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Research article

Relationships among compressive strength and UPV of concrete reinforced with different types of fibers

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A R T I C L E I N F O

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Prediction of compressive strength

A B S T R A C T

This paper determines the effect of steel, glass, and nylon fibers on the compressive strength and ultrasonic pulse velocity (UPV) of fiber reinforced concrete. The influence of different fiber types, fiber volume fraction, and water to cement ratios on the compressive strength of fiber reinforced concrete was tested using the compression test machine (CTM) and ultrasonic pulse velocity tester. Experiments were carried out at different ages on more than 100 cylindrical specimens. A comparison between the experimental results and equations available in the literature for prediction of compressive strength in terms of UPV was conducted to better evaluate the accuracy of available methods, when the type and volume fraction of fibers change. A new empirical equation that accounts for the presence of different types of fibers and fiber volume fraction is proposed to better estimate the compressive strength of steel, glass, and nylon fiber reinforced concrete.

1. Introduction

Concrete is broadly used material in civil engineering and construction due to its high compressive strength and relatively low cost. However, plain unreinforced Portland cement concrete is a brittle material possessing a very low tensile strength, limited ductility, and little resistance to cracking. These problems were proven to be diminished by adding short discrete fibers. ACI 544.1R-96, Report on Fiber Reinforced Concrete, defines Fiber Reinforced Concrete (FRC) as concrete made primarily of hydraulic cements, aggregates, and discrete reinforcing fibers. ASTM C1116, Standard Specification for Fiber Reinforced Concrete (FRC), classifies FRC by the type of the fiber incorporated. Type I: Steel Fiber Reinforced Concrete (SFRC). Type II: Glass Fiber Reinforced Concrete (GFRC). Type III: Synthetic Fiber Reinforced Concrete, from which Nylon Fiber Reinforced Concrete (NFRC) was chosen. Based on the literature review the most popular fiber used in concrete materials is steel fiber. Glass and Nylon fibers haven't been investigated as much as steel fibers. Nonetheless, the behavioral efficiency of FRC is far superior to plain concrete and many other materials of equal cost. Numerous studies have been conducted to investigate the advantages and disadvantages of SFRC, GFRC, and NFRC. Findings indicate that supplementing concrete with the appropriate fiber type and fiber volume fraction can reduce shrinkage cracks; increase compressive strength; increase impact and shatter resistance; and improve the homogeneity of concrete (Pawade et al., 2011; Nitin and Verma, 2016; and Bobde et al., 2018). It was also observed that increasing the fiber volume fraction and the fiber tensile strength increases the splitting and flexural strength of concrete. In addition, the unit weight of the fresh concrete changes depending on the increase of fiber content and the specific gravity of the fiber (Koksal et al., 2013), which can affect the pulse velocity in concrete specimen. The addition of steel and Forta-Ferro fibers (Synthetic) to high-strength concrete led to increase in the compressive strength, strain at peak stress, ultimate strain, and toughness index relative to plain concrete. Yet, this increase is much more emphasized for steel fibers than for synthetic fibers. Many researchers have studied the mechanical properties of Fiber Reinforced Concrete using the UPV method (Gebretsadik, 2013; Lin et al., 2007; Hoe and Ramli, 2010; and Khademi et al., 2016). However, the relationship between strength and pulse velocity is not unique and is affected by many factors such as aggregate type, size, and content; cement type and content; water to cement ratio; and fiber type

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and content. While the majority of the equations found in the literature relating concrete's compressive strength to UPV are applicable to plain concrete (Mahure et al., 2011; Khademi et al., 2016; Kheder, 1999; Lin et al., 2007). Few studies have been conducted that include nylon fiber and at the same time study the performance of steel, glass, and nylon FRC against each other while keeping the fiber volume fraction range constant and propose an equation that is applicable to all of the mentioned fibers (Gebretsadik, 2013; Mahure et al., 2011; Nitin and Verma, 2016; Raouf and Ali, 1983; Suksawang et al., 2018).

Table 1. Experimental program outline.

Coarse Aggregate Nominal Maximum Size	4.7625 mm (0.1875″)
Portland Cement	TYPE I/II
Specimen Geometry	Cylinder 100 mm × 200 mm (4″ x 8″)
Water-Cement Ratio	0.32, 0.38, 0.44, 0.50
Mix Proportions	1C:1.96FA:1.41CA:0.32W
Fiber Volume Fraction (%)	0, 0.1, 0.25, 0.5, 0.75, 1.0, 1.5
Curing Time (days)	7, 28, 44

In this experimental study the effect of different discrete fibers on the Ultrasonic Pulse Velocity and Compressive Strength of fiber reinforced concrete will be investigated. The discrete fibers in this study include: Steel, Glass, and Nylon fibers. The influence of concrete mixture parameters such as fiber type, fiber volume fraction, water-to-cement ratio, and curing time will be inspected. Non-destructive and Destructive test will be carried out to obtain the compressive strength of Fiber Reinforced Concrete. Several available empirical equations relating compressive strength to UPV were examined to measure their accuracy with respect to the experimental data. A coefficient of variation was employed to comprehend the variability between calculated and measured results. A new empirical equation is offered to account for the presence of steel, glass, and nylon fibers at different fiber volume fractions and accurately predict the compressive strength of FRC in terms of UPV.

2. Experimental investigation

In this experimental study, destructive and nondestructive test were conducted to determine the effect of fibers on the Ultrasonic Pulse Velocity and Compressive Strength of FRC. The equipment used consist of Ultrasonic Pulse Velocity Tester and Compression Test Machine (CTM).

Table 2. Fiber properties.

Fiber Material	Fiber Name	Specific Gravity	Length	Tensile Strength	Young's Modulus	Acid/Alkali Resistance
Steel	TYPE V	7.8	25.4 mm	1100 MPa	200 GPa	High
Glass	AR-DM	2.68	13 mm	1700 MPa	72 GPa	High
Nylon	Nylon Fibers	1.14	19 mm	966 MPa	2.8 GPa	High

Table 3. Mix proportions.

Name	Fiber Vol%	w/c	Cement (Kg/m^3)	Fine Agg. (Kg/m^3)	Coarse Agg. (Kg/m3)	Water (Kg/m^3)	Fiber (Kg/m^3)
SFRC-1	0	0.32	524.42	1027.85	739.45	167.82	0.00
SFRC-2	0.1	0.32	523.90	1026.83	738.71	167.65	7.79
SFRC-3	0.25	0.32	523.11	1025.29	737.60	167.40	19.5
SFRC-4	0.5	0.32	521.80	1022.71	735.75	166.98	39.0
SFRC-5	0.5	0.38	505.88	991.51	713.30	192.23	39.0
SFRC-6	0.5	0.44	490.90	962.16	692.19	215.98	39.0
SFRC-7	0.5	0.5	476.78	934.47	672.26	238.39	39.0
SFRC-8	0.75	0.32	520.49	1020.15	733.91	166.56	58.5
SFRC-9	1	0.32	519.18	1017.57	732.05	166.14	78.0
SFRC-10	1.5	0.32	516.56	1012.44	728.36	165.30	117
GFRC-1	0	0.32	524.42	1027.85	739.45	167.82	0.00
GFRC-2	0.1	0.32	523.90	1026.83	738.71	167.65	2.70
GFRC-3	0.25	0.32	523.11	1025.29	737.60	167.40	6.75
GFRC-4	0.5	0.32	521.80	1022.71	735.75	166.98	13.5
GFRC-5	0.5	0.38	505.88	991.51	713.30	192.23	13.5
GFRC-6	0.5	0.44	490.90	962.16	692.19	215.98	13.5
GFRC-7	0.5	0.5	476.78	934.47	672.26	238.39	13.5
GFRC-8	0.75	0.32	520.49	1020.15	733.91	166.56	20.2
GFRC-9	1	0.32	519.18	1017.57	732.05	166.14	27.0
GFRC-10	1.5	0.32	516.56	1012.44	728.36	165.30	40.5
NFRC-1	0	0.32	524.42	1027.85	739.45	167.82	0.00
NFRC-2	0.1	0.32	523.90	1026.83	738.71	167.65	0.91
NFRC-3	0.25	0.32	523.11	1025.29	737.60	167.40	2.27
NFRC-4	0.5	0.32	521.80	1022.71	735.75	166.98	4.55
NFRC-5	0.5	0.38	505.88	991.51	713.30	192.23	4.55
NFRC-6	0.5	0.44	490.90	962.16	692.19	215.98	4.55
NFRC-7	0.5	0.5	476.78	934.47	672.26	238.39	4.55
NFRC-8	0.75	0.32	520.49	1020.15	733.91	166.56	6.82
NFRC-9	1	0.32	519.18	1017.57	732.05	166.14	9.10
NFRC-10	1.5	0.32	516.56	1012.44	728.36	165.30	13.64

In this experimental investigation fiber reinforced concrete (FRC) is divided into three different categories. 1) Steel Fiber Reinforced Concrete (SFRC), 2) Glass Fiber Reinforced Concrete (GFRC), and 3) Nylon Fiber Reinforced Concrete (NFRC). Each category contains ten different mixtures of concrete: one control mix, six mixes with fiber volume fractions of 0.10%, 0.25%, 0.50%, 0.75%, 1.00%, and 1.50% while the water to cement ratio is held constant and equal to 0.32, and additional three mixes with water to cement ratios of 0.38, 0.44, and 0.50 while the fiber volume fraction is constant and equal to 0.50%. The fiber volume fraction range of 0%–1.5% was selected because it was applicable to all fiber types in this study based on the literature and the preliminary study that was conducted prior to this research. Additionally, having the same fractional range of fiber volume for all types of fibers allows more accurate comparison between them. The pouring and curing of the 100 mm × 200 mm cylindrical specimens was done in accordance to ASTM C192/C192, *Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory*, using a laboratory mixer. The specimen's UPV was measured at the ages of 7, 28 and 44 days. The Ultrasonic Pulse Velocity was determined in accordance to ASTM C597, *Standard Test Method for Pulse Velocity through Concrete*. The compressive strength was measured at the ages of 28 and 44 days. The Compressive Strength was determined in accordance to ASTM C39/C39M, *Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens*. According to ASTM C39, the rate of gain in concrete compressive strength is higher during the first 28 days of casting and then it slows down. In addition, in most cases strength requirements for concrete are at the age of 28 days. Therefore, the measurements were conducted at 28 days and at 44 days since the gain in strength after 44 days was found to be negligible. Table 1 shows the experimental program outline; Table 2 displays the properties of steel, glass and nylon fibers; and Table 3 shows the thirty different mixtures utilized for the experimental program.

3. Equations

To evaluate the effect of steel, glass, and nylon fiber on the ultrasonic pulse velocity and compressive strength of FRC specimens, empirical equations found in the literature relating UPV to compressive strength were investigated. The UPV was obtained by diving the length of the specimen by the transit time. Eq. (1) was used to compute the UPV of each specimen. The empirical equations used to predict compressive strength based on UPV typically have the exponential from and contain a single variable (UPV). The empirical equations (Eqs. 2–7), obtained from the literature, which relate compressive strength and UPV are shown in Table 4. Where V is the ultrasonic pulse velocity in km/sec and f'_c is the compressive strength in MPa. It was observed that these equation are applicable to only one type of FRC and very specific mix designs. Therefore there is a need for a new empirical equation capable of predicting the compressive strength of concrete including different types of fiber by introducing a correction factors. The compressive strength was determined using the compression test machine. However, since the specimens in this study are 100 mm × 200 mm (4″ x 8″) cylinders. Eq. (8) was used to include size effect on the measured compressive strength, f_c (Benjamin and Cornell, 1970). Where f_{cy} (d) is the compressive strength of the cylinders with arbitrary dimension, f'_c is the compressive strength of the standard 150 mm × 300 mm cylinder (MPa), and d is diameter of the arbitrary specimen (cm). In order to understand the variability between the calculated results from the compression test machine and the predicted results from the equations in Table 4 a coefficient of variation (COV) was used (Suksawang et al., 2018). The COV was calculated using Eqs. (9) and (10). Where μ is the mean measured value, n is the number of data points, f'_{ci} is measured compressive strength for the i-th data point, f_{cpi} is the predicted compressive strength for the i-th data point.

$$V = \frac{L}{T} \tag{1}$$

Table 4. Compressive Strength formula for concrete using Ultrasonic Pulse Velocity.

Reference	Equation	Eq#
Jones (1962)	$f'_c = 2.8e^{0.53V}$	2
Raouf and Ali (1983)	$f'_c = 2.016e^{0.61V}$	3
Nash't et al., 2005	$f'_c = 1.19e^{0.715V}$	4
Mahure et al. (2011)	$f'_c = 9.502V - 18.89$	5
Mahure et al. (2011)	$f'_c = 2.701V + 17.15$	6
Kheder (1999)	$f'_c = 1.2{*}10^{-5}(V{*}10^3)^{1.7447}$	7

$$f_{cy}(d) = \frac{0.49f'_c}{\sqrt{1 + d/2.6}} + 0.81f'_c \tag{8}$$

$$\mu = \frac{\sum_{i=1}^{n} f'_{ci}}{n} \tag{9}$$

$$COV = \frac{\sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(f'_{cpi} - f'_{ci}\right)^2}}{\mu} \tag{10}$$

4. Results and discussion

The results of Ultrasonic Pulse Velocity for steel, glass, and nylon fiber reinforced concrete were reported in Table 5. The transit time (μs) of each cylindrical specimen was obtained experimentally using the Ultrasonic Pulse Velocity Tester after the specimens cured in water for 7, 28, and 44 days. The Ultrasonic Pulse Velocity (Km/sec) was calculated using Eq. (1). In Figure 1, the effect of steel, glass, and nylon fibers and the change in water to cement ratio on the Ultrasonic Pulse Velocity of concrete at the ages of 7, 28, and 44 days is displayed. The fiber volume fractions considered are 0%, 0.10%, 0.25%, 0.5%, 0.75%, 1.00%, and 1.5% and the water to cement ratios are 0.32, 0.38, 0.44, and 0.50. It can be observed that SFRC's ultrasonic pulse velocity decreases with the addition of fibers. The reason behind this is the development of voids and non-homogeneity in SFRC, which highly retards the UPV (Gebretsadik, 2013). The UPV of GFRC also decreased with an increase in fiber content for similar reasons (Hoe and Ramli, 2010). The UPV of NFRC increased with an increase in fiber dosage. This is partially attributed to the bridge effect of the nylon fiber which leads to the reduction of micro-cracks in the cement matrix by the addition of NF (Lee, 2019). The Fiber-bridging constitutive law describes the relationship between the bridging stress transferred across a crack and the opening of this crack (Yang et al., 2008). The use of fibers reduces the fluidity of the material, thus reducing the workability of concrete. According to ASTM C1116, reduced workability causes fiber ball production (balling) generating lack of homogeneity and reduction in fiber reinforced concrete performance. Furthermore, the use of steel and glass fibers reduced the workability of concrete more than nylon fibers based on the experiments. Ultimately what caused the decrease in UPV of both SFRC and GFRC at higher fiber volume fractions was a result of poor fiber bridging effect caused by reduced workability. On the other hand, nylon fibers achieved a good fiber bridging effect because they didn't reduce the workability of concrete as much as steel and glass fibers. Consequently, a higher UPV was obtained for NFRC. The highest pulse velocity for each type of fiber reinforced concrete are the following: SFRC-1: 6.24 km/s, GFRC-1: 6.15 km/s, and NFRC-10: 5.79 km/s. The lowest pulse velocity for each type of fiber reinforced concrete are the following: SFRC-7: 4.65 km/s, GFRC-7: 4.81 km/s, and NFRC-7: 4.84 km/s. With respect to the water-to-cement ratio; the ultrasonic pulse velocity decreases with an increase in water to cement ratio for all types of fiber reinforced concrete. Increasing the water-to-cement ratio leads to a decrease in the ultrasonic pulse velocity of concrete due to an increase in the volume of capillary voids and micro

Table 5. Ultrasonic pulse velocity experimental data.

Name	Transit Time (μs)			Ultrasonic Pulse Velocity (Km/sec)		
	7 Day	28 Day	44 Day	7 Day	28 Day	44 Day
SFRC-1	38.78	34.80	32.55	5.24	5.84	6.24
SFRC-2	39.45	35.35	32.85	5.15	5.75	6.19
SFRC-3	39.60	35.45	32.88	5.13	5.73	6.18
SFRC-4	39.88	35.98	33.25	5.10	5.65	6.11
SFRC-5	41.85	37.70	37.15	4.86	5.39	5.47
SFRC-6	43.13	38.90	38.10	4.71	5.22	5.33
SFRC-7	43.68	39.78	38.75	4.65	5.11	5.24
SFRC-8	40.73	36.45	33.33	4.99	5.57	6.10
SFRC-9	40.93	36.60	34.13	4.97	5.55	5.95
SFRC-10	41.58	37.53	34.30	4.89	5.42	5.92
GFRC-1	37.13	36.05	33.05	5.47	5.64	6.15
GFRC-2	37.25	37.38	33.38	5.46	5.44	6.09
GFRC-3	38.10	37.68	34.10	5.33	5.39	5.96
GFRC-4	38.68	38.05	34.75	5.25	5.34	5.85
GFRC-5	39.95	41.10	36.90	5.09	4.94	5.51
GFRC-6	40.08	42.13	37.10	5.07	4.82	5.48
GFRC-7	40.65	42.23	38.48	5.00	4.81	5.28
GFRC-8	38.85	38.35	34.88	5.23	5.30	5.83
GFRC-9	39.23	39.13	36.23	5.18	5.19	5.61
GFRC-10	39.35	39.55	36.43	5.16	5.14	5.58
NFRC-1	38.78	38.70	37.60	5.24	5.25	5.40
NFRC-2	38.48	38.50	37.38	5.28	5.28	5.44
NFRC-3	37.98	38.25	37.25	5.35	5.31	5.46
NFRC-4	37.75	37.75	37.03	5.38	5.38	5.49
NFRC-5	38.88	38.88	37.68	5.23	5.23	5.39
NFRC-6	39.15	41.53	37.90	5.19	4.89	5.36
NFRC-7	40.10	41.95	39.40	5.07	4.84	5.16
NFRC-8	37.20	37.68	35.98	5.46	5.39	5.65
NFRC-9	37.08	36.70	35.55	5.48	5.54	5.72
NFRC-10	36.93	36.43	35.13	5.50	5.58	5.79

cracks in the concrete (Khademi et al., 2016). Lastly the effect of increase in curing time and age on ultrasonic pulse velocity is observed as an increase in UPV. This can be explained due to the decrease in void spaces or the increase in the gel/space ratio that takes place with paste hydration (Gebretsadik, 2013).

The results of the compression tests for steel, glass, and nylon fiber reinforced concrete were reported in Table 6. The compressive strength of each cylindrical specimen was obtained experimentally using the Compression Test Machine after curing in water for 28 and 44 days. The compressive strength of each type of FRC was displayed in Figure 2. It was observed that fiber increases the compressive strength of concrete due to the confining effect and fiber-bridging constitutive law up to a certain fiber content. Tearing the fibers requires more energy, resulting in a substantial increase in the toughness and fracture resistance of the material. However, with higher fiber volume content, the workability of concrete can be reduced. Consequently, concrete cannot be compacted properly due to lack of workability. If this happens, high fiber content has a detrimental effect on the compressive strength of concrete. This observation was also reported in another study (Pawade et al., 2011). The limited/poor bridging effect resulting from low workability caused the decrease in the UPV of SFRC and GFRC. However, the capability to resist the bridging stress transferred across a crack of SFRC and GFRC is greater than that of NFRC. Hence, the compressive strength of SFRC and GFRC was greater than NFRC. The drop in both SFRC's and GFRC's compressive strength is expected at higher fiber volume fractions. However, if the workability of concrete is not improved, the higher fiber volume fractions will worsen the fiber bridging effect even more resulting in limited gain in compressive strength. The drop in NFRC's compressive strength after 1% fiber volume fraction occurs due to limited fiber properties and reduced workability. The compressive strength of SFRC and GFRC increases with the addition of fiber volume fraction after 28 and 44 days curing in water. The compressive Strength of NFRC increased with fiber volume fraction up 1% then it decreased. It was also be observed that the compressive strength decreases with an increase in water to cement ratio.

Figures 3, 4, and 5 show the comparison between the measured compressive strength to the predicted compressive strength of SFRC, GFRC, and NFRC respectively using equations shown in Table 4. To understand the variability between calculated and measured results, the coefficient of variation (COV) is used. A perfect correlation is achieved when the data points form a 45-degree line. Data points above this 45-degree line represent unconservative deviations while the data points below this line represent conservative deviations. Figure 3 shows that the equations found in the literature have high COV's when used for predicting the compressive strength of SFRC. The lowest COV belongs to Eq. (5) (COV = 23.2%) and the highest COV belongs to Eq. (4) (COV = 78.6%). Similarly, Figure 4 shows that the equations found in the literature have high COV's when used for predicting the compressive strength of GFRC. The lowest COV belongs to Eq. (7) (COV = 24.0%) and the highest COV belongs to Eq. (4) (COV = 54.2%). Likewise, Figure 5 shows that the equations found in the literature have high COV's when used for predicting the compressive strength of NFRC. The lowest COV belongs to Eq. (5) (COV = 22.4%) and the highest COV belongs to Eq. (4) (COV = 65.1%).

After analyzing Figures 3, 4, and 5 it was determined that the equations found in the literature do not provide a good prediction of

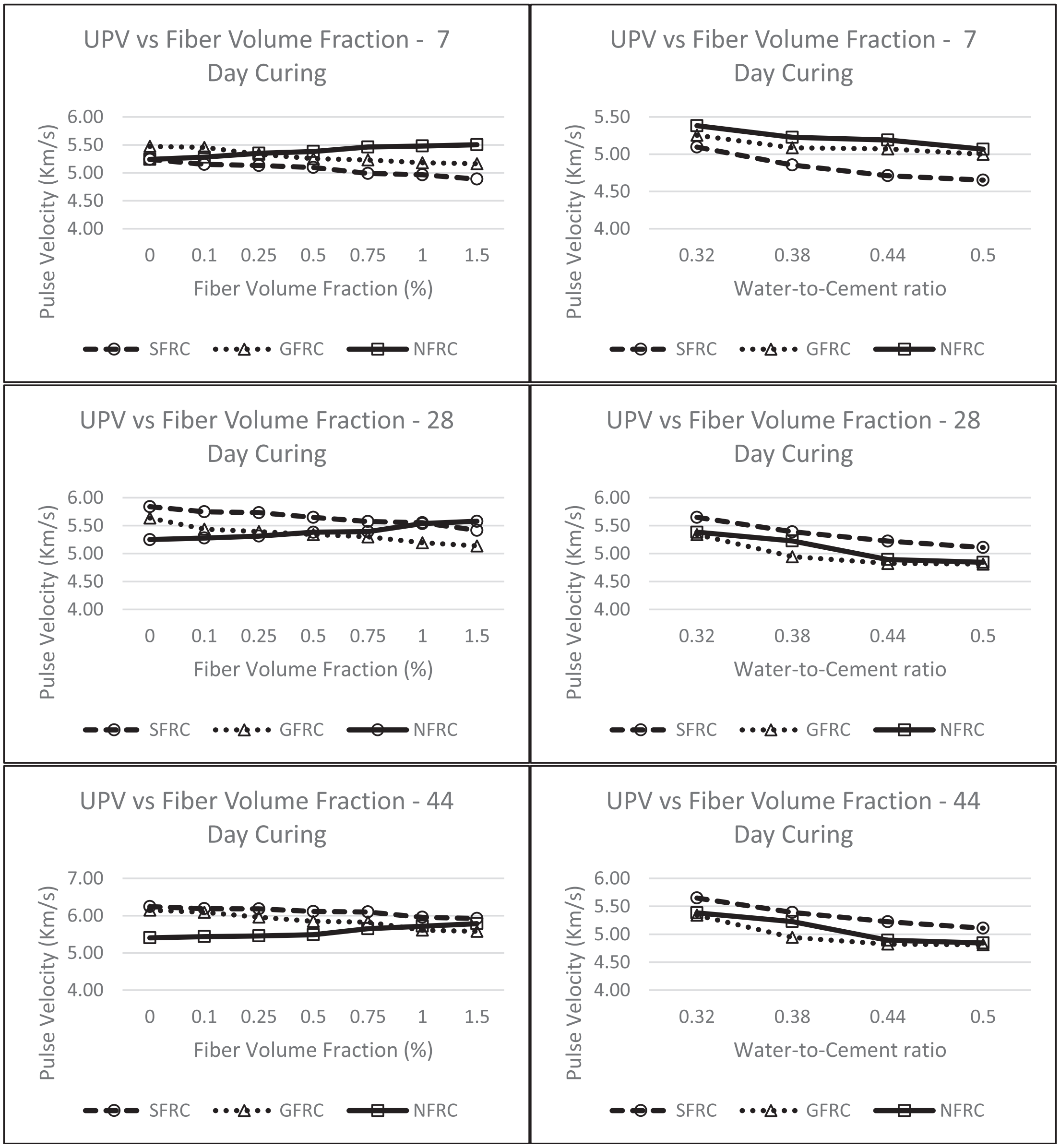


Figure 1. Ultrasonic Pulse Velocity of Steel, Glass, and Nylon Fiber Reinforced Concrete vs fiber volume fraction and water to cement ratio.

Table 6. Compression test machine experimental data.

Name	Compressive Strength, F_c (MPa)	
	28 Day	44 Day
SFRC-1	36.50	41.60
SFRC-2	38.72	47.42
SFRC-3	41.50	49.50
SFRC-4	41.57	50.07
SFRC-5	30.71	39.71
SFRC-6	22.48	31.48
SFRC-7	19.43	28.43
SFRC-8	43.03	52.03
SFRC-9	44.77	53.77
SFRC-10	45.80	54.80
GFRC-1	35.91	40.42
GFRC-2	37.58	46.58
GFRC-3	38.54	47.54
GFRC-4	39.53	48.53
GFRC-5	28.12	37.12
GFRC-6	19.66	28.66
GFRC-7	15.26	24.26
GFRC-8	40.22	49.22
GFRC-9	42.61	51.61
GFRC-10	43.61	53.61
NFRC-1	35.76	41.10
NFRC-2	36.61	45.01
NFRC-3	37.11	46.11
NFRC-4	37.92	46.92
NFRC-5	27.19	36.19
NFRC-6	21.28	30.28
NFRC-7	14.44	23.44
NFRC-8	40.86	49.86
NFRC-9	42.46	51.46
NFRC-10	32.72	39.72

FRC's compressive strength based on UPV. Thus, more studies need to be done to investigate how fiber type, fiber volume fraction, and other mix proportions affect the propagation of ultrasonic pulse velocity because this alteration has not been accounted for by many equations. The majority of equations attempting to predict the compressive strength based on UPV mainly focus on plain concrete and SFRC, not many equations focus on GFRC and NFRC. Eq. (11), also referred to as the proposed equation, is capable of predicting the compressive strength of SFRC, GFRC, and NFRC with fiber volume fractions ranging from 0-1.5% and water to cement ratio ranging from 0.32-0.50. Figure 6 shows the comparison between the predicted and measured compressive strength using the proposed equation. It can be observed that the COV of the proposed equation is lower than those of equations shown in Figures 3, 4, and 5. Where V is ultrasonic pulse velocity (Km/sec) and A, B, and C are defined in Table 7. Figure 7 shows the proposed Eq. (11) being used to predict the compressive strength of SFRC, GFRC, and NFRC. The dotted line represents the proposed equation and the black circles represent the measured data. A good agreement between the experimental results and those predicted by the proposed equation can be observed in this figure.

$$f_c' = A*V^2 + B*V - C \tag{11}$$

5. Conclusion

This article investigates how three different structural fibers (steel, glass, and nylon) compare against each other when it comes to increasing concrete's performance. In particular comparison of the synthetic fiber against the other two fibers is the focus of this study since there is less experience working with synthetic fibers. These fibers were compared with one another while keeping the cement, aggregate type, and coarse to fine aggregate ratio constant and changing the water to cement ratio – which affects workability - and fiber volume fraction. A specific fiber volume fraction range (0–1.5%) was selected and used to allow better comparison for all different types of fibers. After in detail comparison between the effects of the three different types of fibers on the behavior of concrete it was discovered that the UPV of SFRC and GFRC decreased with an increase in fiber volume fraction because high dosages of steel and glass fibers reduce workability causing fiber ball production (balling) and generating lack of homogeneity. However, the capability to resist the bridging stress transferred across a crack of SFRC and GFRC is eminent, resulting in high compressive strength. On the other hand, nylon fiber does not reduce the workability of concrete similar to what is observed in steel and glass fibers, but its capability to resist the bridging stress transferred across a crack is considerably lower than the other fiber types, and this results in lower compressive strength. The specimens were examined for ultrasonic pulse velocity and compressive strength at different ages (7, 28, and 44 days). The Ultrasonic Pulse Velocity of SFRC and GFRC decreased with the addition of fibers while the UPV of NFRC increased with the addition of fibers. The highest pulse velocity was achieved by SFRC-1 (6.24 km/s) and the lowest pulse velocity was achieved by NFRC-7 (5.16 km/s). The compressive strength of SFRC and GFRC increased with the addition of fiber up to 1.5% vol. The

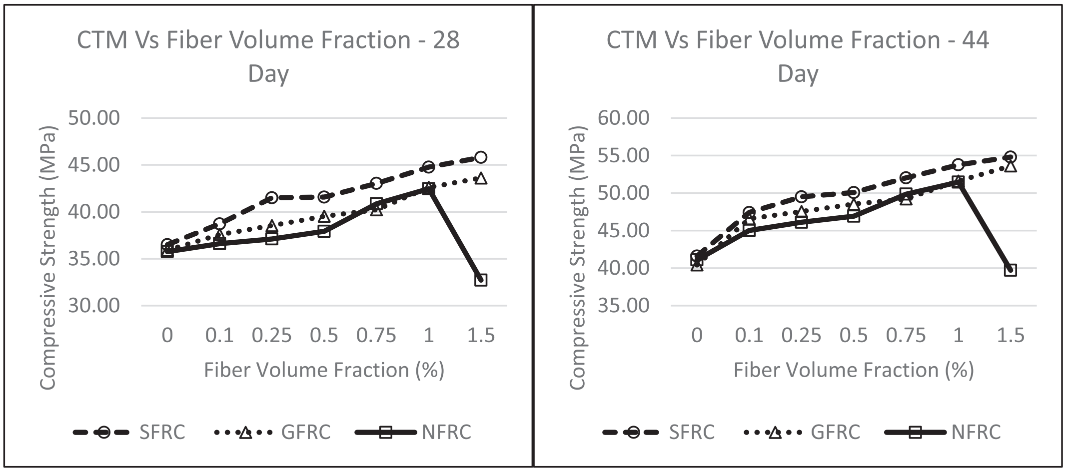
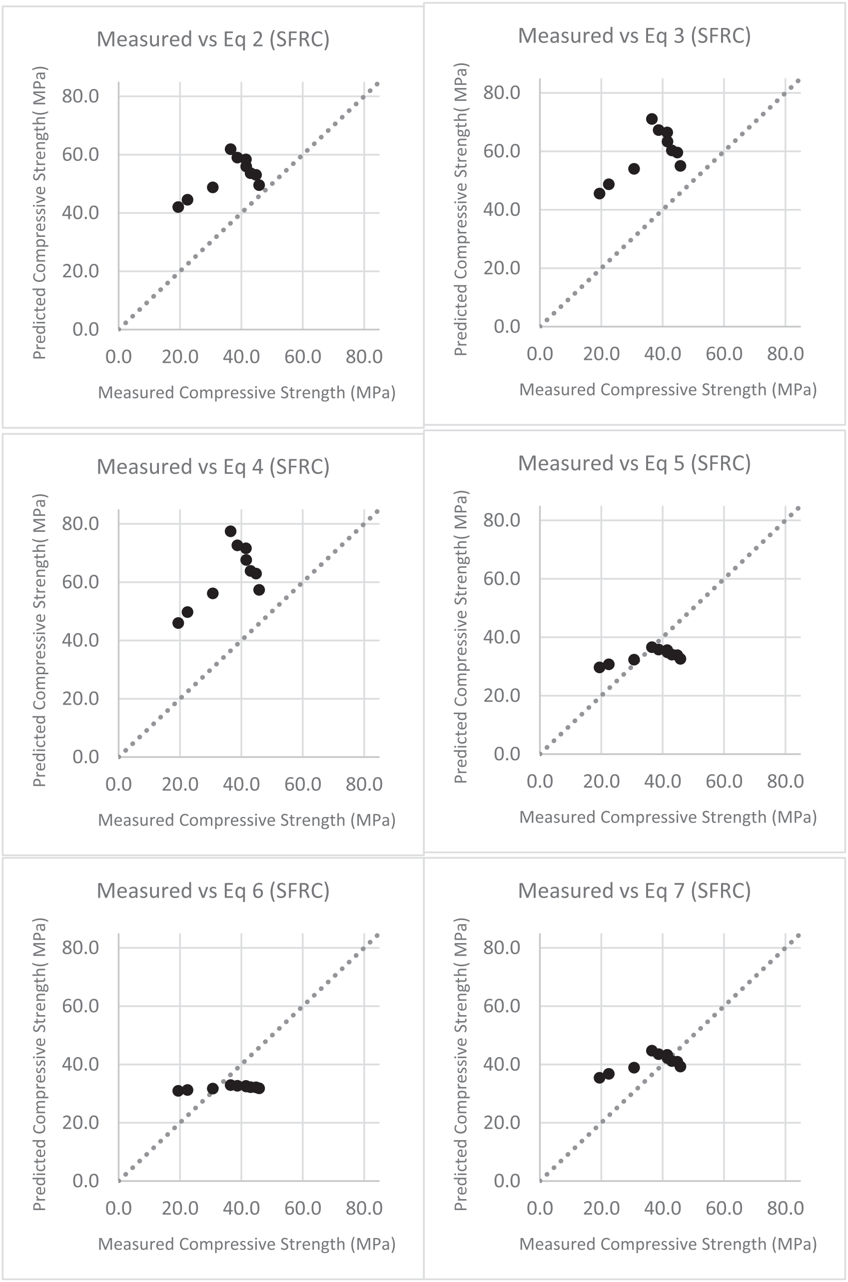
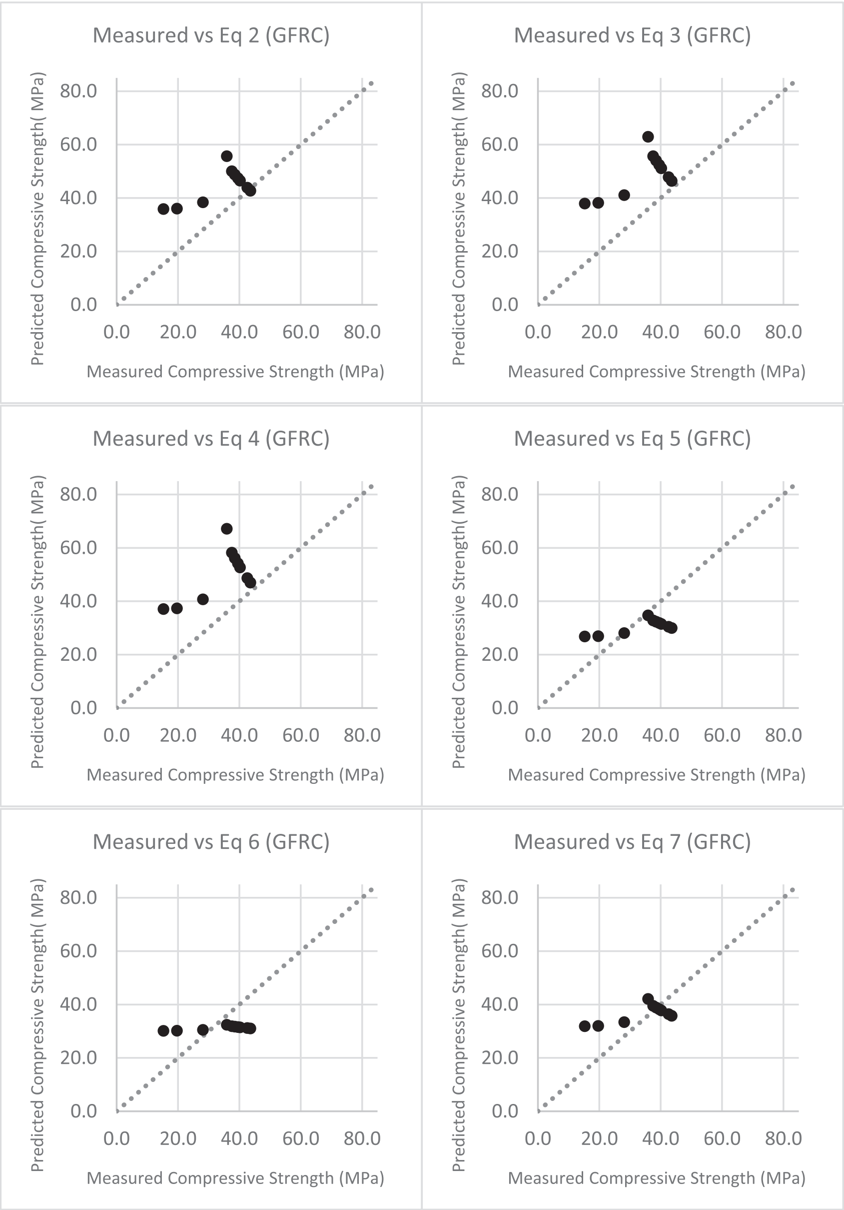


Figure 2. Compressive strength of steel, glass, and nylon fiber reinforced concrete.



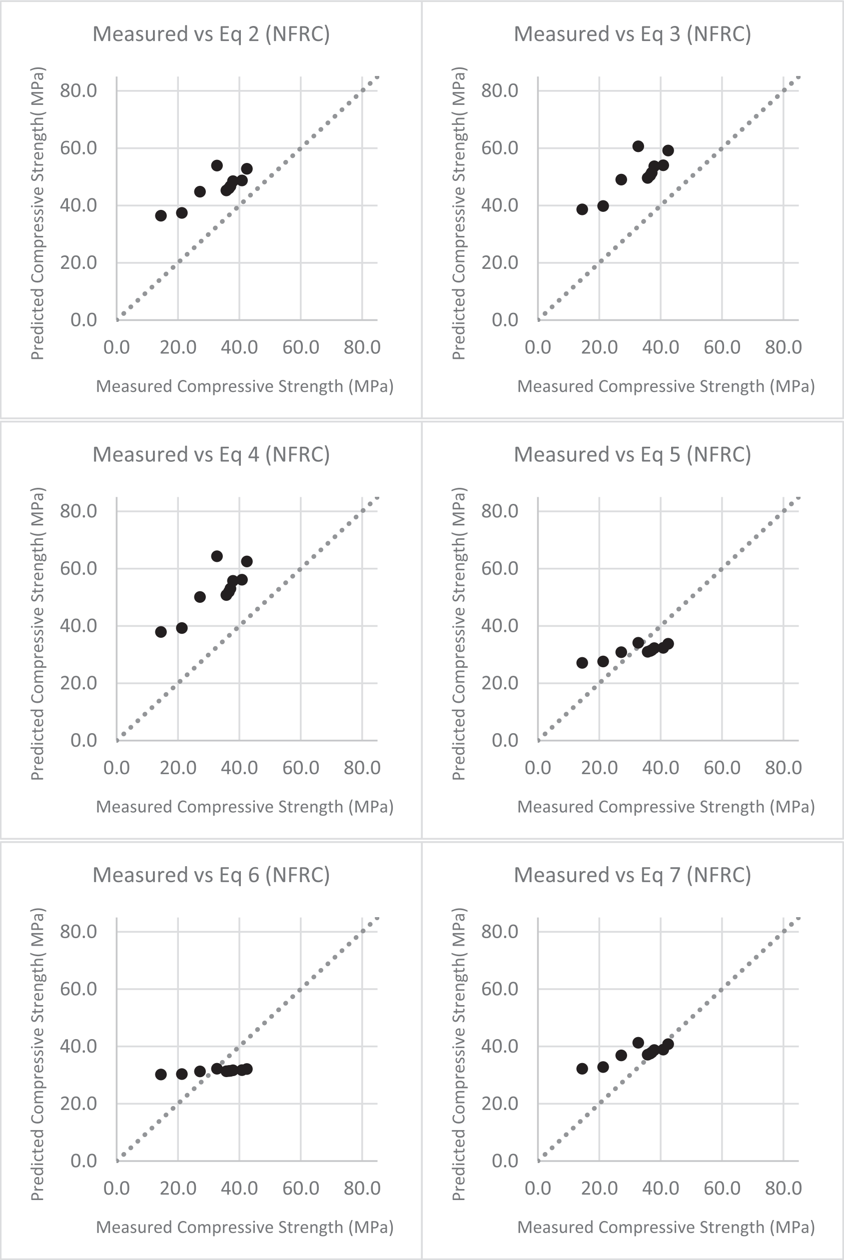
Equation	2	3	4	5	6	7
COV	50.6%	68.5%	78.6%	23.2%	27.4%	23.9%

Figure 3. SFRC's measured vs predicted compressive strength.



Equation	2	3	4	5	6	7
COV	38.4%	50.2%	54.2%	26.1%	28.6%	24.0%

Figure 4. GFRC's measured vs predicted compressive strength.

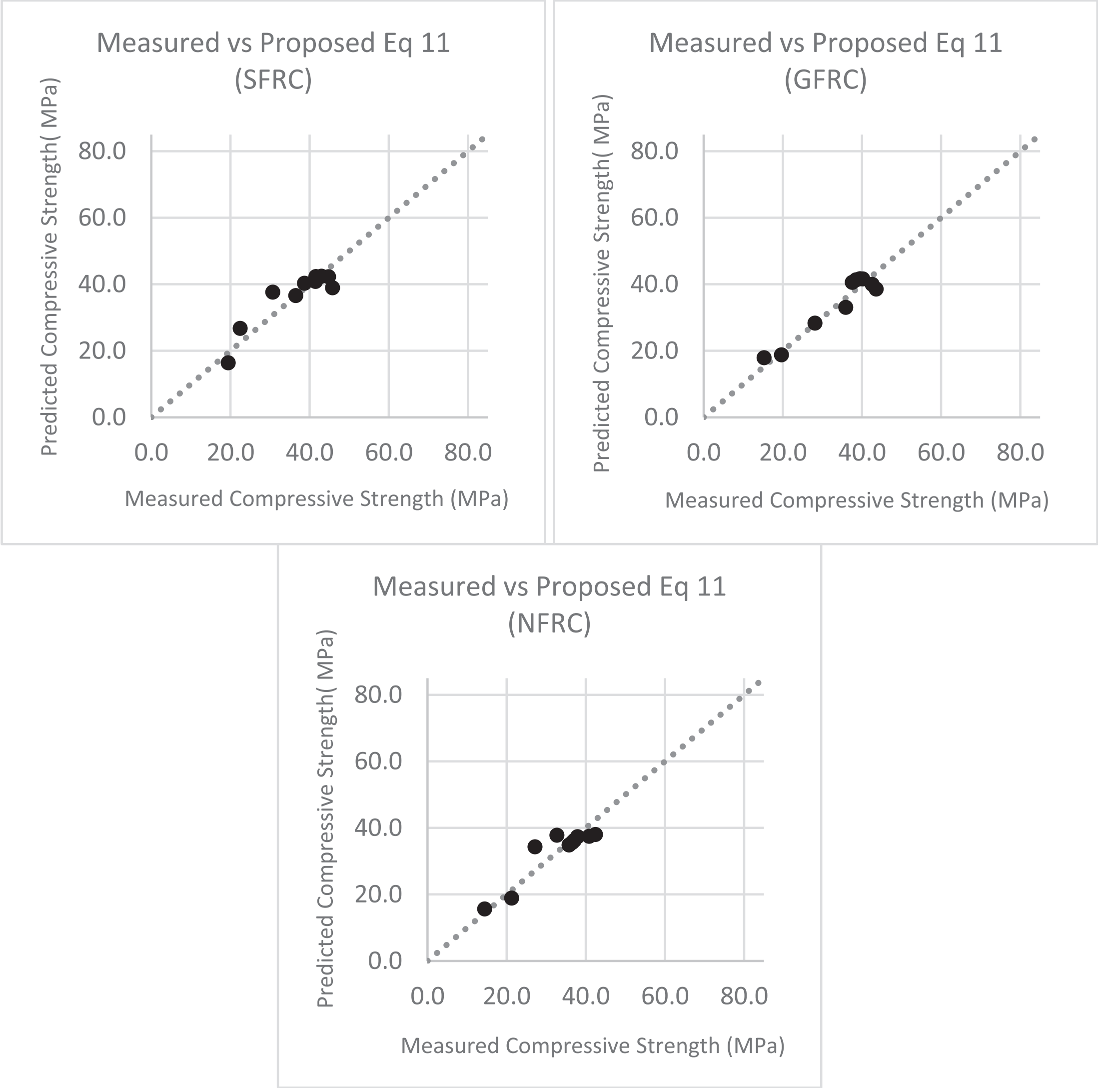


Equation	2	3	4	5	6	7
COV	46.2%	60.2%	65.1%	22.4%	26.2%	25.6%

Figure 5. NFRC's measured vs predicted compressive strength.

Table 7. Values for A, B, and C coefficients.

Type of FRC	A	B	C
SFRC	-107.07	1200.1	3320.3
GFRC	-88.553	943.65	2472.3
NFRC	-51.451	566.09	1519



Proposed Equation	11	11	11
COV	10.5%	8.3%	11.1%

Figure 6. Proposed Equations vs Measured Data.

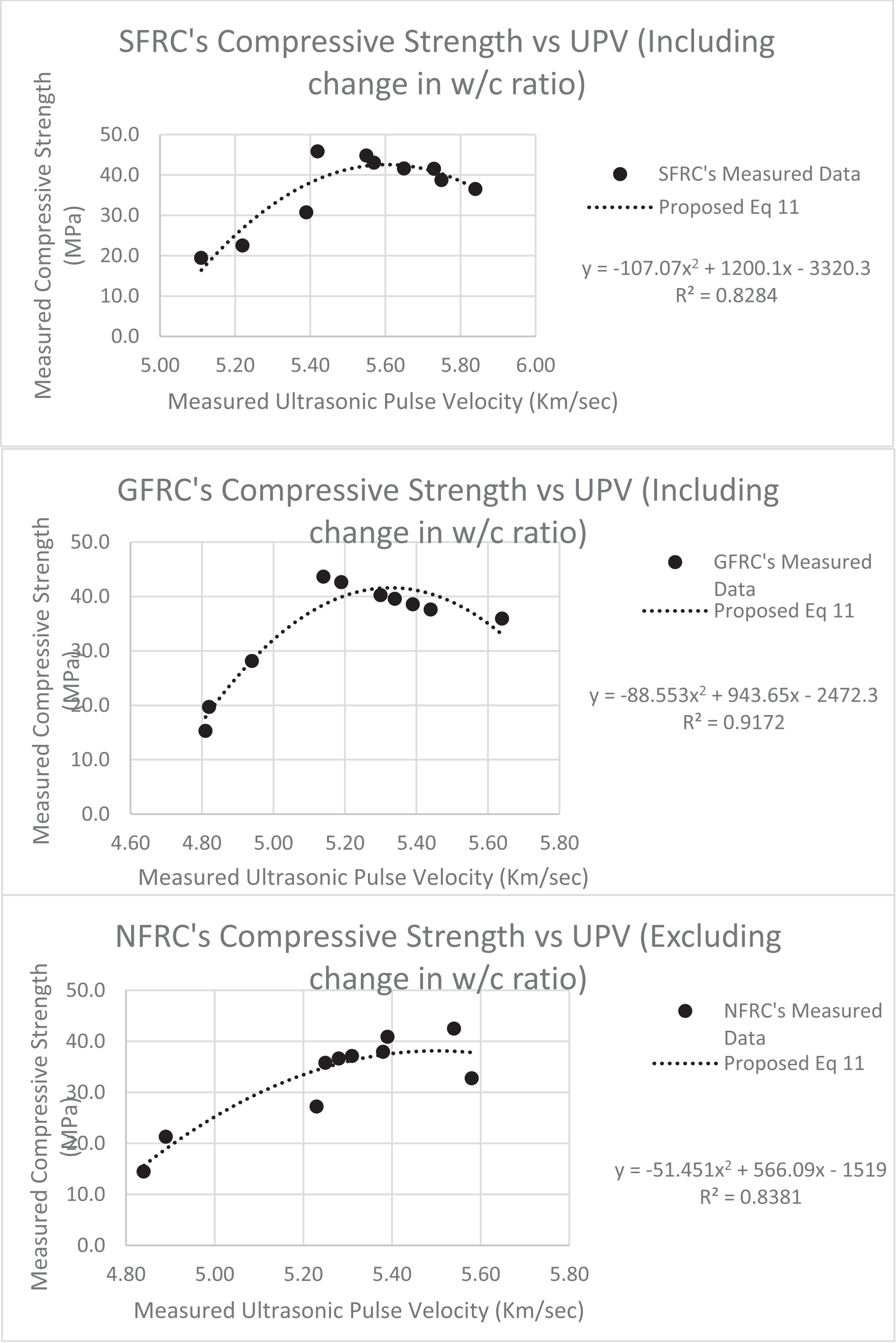


Figure 7. Measured Compressive Strength vs Measured UPV for SFRC, GFRC, and NFRC.

compressive strength of NFRC increased with the addition of fiber volume up to 1.0%. The highest compressive strength was achieved by SFRC-10 (54.8 MPa) and the lowest compressive strength was achieved by NFRC-7 (14.44 MPa). Moreover, it was observed that the equations found in the literature relating FRC's ultrasonic pulse velocity to its compressive strength had high coefficients of variations and the need for a single equation applicable for more than one type of fiber was identified. In this study a simple equation was created capable of predicting the compressive strength of SFRC, GFRC, and NFRC with fiber volume fractions ranging from 0-1.5% and water to cement ratio ranging from 0.32-0.50. The proposed empirical equation can better estimate the compressive strength of SFRC, GFRC, and NFRC compared to other equations that do not consider the type of fiber as a variable. The COV for the proposed equation is 10.5%, 8.3%, and 11.1% for steel, glass, and nylon FRC respectively. Which shows the accuracy of the proposed equation.

Declarations

Author contribution statement

SAMAN HEDJAZI: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

DANIEL CASTILLO: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

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Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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