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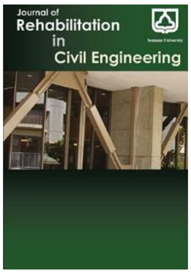

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Estimation of Mechanical and Durability Properties of Self-Compacting Concrete with Fibers Using Ultrasonic Pulse Velocity

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ABSTRACT

This study addressed the efficiency of ultrasonic pulse velocity (UPV) as a nondestructive test in concrete in estimating the mechanical (compressive and tensile strength) and durability (water absorption) properties of fiber-reinforced self-compacting concrete. To do so, 11 mixture designs containing 3 fiber types (steel: 0.1, 0.2, 0.3 and 0.4 percent by volume, Poly-phenylene Sulfide (PPS): 0.1, 0.2, 0.3 and 0.4% by volume and poly-propylene: 0.1 and 0.2 percent by volume) and a design without fibers as reference concrete have been tested and compared. To measure ultrasonic pulse velocity, cubic specimens were tested. The obtained results were used to develop correlation relationships between UPV of the specimens and the compressive and tensile strength as well as water absorption.

For the self-compacting concrete in this study, the range of pulse velocity was obtained. The proposed relations accurately estimate the mechanical and durability properties of this concrete type.

1. Introduction

In the 1980s, researchers in Japan developed self-compacting concrete (SCC) as a highly flowable concrete to enhance the constructability of reinforced concrete structures [1]. Considering the lack of any significant vibration during the placement of this concrete, considerable amount of labor costs and construction time can be saved [2]. SCC is theoretically a concrete with high flowability and coherency capable of compacting under its own weight with no vibration. Furthermore, this concrete can retain its coherency after casting and given its flowability, it is able to fill inside places with congested reinforcement [3–5].

On the other hand, due to low tensile strength of concrete as well as its high brittleness and weak formation in its plain form, it can’t be used in many structural applications including in bridges, airports, and dams. Reinforcing steel bars are placed

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in concrete to deal with the above issues with concrete. Despite the fact that these bars are placed centrally in concrete and largely compensate for the weakness, they are expensive and cannot be used in places such as airports overlays and the surface of canals. For solving this problem, string fibers have been added in concrete over the last decade. The use of fibers can be traced back many centuries ago at a time of using straws, hay, or crop residues for strengthening mud bricks [6,7].

Research conducted by previous researchers has shown that adding fibers in concrete increases its impact and scratching resistance as well as tensile and bending strength while decreasing its cracking [8–11]. given the low viscosity of self-compacting concrete, issues such as aggregate segregation and becoming watery are avoided. In addition, due to its heavy weight, it can be compacted without the need for any external or internal vibration. When there is a rebar congestion, this characteristic can be very beneficial in structural applications. [12-16].

Quality control of concrete using nondestructive techniques is receiving increasing interest of civil engineers across the globe. These tests are popular due to their low cost and short time, and also their simplicity compared with destructive techniques. They are used to ensure the strength of conventional standard specimens and check for local damage induced by fire, chemical attack, and airing. different types of nondestructive techniques have been accepted [17–21].

On such technique is the ultrasonic pulse velocity (UPV) which in based on the transmission speed of ultrasonic pulses inside concrete, and through which it is feasible to obtain some of the properties in structural concrete [20]. Many studies have been conducte on various concretes types using the UPV test, which have resulted in positive findings [22–27]. Entrapped air bubbles and the porosity inside a solid object affect the way by which ultrasonic pulses travel through it. Multiple different factors including the cement type, water-cement ratio, concrete age, aggregate type, curing method, measuring distance, and the measuring region's temperature affect the ultrasonic pulse velocity [17–20]. Extenside research has addressed the effect of different parameters on the UPV [28–32]. In their work, Rommel and Malhotra reported on the UPV in concrete specimens having different water-to-cement ratios and gravel volumes. In terms of different variables in the concrete specimens, they reached different UPVs, and subsequently proposed a pattern for evaluatiing concrete quality [28,29]. Given smaller number of air bubbles present in self-compacting concrete relative to conventional concrete because of its specific properties as well as the powder ingredient, this study attempted to evaluate the efficiency of the nondestructive technique in self-compacting concrete containing fibers. The aim was to develop a relationship between compressive strength and the UPV in this concrete. Here, 11 mix designs including different percentages of steel, Poly-phenylene Sulfide (PPS) and poly-propylene (PP) fibers were used to prepare the concrete specimens.

2. Materials

The gravel with a maximum size of 12.5mm according to the grading curve given by the ASTM C33 standard, and sand selected from sieve No.4.75 mm equivalent to 80% sand were used in this work. Figure 1 shows the grading curve of coarse and fine aggregates in accordance with ASTM C33 standard [33].

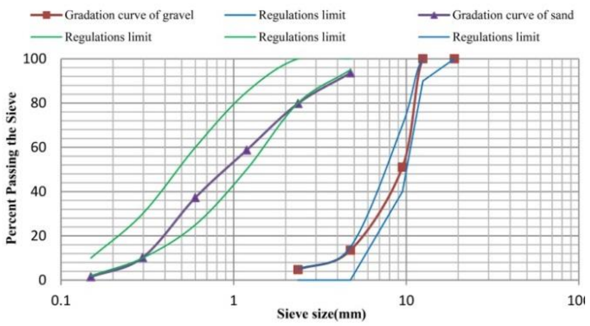


Fig. 1. Grading curve of coarse and fine aggregates in this work.

Type II Portland cement produced by Mazandaran cement Co. was employed here. Tables 1 and 2 present the chemical and physical properties of the cement, respectively. To prepare the concrete mixt, limestone powder with the density of 2.6 g/cm3 was used. Table 1 lists the chemical properties of this powder.

Table 1. Chemical composition of cement and limestone powder (wt.%).

Items	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	$CaCo_3$	L.O.I
PC	21.9	4.86	3.3	63.3	1.15	2.10	-	2.4
LS	0.45	0.33	0.02	52.3	0.02	52.3	99.3	-

PC: Portland cement.
LS: limestone powder.

Table 2. Physical properties of Portland cement.

Blaine (cm^2/g)	Expansion (autoclave) (%)	Compressive strength (kg/cm^2)		
		3 days	7 days	28 days
3050	0.05	185	295	397

In addition, an ether carboxylic-based super plasticizer (commercially available as P10-3R) with a specific gravity of 1.1 g/cm^3 was poured in all mix designs with the content of 7 kg/m^3. Three types of fibers were used, namely steel, Poly-propylene and Poly-Phenylene Sulfide (see Table 3 for more details).

3. Experimental Program and Mix Design

After the 11 mix design reached the 28-day age, tests for obtaining the Ultrasonic pulse velocity (UPV), compressive strength the cubic specimens and tensile strength of the cylindrical specimens were conducted. In accordance to ASTM C642-06, the water absorption test was conducted at the age of 70 days. Mix designs contained various volume percentages of the three fiber types, i.e., steel with 0.1, 0.2, 0.3 and 0.4 vol.%, polypropylene with 0.1 and 0.2 vol.% and PPS with 0.1, 0.2, 0.3 and 0.4 vol.%, as can be seen in Table 4. Except for the type and content of the fibers, all the other constituents of the concrete in all the 11 mix designs were fixed. In one cubic meter of the concrete, 722 kg gravel, 826 kg sand, 413 kg cement, 288 kg limestone powder and 7 kg super plasticizer were used. Water-to-cement ratio was 0.39 in all the mixes, and the fiberless control mix design was considered as the reference mix design. In Table 4, Vf is the volume percentage of fibers, namely the volume ratio fiber to concrete.

The nondestructive UPV test was initially performed on different specimens at ages mentioned above, so that the transmission time of ultrasonic pulses could be obtained based on the direct transmission method. A pundit tester device was used to conduct the test, as shown in Figure 2.

The pulses were emitted as a frequencies of 54 kHz. The transmission time was measured at the microsecond level and shown on a digital screen per µs. Previous researchers have suggested that using the 40–80kHz range for ultrasonic pulses is appropriate for concrete [17,28]. Refractory grease was applied to the surface of all the specimens to connect the transducers to the concrete surface in all the tests. The concrete surfaces were flattened and became smooth prior to the tests. Five different locations of the surface of the specimens were checked for the transmission of pulses in order to examine the whole volume of the specimens. The exact location of each of the five points on the surface can be seen in Figure 3. The mean velocity along directions perpendicular to one another was regarded for the pulses of each specimen. In addition, the mean compressive strength of the three identical specimens was considered as the corresponding strength. The transmission time was measured from the UPV test on each specimen as the mean of the five corresponding measurements. Afterwards, the transmission velocity of the ultrasonic pulse was calculated in km/s considering the transmission time of the pulses and knowing the transmission distance of 100 mm (each side of the $100 \times 100 \times 100$ mm cubic specimens) by the equation below,

$$V = \frac{L}{T} \qquad (1)$$

where L, T, and V are the transmission distance in km, transmission time in s and pulse transmission velocity in km/s, respectively [20].

A compression test in accordance with the BS EN 12390-3 standard) was performed on the specimens at a speed of 0.3 KN/s following the UPV nondestructive test, with the compressive strength expressed in MPa. Table 5 gives the compressive strength and UPV results. Moreover, the splitting tensile test was carried out based on the recommendations of the ASTM C496 [34] for 150×300 mm cylindrical concrete specimens; however, the use of this test on fiber-reinforced concrete (FRC) is hardly recommended by ACI committee 544.2R [35]. Since the fiber length to cylinder diameter ratio was low and equal to 0.3, the running arose, and also some researchers have shown that the ASTM C496 test is applicable to FRC specimens [36].

Fig. 2. Pundit tester device.

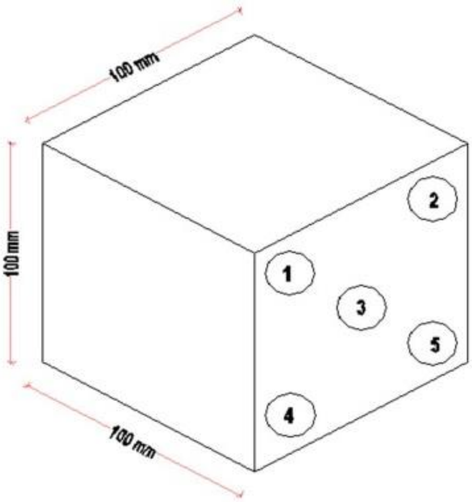


Fig. 3. Location of test points.

Table 3. Characteristics of fibers investigated in this study.

Fiber type	Fiber name	Densit (Kg/m^3)	Dimention (mm)				Moudulus of elasticity (GPa)	Tensile strength (MPa)	Geometry	Cross section
			L	W	T	D				
Steel	DUOLOC 36/0.8	7850	36	-	-	0.7	160	2100	Hooked end	Circular
PPS	PPS fiber	910	50	2	1	-	3.5	275	Rough	Rectangular
PP	PP fiber	910	60	-	-	0.1	5	450	Rough	Circular

Table 4. Details of specimens mixdesigns.

Mixture	Fiber V_f (%)		Gravel (kg/m^3)	Sand (kg/m^3)	Lime stone powder (kg/m^3)	Cement (kg/m^3)	Water (kg/m^3)	SP (kg/m^3)
Control	-		722	826	288.9	413.1	162	7
Steel10	Steel	0.1	722	826	288.9	413.1	162	7
Steel20		0.2	722	826	288.9	413.1	162	7
Steel30		0.3	722	826	288.9	413.1	162	7
Steel40		0.4	722	826	288.9	413.1	162	7
PP10	PP	0.1	722	826	288.9	413.1	162	7
PP20		0.2	722	826	288.9	413.1	162	7
PPS10	PPS	0.1	722	826	288.9	413.1	162	7
PPS20		0.2	722	826	288.9	413.1	162	7
PPS30		0.3	722	826	288.9	413.1	162	7
PPS40		0.4	722	826	288.9	413.1	162	7

4.1. Effect of Fiber Type and Content on Ultrasonic Pulse Velocity

In Figure 4 and Table 5, UPV is shown for different mixture designs. In this figure the influence of the fiber content and type on the UPV is shown. As can be seen, in the presence of the fibers, the UPV reduces. However, this reduction was not the same for all fibers. UPV of reference SCC is equal to 5.13Km/s. The UPV for PPS and Steel fiber sees a steep reduction and reaches 5.05 and 5.04 for the Steel40 and PPS40, respectively. However, UPV in mixes including PP fibers declines with a steeper slope and reaches 4.9 PP20.

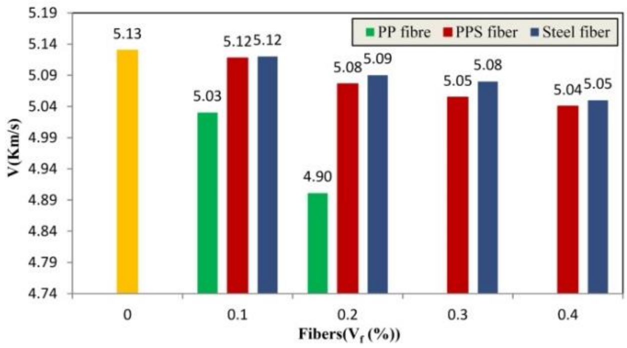


Fig. 4. Ultrasonic pulse velocity of the mixture.

4.2. Compressive Strength

Average value of compressive strength of test samples for each mix design is given in Figure 5. The compressive strength of reference concrete to an average was equal to 70.2MPa. By surveying this figure can find that with presence and adding fiber content in concrete, the compressive strength of the samples decreases. Of course, this reduction for plans containing PPS and steel fibers has been impalpable. As for plan Steel40, PPS40, respectively, the compressive strength is reached to 68.6 and 63.7MPa. Changes in compressive strength for plans containing PP fiber were more tangible and in plan PP20 than the reference concrete on average 17 percent drop.

There is no established relationship between the UPV and compressive strength of the concrete. On one hand, modulus of elasticity has relationship with the compressive strength. On the other, the velocity is related to the modulus of elasticity and the concrete density. Thus, evaluating the compressive strength of concrete in terms of the UPV is justified. Several researchers have stated that the compressive strength-UPV relationship can be calculated via the exponential equation below:

$$F'_c = A.\, e^{(BV)} \qquad (2)$$

where F'_c and V are the compressive strength and is the pulse velocity in km/s, respectively, with A and B being empirical constants [18].

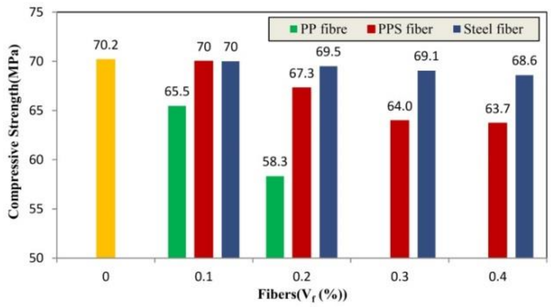
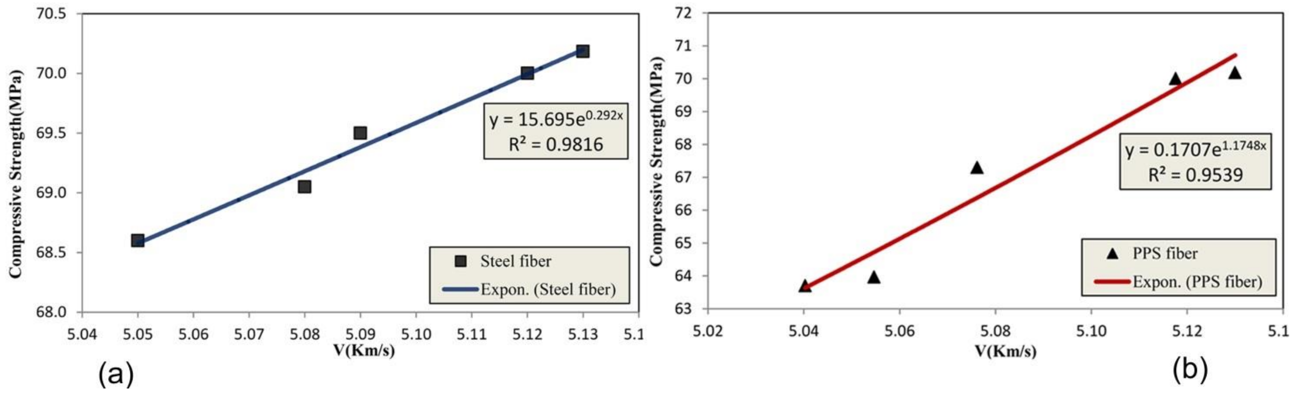


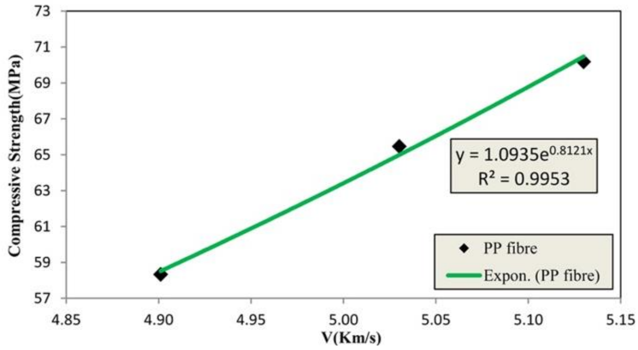
Fig. 5. The compressive strength of the sample.

Based on the equation, regression of the data shows that there is an exponential correlation between the pulse velocity and the compressive strength for the cubic specimens. Figure 6 shows the regression of the curve on the data with the equation of the regressed curve and also Regression Coefficient (R). The closer R^2 (Regression Coefficient) to 1, the lower the dispersion. In Figure 6 the suggested for estimating compressive strength of self-compacting concrete containing fiber has brought. Also, coefficients for the exponential curves estimated in Table 6 are given. Figure 6(a) represents UPV against the compressive strength of specimens containing steel fiber and estimated the relationship between them, Figure 6(b) and Figure 6(c) show the same curve for samples containing PPS and PP fibers, respectively. By surveying Figure 6 can find that equations can express with very good accuracy relationship between compressive strength and UPV.

Table 5. Compressive strength and UPV results.

Concrete mixture	Fiber type		Ultrasonic pulse velocity (Km/s)	Compressive strength (MPa)	Splitting tensile strength (MPa)	Water absorption (%)
Control	-		5.13	70.2	4.25	1.83
Steel10	Steel	0.1	5.12	70.0	4.6	1.9
Steel20		0.2	5.09	69.5	4.98	2.15
Steel30		0.3	5.08	69.1	5.06	2.17
Steel40		0.4	5.05	68.6	5.12	2.22
PP10	PP	0.1	5.03	65.5	4.3	2.1
PP20		0.2	4.90	58.3	4.07	2.28
PPS10	PPS	0.1	5.12	70.0	4.3	1.9
PPS20		0.2	5.08	67.3	4.5	2.03
PPS30		0.3	5.05	64.0	4.79	2.07
PPS40		0.4	5.04	63.7	5	2.12





(c)

Fig. 6. The compressive strength-UPV relationship for the specimens containing: (a) Steel fiber, (b) PPS fiber, (c)PP fiber.

4.3. Tensile Strength

Effects of fiber content and type on the tensile strength are given in Figure 7. Of course, these values are also presented in Table 5. Tensile strength for reference design which is without fiber is equal to 4.25MPa. As seen in the figure, in plans containing PPS and Steel fibers, the tensile strength rises with increasing fiber content.

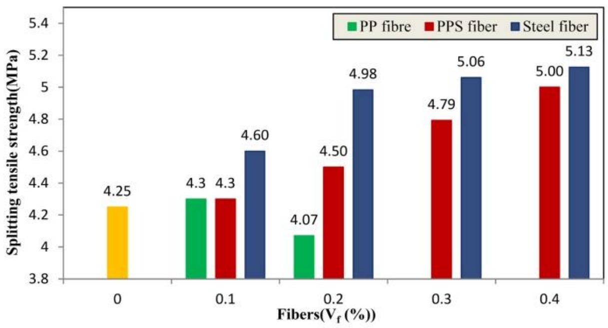


Fig. 7. The tensile strength of samples.

As this value for Plans, Steel40 and PPS40 reach 5.13 and 5 MPa, respectively. In this plans Tensile strength respectively 21 and 17 % is growth due to the intrinsic effect of fiber in tension.

Based on the equation, regressing shows an exponential curve (correlation Relation) among the data for the relationship between the pulse velocity and the tensile strength for the cylindrical specimens. Figure 8 shows the regression of the curve on the data with the formula of the regressed curve between tensile strength and UPV for different fibers. In figure 8(a) presented relation the tensile strength and UPV for specimens containing steel fiber and Figure 8(b) and Figure 8(c), the same relationship for samples containing PPS and PP fibers is given. As in Figure is seen clearly, proposed correlation Relations with relatively few errors have been able to express the relationship between tensile strength and UPV. As Regression Coefficient(R) for samples containing PPS fiber is obtained equal to 0.945. Also coefficients for the exponential curves estimated in the Table 6 are given.

Table 6. Regression coefficients of the exponential function.

Experimental groups	Compressive Strength			Splitting tensile strength			Water absorption		
	A	B	R^2	A	B	R^2	A	B	R^2
PP Fiber	1.093	0.812	0.995	1.538	0.200	0.631	237	-0.945	0.953
PPS fiber	0.171	1.175	0.954	32230	-1.473	0.945	5582	-1.562	0.981
Steel fiber	15.695	0.292	0.982	450557	-2.248	0.829	952459	-2.562	0.886

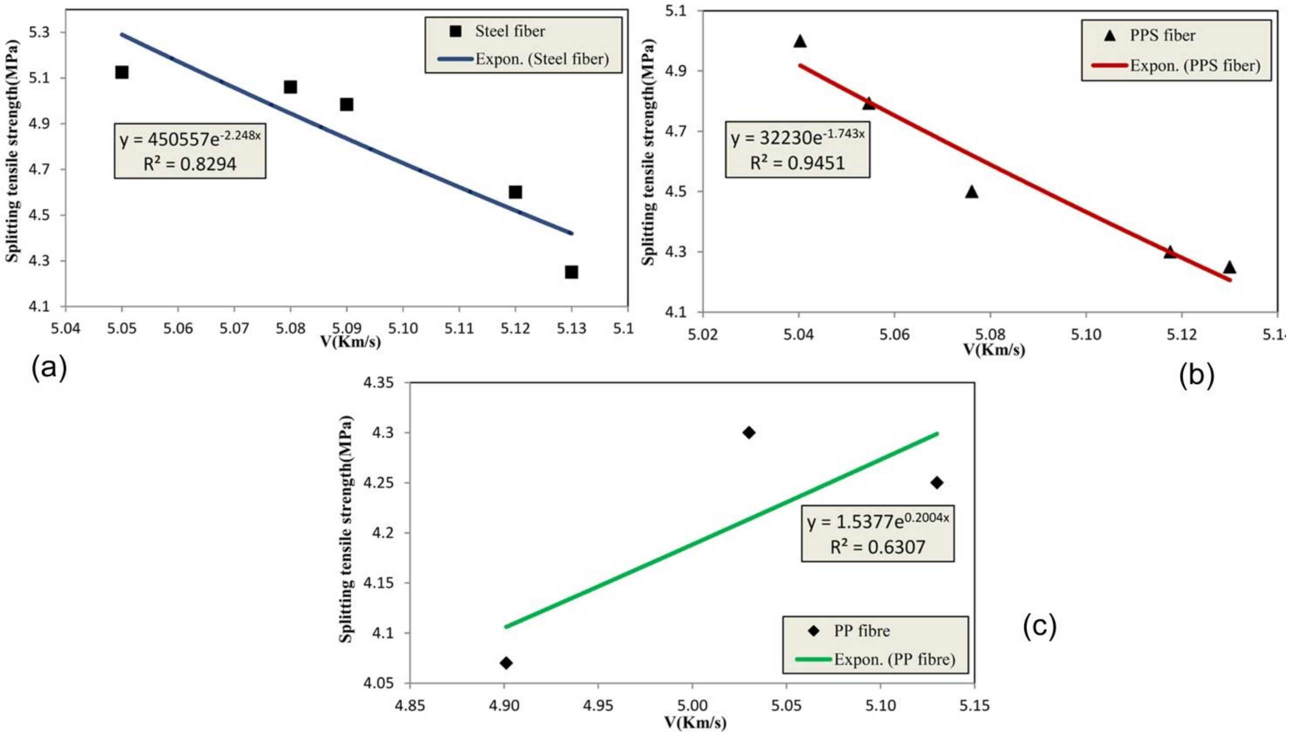


Fig. 8. The tensile strength-UPV relationship for the specimens containing: (a) Steel fiber, (b) PPS fiber, (c) PP fiber.

4.4. Concrete water Absorption Percent

Water absorption values for studied designs samples are presented in Table 5 and Figure 9. This value was equal to1.83 % for a plan without fiber (control). While this value for mix designs (Steel40, PPS40 and PP20), respectively reach to 2.12, 2.22 and 2.28%, indicating that the growth is 16, 21 and 24% (respectively) in water absorption (relative to the reference design). By comparing Water absorption values of different designs can be found that PPS fiber had less Influence on water absorption and causes less impact on the durability of concrete.

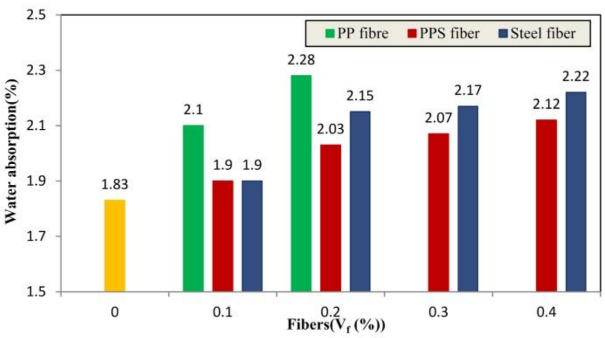


Fig. 9. Concrete water absorption percent.

Also, relationship (correlation Relations) between water absorption of self-compacting concrete containing different fibers and UPV provided in Figure 10. In Figure 10(a), 10(b) and 10(c) are presented estimated relationship concerning of concrete containing Steel, PPS and PP fibers, respectively. The coefficients of the exponential functions are also provided in Table 6. R2 factor (Regression Coefficient) for the mix designs examined in this study is equal to 0.981, 0.886 and 0.935 respectively for Steel, PPS and PP fibers that indicating the high accuracy of obtained relations.

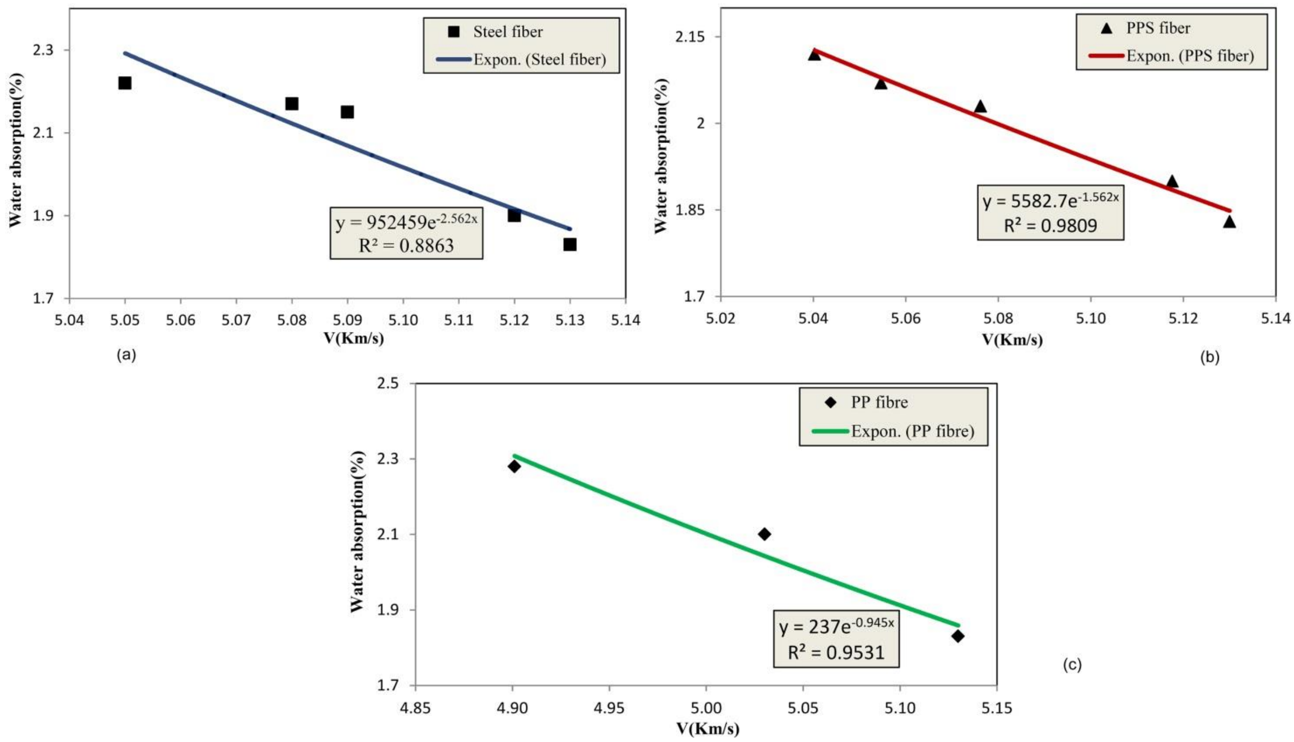


Fig. 10. The water absorption-UPV relationship and for the specimens containing: (a) Steel fiber, (b) PPS fiber, (c) PP fiber.

5. Conclusion

In this research, important parameters, namely the mechanical and durability properties, of self-compacting concrete including different contets of steel, Poly-Phenylene Sulfide and poly-propylene fibers were studied based on ultrasonic pulse velocity (UPV). The following results are drawn from the study:

- It appears that the presence and increase of fiber percentage in concrete without fiber causes reduction in UPV, however, is impalpable. As by presence 0.4 % of Steel and PPS fiber, UPV has dropped to 1.5 and 1.7 %, respectively.
- By survey results can find that fiber presence leads to an intangible reduction in compressive strength. These changes in samples containing Steel and PPS fiber have been more intangible.
- In this experimental study, self-compacting concretes with different fibers were shown to have different mechanical properties. For the compressive strength, fiber presence has decreased resistance unsensible but Related to the tensile strength, fiber presence had a significant effect on tensile strength. With 0.4% presence by volume of steel and PPS fibers, tensile strength than concrete without fiber 21 and 17% increased.
- Water absorption test results show fiber presence of fiber has increased water absorption of samples. This can be due to a reduction in the density of samples by fiber presence. Of course, increasing the value of water absorption in designs containing PPS fiber was lower than other designs that show less impact of the fiber on concrete durability.
- The equation proposed by previous researchers [18], in the form of an exponential relationship between

compressive strength and the transmission velocity of ultrasonic pulses in concrete, shows good agreement with the experimental results of this work.

- In this laboratory study between the mechanical properties and durability of concrete (compressive strength, tensile strength and water absorption) on the one and UPV on the other hand, relations have been established. By survey, these correlation Relations can be found that the relations can estimate parameters with high accuracy so that the Regression Coefficient for most relations is obtained more than 0.95.

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