the fiber volume fraction increases, the both modulus types increase, with the difference between them getting smaller with higher volume fractions. In the PVA fiber-containing specimens, however, as the fiber volume fraction increases, a completely opposite trend is observed between the variations of the static and those of the dynamic modulus of elasticity, with the difference between them being the smallest at 5% fiber volume fraction. Furthermore, in the hybrid fiber-containing specimens, the variations of the static and dynamic modulus of elasticity are similar to one another and demonstrate an ascending trend after an initial reduction. The lowest and highest dynamic modulus values among the hot water-cured cylindrical RPC specimens belong to the specimen containing 0.25% PVA fibers (RPC14) and the one containing 3% steel fibers (RPC7), respectively.

By performing an overall review of the diagrams shown in Fig. 6, it is also found that the trend of variations of the UPV has a high resemblance to that of the static modulus of the specimens, indicating the fact that ultrasonic pulse velocity is among the elastic properties of materials.

The effect that the curing type has on the dynamic-to-static elastic modulus ratio is presented in Fig. 7, in which it is observed that the modulus ratio of the specimens under heat curing (1.02-1.07) is higher than that under normal curing (0.97-1.0). Moreover, the improvement of the dynamic-to-static modulus ratio due to heat curing is more evident in fiber-lacking specimens, and less evident in the steel fiber-containing specimens.

Furthermore, the modulus ratio in the specimens having experienced normal curing is smaller or equal to 1, suggesting that the dynamic modulus of these specimens cannot become greater than the static modulus, while the opposite is observed for the heat curing.

From Tables 4 and 6 it is understood that the heat curing shows no positive effect on the static modulus of the RPC specimens, and it led to a drastic reduction in the modulus of ordinary concrete and a negligible increase in that of the concrete containing steel fibers. However, heat treatment demonstrated a positive effect on the dynamic modulus of RPC specimens, with this effect being more pronounced in the ordinary specimens.

Note that there are several reasons underlying the difference observed between the dynamic modulus value measured by ultrasonic waves and the static one determined by conventional engineering methods. One of them is that the modulus obtained by the first method is adiabatic, while the modulus determined using the second is isothermal. Moreover, concrete constituents do not behave as linear elastic materials, hence the rate and magnitude of the applied stress affect the resulting strain and subsequently the static modulus. As previously mentioned, this behavior also affects dynamic modulus obtained by Eq. 1. However, these effects are less significant for RPC relative to conventional concretes due to the homogeneous nature of materials and the more linear stress-strain behavior of this concrete type (Washer *et al*. 2004).

The relationship of the static and dynamic modulus of elasticity with the UPV is given in Fig. 8, in which, as can be seen, there is a direct relationship between the both modulus and the UPV, with the increase rate of dynamic modulus with the increasing UPV being higher than that of

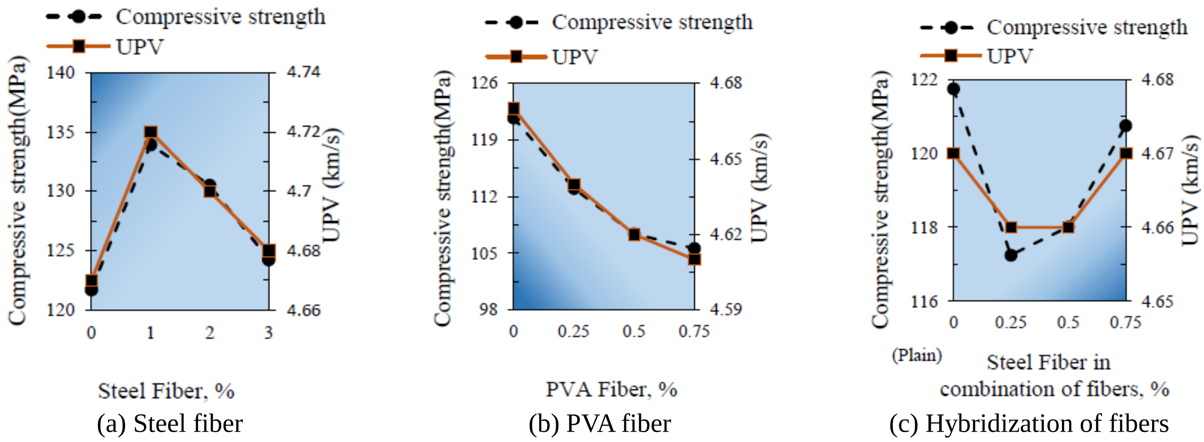


Fig. 9 Compressive strength and UPV of hot water-cured cylindrical RPC specimens vs. fiber volume fraction

the static elastic modulus. By applying nonlinear regression analysis to the entire experimental dataset, the static and dynamic modulus of elasticity in terms of UPV can be estimated as Eqs. (2) and (3), respectively, which possess relatively good correlation coefficients of 0.61 and 0.81 for the static and dynamic elastic modulus, respectively.

$$E = 0.217\, e^{1.144 V_P} \tag{2}$$

$$E_d = 0.096\, e^{1.328 V_P} \tag{3}$$

Since reactive powder concretes behave like homogenous solids, the isotropic elastic constants (Lame constants) can be related to the ultrasonic velocity values by the following (Green 1973),

$$V_P = \sqrt{\frac{(\lambda + 2\mu)}{\rho}} \tag{4}$$

Where ρ is density, and λ and μ are independent elastic constants. For homogeneous materials, only these two independent constants exist, which are referred to as Lame constants. Lame constants have direct relationship with the engineering constants of Young's Modulus (E), shear modulus (G), and Poison's ratio (v) based on the following equations (Green 1973)

$$E = \frac{\mu(3\lambda + 2\mu)}{(\lambda + \mu)} \tag{5}$$

$$v = \frac{\lambda}{2(\lambda + \mu)} \tag{6}$$

$$G = \mu \tag{7}$$

Hence, by knowing the values of E, ρ, and V, it is possible to determine the elastic properties of shear modulus and static Poisson's ratio, whose results for all the cylindrical RPC specimens are presented in Table 6, where it is observed that the heat treatment led to a reduction or negligible increase in the shear modules, similar to the case for the static elastic modulus and contrary to the dynamic

Table 6 Values obtained for shear and dynamic modulus together with Poisson's ratio using ultrasonic pulse velocity results

Series	Specimen ID	Shear modulus (GPa)	Dynamic modulus (GPa)	Poisson's ratio
RPC1	CTRL-HWC-Cy	17.6	46.75	0.24
RPC2	CTRL-NC-Cy	19.66	44.93	0.18
RPC5	ST1-HWC-Cy	18.70	49.04	0.24
RPC6	ST2-HWC-Cy	20.43	49.52	0.20
RPC7	ST3-HWC-Cy	20.92	51.78	0.21
RPC8	ST3-NC-Cy	20.81	50.16	0.20
RPC11	P.S0.75-HWC-Cy	18.33	46.73	0.23
RPC12	P.S0.5-HWC-Cy	17.32	46.34	0.25
RPC13	P.S0.25-HWC-Cy	16.72	45.91	0.27
RPC14	PVA0.25-HWC-Cy	19.17	43.83	0.18
RPC15	PVA0.5-HWC-Cy	18.22	44.09	0.20
RPC16	PVA0.75-HWC-Cy	17.15	44.28	0.23
RPC17	PVA0.75-NC-Cy	18.2	43.02	0.19

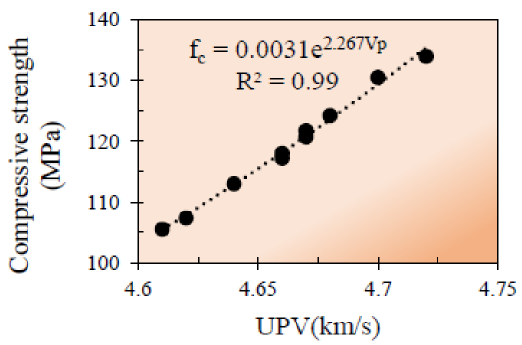
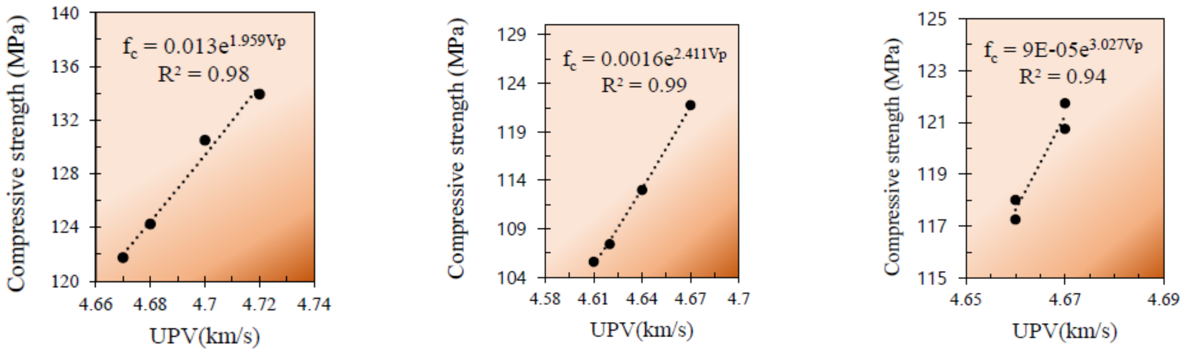


Fig. 10 Relationship between UPV and compressive strength of cylindrical RPC specimens cured in hot water

one. In addition, similar to the static modulus of elasticity, shear modulus increases as the volume fraction of steel fibers increases, while as the volume fraction of PVA fibers increases in the specimens containing these fibers and those containing hybrid fibers, the shear modulus decreases.

The maximum shear modulus improvement of the RPC



(a) Steel fiber (b) PVA fiber (c) Hybridization of fibers

Fig. 11 Relationship between compressive strength and UPV for RPC specimens containing different type of fibers

specimens relative to the ordinary ones occurs in the specimen containing 3% steel fibers as 18.9%, and the maximum shear modulus reduction of % occurs in the specimen containing hybrid fibers consisting of 0.25% steel fibers and 0.75% PVA fibers. The results given in Table 6 also indicate that in the RPC specimens containing different types and contents of fibers, a concrete mixture with a higher Poisson's ratio has a lower elastic modulus; for example, hybrid mixtures being the weakest mixtures in terms of their elastic modulus values demonstrate the highest Poisson's ratio values. Additionally, the calculated static Poisson's ratio depends on the type and amount of fibers and increases via hot water curing, with values ranging from 0.18 to 0.27 with the mean of 0.22.

3.3 Compressive strength-ultrasonic pulse velocity relationship

The compressive strength and UPV of the cylindrical RPC specimens cured in hot water vs. the volume fraction of used fibers are plotted in Fig. 9, according to which the variations of the compressive strength and UPV with the increasing fiber volume fraction are slimier to each other. In the steel fiber-containing RPC specimens, as the volume fraction of fibers increases, the compressive strength and UPV exhibit an initial ascending trend followed by a descending one; however, the values of these two parameters are higher than those of the ordinary specimen, indicating the improvement of compressive strength (up to 10% at V_f=1%). In the PVA fiber-containing RPC specimens, though, both the compressive strength and UPV decreases as the fiber content increases; this can be attributed to the fact that the concrete porosity increases in the form of voids developed among the aggregate grains, cement binder, and fibers due to incomplete mixing and consequently the presence of excess/free water in concrete. On the other hand, given the lower pulse velocity in voids relative to that in solid matter-containing regions (cement gel), the smaller the gel-to-void ratio, the lower the transmitted ultrasonic pulse velocity. In the PVA fiber-containing concrete, the highest compressive strength loss occurs at V_f=0.75% as 13.3%. It is also seen in Fig. 9 that as the content of steel fibers in the hybrid fiber-containing concrete increases, an initial descending trend followed by an ascending one is observed in the compressive strength. The same behavior was previously observed regarding the static and dynamic modulus of elasticity of hybrid fiber-reinforced concrete.

By comparing the RPC-HWC and RPC-NC results for the cylindrical and cubic specimens in Table 4, it is found that similar to the UPV case, the heat curing also had a positive effect on the compressive strength of the RPC specimens. This can be attributed to the faster hydration process of cementitious materials at high temperatures and the formation of a dense matrix. Similar to the UPV case, the greatest improvement in the reactive powder concrete strength due to heat curing belongs to the cubic specimen containing 3% steel fibers as 37.3%.

The relationship between UPV and compressive strength for all the cylindrical RPC specimens cured in hot water is presented in Fig. 10. Several relationships such as linear, lognormal, power, and exponential one have been presented for the UPV-f_c relationship of various concretes (Lin *et al*. 2007, Trtnik *et al*. 2009, Demirboğa *et al*. 2004); among which the exponential relationships have been used more widely in the literature. In this study, using the nonlinear regression of the experimental results, an exponential relationship between the UPV and compressive strength of RPC specimens containing steel, PVA, and hybrid fibers was developed, which is written as Eq. (8).

$$f_c = 0.0031e^{2.267V_P} \tag{8}$$

Where V_P and f_c are the velocity of ultrasonic waves per km/s and concrete compressive strength per MPa, respectively.

As can be seen in Fig. 10, a good agreement exists between the empirical equation and the experimental dataset. Fig. 11 shows the relationship of the compressive strength with the UPV for the cylindrical RPC specimens containing steel, PVA, and hybrid fibers separately. Moreover, the relationships obtained by performing the regression of results are expressed as Eqs. (9)-(11) in order for the three fiber types (i.e., steel, PVA, and hybrid fibers), all of which possess high correlation coefficients.

$$f_c = 0.013e^{1.959V_P} \tag{9}$$

$$f_c = 0.0016e^{2.411V_P} \tag{10}$$

$$f_c = 9 \times 10^{-5} e^{3.027 V_P} \quad (11)$$

4. Conclusions

In this research, the ultrasonic pulse velocity test was employed as a qualitative method to investigate the homogeneity and consistency of RPC specimens, to predict the dynamic modulus, shear modulus, and static Poisson's ratio, and to provide an equation capturing the relationship between the UPV and the compressive strength of RPC concrete. To do so, RPC specimens containing different volume fractions of steel and PVA fibers, as well as their hybridization were prepared under the two curing regimes, i.e., normal and heat curing, in cylindrical and cubic shapes. Based on the experimental work carried out here, the following conclusions can be drawn:

1. RPC specimens containing steel fibers demonstrate the highest level of the UPV. The UPV values of the steel fiber-containing specimens are greater than those of the ordinary (fiber-lacking) specimens, while the opposite is observed for the concretes containing PVA and hybrid fibers, with the highest and lowest UPV values belonging to the specimen containing % steel fibers and the one containing 0.75% PVA fibers, respectively.

2. Comparing the UPV test results with the ranges proposed by various codes or other studies in the literature indicates that the quality and physical conditions of the RPC specimens containing steel, PVA, and hybrid fibers are at an excellent level.

3. The dynamic modulus values of the RPC specimens are greater than the corresponding values of the static modulus. As the volume fraction of steel fibers increases, both the static and dynamic modulus values also increase, while in the PVA fiber-containing specimens, the variations of these two parameters follow completely opposite paths. The lowest and highest dynamic modulus among the specimens cured thermally belongs to the one containing 0.2 % PVA fibers and the one containing 3% steel fibers, respectively. Furthermore, the variations of the UPV shows a trend more similar to that of the static modulus variations, suggesting that the ultrasonic pulse velocity is an elastic property of materials.

4. The shear modulus of the RPC specimens increases with the increasing volume fraction of steel fibers, while with the increasing volume fraction of PVA fibers in the specimens containing these fibers and hybrid fibers, the shear modulus shows reduction. The greatest shear modulus improvement of 18.9% occurs in the specimen containing 3%, and the greatest shear modulus reduction of 5% occurs in the specimen containing hybrid fibers consisting of 0.2% steel fibers and 0.7% PVA fibers. Moreover, the static Poisson's ratio of the RPC specimens depends on the type and content of fibers and varies in the range 0.18-0.27 with the mean value of 0.22.

5. The variations of the compressive strength and UPV of the RPC specimens as the volume fraction of fibers increases demonstrate similar trends. As the content of steel fibers increases, the both parameters show an initial increasing trend followed by a decreasing trend, while as the content of PVA fibers increases, the both parameters decreases. In addition, in the hybrid fiber-reinforced specimens, with the increasing volume fraction of steel fibers, these two parameters first decrease and then increase, similar to the behavior shown by the dynamic and static modulus of elasticity.

6. Relative to the curing under standard conditions, the heat curing has a positive effect on the density, UPV, dynamic modulus, Poisson's ratio, and compressive strength of the RPC specimens, while it leads to a slight decrease or increase in the shear modulus and static elastic modulus.

7. The specimen shape and in fact the measuring distance length affects the UPV of the fiber-lacking RPC specimens while having a negligible effect on the UPV of the fiber-reinforced specimens.

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