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JAITA

http://publisher.uthm.edu.my/ojs/index.php/jaita

e-ISSN : 2716-7097

Journal of Advanced Industrial Technology and Application

Experimental Investigation of Ultrasonic Pulse Velocity (UPV) Test Specimen in Assessing the Strength of Steel Fiber Reinforced Concrete Structure

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DOI: https://doi.org/10.30880/jaita.2021.02.02.004
Received 14 November 2021; Accepted 30 November 2021; Available online 15 December 2021

Abstract: This study aims to conduct the Ultrasonic Pulse Velocity (UPV) test and compressive strength test of Steel Fiber Reinforced Concrete (SFRC). This paper also examines the correlation of UPV test data and compressive strength test data for SFRC specimens. The experiments were carried out with the same value of the water-cement ratio, superplasticizer but different fiber volumes of steel fiber. Twelve prism sizes 100mm x 100mm x 500mm were casted and 0.5%, 1.0%, and 1.5% of steel fiber reinforced concrete were added and the prisms undergone curing for 7, 14 and 28 days. The highest value of the UPV test at the x-axis is SFRC-0.5%, 6.26 km/s at seven days and 6.8377 km/s at 14 days. The highest value of the UPV test at the y-axis is SFR-0.5%, 6.68 km/s at seven days and 6.34 km/s at 28 days. Nevertheless, the grading is still considered excellent concrete quality based on BS1881. The highest value of compressive strength is SFRC-1.0%, 193.2 MPa at 14 days. The R-squared value for the correlation coefficient between UPV result and the compressive strength result at the x-axis and y-axis is 0.9963 and 0.9966 respectively. The non-linear models show high regression coefficient of R-squared close to 1.00, which means the parameters are strongly correlated. The correlation equation obtained can be used to predict compressive strength based on UPV data for steel fiber volume fraction up to 1.5%. Thus, it can be concluded that percentage of steel fiber added, affect the strength of the tested concrete specimens and the optimized value of steel fiber added is at 1% in this study.

Keywords: Ultrasonic Pulse Velocity (UPV), compressive strength, Steel Fiber Reinforced Concrete, prism

1. Introduction

Concrete is one of the most convertible and generally acknowledged structural materials in the world. It is made of Portland Cement, which is relatively strong in compression but weak in tension and eventually breaks. It can also crack even before it has completely hardened. To overcome the deficiencies in tension is by using steel reinforcement and a sufficient volume of steel fiber. Steel-fiber reinforced concrete generally works for shotcrete technology. It has become widely used for structural elements as its heterogeneous structural material [1]. It can reduce construction time and protect the structure from cracking. It offers more excellent protection in extreme loading conditions, natural hazards, and disasters. Steel fiber reinforcement may also increase concrete's energy absorption and impact strength [2]. The

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real contribution is to increase the durability of the concrete under any loading. Apart from shotcrete application, steel fibers have also been used in pavement, pipes, thin sheet elements and other part of structures.

The Non-Destructive Test (NDT) is to inspect the condition of the building structure without demolition. The function of the NDT is to estimate the ultrasonic wave velocity required for distribution in concrete. It is also time-saving, cheap, practical and can identify the areas positively affected by the deterioration. It can also be accomplished even if the structures are in service or occupied, leading to no idle time investigating damage due to the stiffness of the elasticity affecting the results. The Ultrasonic Pulse Velocity (UPV) wave velocity is reduced in concrete with poor compaction or material damage [3].

Ultrasonic Pulse Velocity test is one of the non-destructive tests that evaluate the concrete's consistency and integrity. UPV test can be used on the structural elements to check the material quality by calculating the compression wave velocities in various locations and modulus of elasticity. Areas with lower velocities have lower strength and density corresponding to high-velocity regions [4], [5]. Therefore, in this research, NDT UPV test could be used to inspect the steel fiber reinforced concrete condition whether it has an excellent concrete quality or not based on the relevant Standard requirement. UPV test is also essential in checking the concrete homogeneity without damaging the concrete's surface.

2. Methodology

2.1 Preparation of Materials

In this experimental study, the testing was conducted to correlate the Ultrasonic Pulse Velocity and Compressive Strength of SFRC. The equipment used consists of an Ultrasonic Pulse Velocity Tester and Compression Test Machine (CTM). Table 1 shows the scope of work of the experiment. Each specimen will have a different volume of steel fiber which are 0%, 0.50%, 1.0% and 1.5%, the water-cement ratio is constant, equal to 0.2, with a constant superplasticizer of 16 kg/m^3, and concrete grade of C30.

Table 2 shows the fiber properties used in the experiment. While Fig.1 illustrating types of steel fibers. The steel fiber used is the straight type (Fig. 1(a)) with a length of 13 mm, a diameter of 0.2 mm, a density of 7800 kg/m^3 and tensile strength of 2600 MPa. The supplier provides the properties of the materials. The pouring and curing of the 100 mm x 100 mm x 500 mm of beam specimens were referred to ASTM C192 Standard Practice for Making and Curing Concrete Test Specimens in Laboratory [6]. For the Ultrasonic Pulse Velocity (UPV) test, Standard referred was ASTM C597 Standard Test Method for Pulse Velocity for Concrete and for the compressive test [7], the Standard referred was ASTM C116-90 Test Method for Compressive Strength of Concrete Using Portions of Beams Broken in Flexure [8]. It is for compressive strength measured by days which are seven days, 14 days and 28 days.

Table 3 shows the mix properties for each of the specimens. It is for the mixture of the concrete mix design. However, the data only refers to 0 %, 0.50%, 1.0% and 1.5% of fiber volume with water to cement ratio of 0.2, it still follows the properties including cement (kg/m^3), fine aggregates (kg/m^3), coarse aggregates (kg/m^3), water (kg/m^3), and the fiber (kg/m^3).

Table 1 - Scope of works of the experiment

Portland Cement	TYPE I/II
Specimen Geometry	Prism 100mm x 100mm x 500mm
Water-Cement Ratio	0.2
Fiber Volume Fraction (%)	0, 0.5, 1.0,1.5
Superplasticizer (kg/m^3)	16
Curing Time (days)	7,14, 28

Table 2 - Fiber properties

Fiber Material	**Fiber Type**	**Length (mm)**	**Diameter (mm)**	**Density(kg/m^3)**	**Tensile Strength (MPa)**	**Aspect Ratio**
Steel	Straight	13	0.2	7800	2600	65

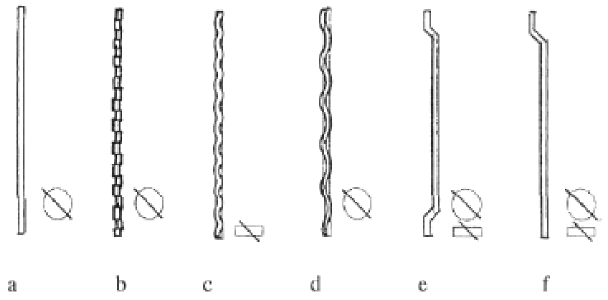

Fig. 1 - Steel fiber types with different geometric properties, (a) straight; (b) waved; (c) crescent; (d) class C hooked end; (e) hooked end; (f) single hooked end [5]

Table 3 - Mix properties

Name	Fiber Vol.	Cement		Coarse Aggregate		Fine Aggregate		Water		SP		Fiber
	(%)	kg/m³	kg	kg/m³	kg	kg/m³	kg	kg/m³	kg	kg/m³	kg	kg
SFRC-0	0	1000	82.5	800	66	433	35.72	200	16.5	16	1.32	0
SFRC-0.5	0.5	1000	82.5	800	66	433	35.72	200	16.5	16	1.32	3.26
SFRC-1.0	1	1000	82.5	800	66	433	35.72	200	16.5	16	1.32	6.52
SFRC-1.5	1.5	1000	82.5	800	66	433	35.72	200	16.5	16	1.32	9.78

2.2 Ultrasonic Pulse Velocity (UPV)

Fig. 2 shows the beam is being tested using UPV's equipment on a direct method for both axes. For UPV test, the equipment needs to be checked to ensure it is functional and has zero-time adjustment. Then, the coupling agent (high grease) was applied to the transducer faces and pressed the faces together. The instrument uses a microprocessor to record this delay time, subtracted from the subsequent transit time measurements. A coupling agent is applied to the end of the calibrated bar and pressed firmly against the ends of the bar until a stable transit time is displayed and then adjust the zero reference until the displayed transit time matches the bar's value. To test the transit time, the beam width of the vibrational pulses transmitted by the transducers is significant. It is admissible to evaluate transit times all over the sides of a structure with some deficit of precision and specificity. Since such measurements may only indicate surface layers and predicted pulse velocities would not match those obtained through transmission, measurements over the same surface should not be used unless just one facet of the structure is accessible. Then, the Ultrasonic Pulse Velocity (UPV) test value in km/s, was obtained. Apparatus and standard procedures are described in ASTM C 597.

(a) (b)

Fig. 2 - UPV test, direct method at both (a) x-axis and; (b) y-axis

2.3 Compressive Strength Test

The length of the broken beam is measured as shown in Fig. 3(a). The broken beam was then positioned on the plate's base in the machine, as shown in Fig. 3(b), so that the load could be applied constantly without causing any shock. The moving head is moving at approximately 3 kN/S when the machine is running idle. Fig. 3(c) shows that the beam specimens are tested until failure. The total load is recorded and then divided with the cross-sectional area from Fig. 3(a) to get the compressive strength. ASTM C116-90, Test Method for Compressive Strength of Concrete Using Portions of Beams Broken in Flexure was referred for this testing.

(a) (b) (c)

Fig. 3 - (a) broken beam; (b) before compressive strength test and; (c) after compressive strength test

3. Results and Discussions

3.1 Ultrasonic Pulse Velocity (UPV)

Table 4 and Table 5 show the result of the UPV data test on the experiment, which focuses on the value of the UPV and the transit time for 7 days, 14 days and 28 days. Some data were incomplete due to the pandemic causing the testing to be halted. Meanwhile, Table 6 and Table 7 show the value of UPV on the experiment converted to distance per second. The specimens were cured for 7 days, 14 days and 28 days. Each of the specimens has a different value of steel fiber volume. It can be seen from Table 6 that the highest value of the UPV test at the x-axis is SFRC-0.5%, 6.26 km/s at seven days and 6.8377 km/s at 14 days. Meanwhile, Table 7 shows that the highest value of the UPV test at the y-axis is SFR-0.5%, 6.68 km/s at 7 days and 6.34 km/s at 28 days. Hence, the shorter the time transmit, the higher the value of UPV (km/s). The distance of X-axis and Y-axis are Lx: 100mm and Ly: 100mm respectively.

Table 4 - UPV test data on transit time at x-axis

Name	Transit Time (μsec)											
	7 Days				14 Days				28 Days			
	Beam 1	Beam 2	Beam 3	Average	Beam 1	Beam 2	Beam 3	Average	Beam 1	Beam 2	Beam 3	Average
SFRC-0%	21.3	21.6	21.3	21.40	21.3	22.1	22	21.80	-	-	-	-
SFRC-0.5%	16.2	13.8	18.7	16.23	10.4	24.7	14.6	16.57	29.2	51.7	29.2	36.70
SFRC-1.0%	243.7	23.3	23.6	96.87	21.2	21.5	26.8	23.17	23.2	22.3	21.9	22.47
SFRC-1.5%	24.7	13.6	45.9	28.07	17.6	21.5	16	18.37	20	21.9	26.6	22.83

Table 5 - UPV test experiment's data on transit time at y-axis

Name	Transit Time (μsec)											
	7 Days				14 Days				28 Days			
	Beam 1	Beam 2	Beam 3	Average	Beam 1	Beam 2	Beam 3	Average	Beam 1	Beam 2	Beam 3	Average
SFRC-0%	21.6	30.6	21	24.40	21.2	21.4	21.7	21.43	-	-	-	-
SFRC-0.5%	14.7	15.8	14.5	15.00	23.6	23.4	24.8	23.93	15.9	15.5	15.9	15.77
SFRC-1.0%	23.5	24.1	25.5	24.37	21.1	20.5	26.2	22.60	20.6	20	20.7	20.43
SFRC-1.5%	39.1	14.6	12.1	21.93	17.4	17.4	22.7	19.17	19.9	21	20.2	20.37

Table 6 - UPV test data at x-axis

Name	Ultrasonic Pulse Velocity (UPV) test (km/s)											
	7 Days				14 Days				28 Days			
	Beam 1	Beam 2	Beam 3	Average	Beam 1	Beam 2	Beam 3	Average	Beam 1	Beam 2	Beam 3	Average
SFRC-0%	4.70	4.63	4.70	4.67	4.70	4.53	4.61	4.61	-	-	-	-
SFRC-0.5%	6.17	7.25	5.35	6.26	9.62	4.05	6.85	6.84	3.43	1.93	3.43	2.93
SFRC-1.0%	0.41	4.29	4.24	2.98	4.72	4.65	3.73	4.37	4.31	4.48	4.57	4.45
SFRC-1.5%	4.05	7.35	2.18	4.53	5.68	4.65	6.25	5.53	5.00	4.57	3.76	4.44

Table 7 - UPV test experiment's data at y-axis

Name	Ultrasonic Pulse Velocity (UPV) test (km/s)											
	7 Days				14 Days				28 Days			
	Beam 1	Beam 2	Beam 3	Average	Beam 1	Beam 2	Beam 3	Average	Beam 1	Beam 2	Beam 3	Average
SFRC-0%	4.63	3.27	4.76	4.22	4.72	4.67	4.61	4.67	-	-	-	-
SFRC-0.5%	6.80	6.33	6.90	6.68	4.24	4.27	4.03	4.18	6.29	6.45	6.29	6.34
SFRC-1.0%	4.26	4.15	3.92	4.11	4.74	4.88	3.82	4.48	4.85	5.00	4.83	4.90
SFRC-1.5%	2.56	6.85	8.26	5.89	5.75	5.75	4.41	5.30	5.03	4.76	4.95	4.91

Table 8 shows the grading of concrete quality at the x-axis. Aside from the non-applicable data from the SFRC-0% at 28 days, SFRC-0.5% at 28 days and SFRC-1.0% seven days displayed poor concrete quality by referring to BS1881 [9] (Table 9). One factor that came out as poor concrete quality is a technical error from the Ultrasonic Pulse Velocity (UPV) test's machine, in which the previous user who used the UPV machine did not clean it after using it, and heavy grease got clogged in the wire connecting the transducers.

Table 8 - The grading of concrete quality at x-axis

Name	Ultrasonic Pulse Velocity (UPV) test, km/s			Concrete Quality (GRADE)		
	7 Days	14 Days	28 Days	7 Days	14 Days	28 Days
SFRC-0%	4.67	4.61	-	Excellent	Excellent	-
SFRC-0.5%	6.26	6.84	2.93	Excellent	Excellent	Poor
SFRC-1.0%	2.98	4.37	4.45	Poor	Excellent	Excellent
SFRC-1.5%	4.53	5.53	4.44	Excellent	Excellent	Excellent

Table 9 - The classification of the concrete quality based on UPV (BS 1881)

Pulse Velocity in Concrete (Km/Sec)	Concrete Quality (GRADE)
> 4.0	Very Good to Excellent
3.5 – 4.0	Good to Very Good, Slightly Porosity May Exist
3.0 – 3.5	Satisfactory but Loss of Integrity is Suspected
< 3.0	Poor and Loss of Integrity Exist

Table 10 shows the grading of concrete quality at the y-axis. By referring to the concrete quality of grading based on BS1881 (Table 9), all concrete quality is excellent. SFRC-0.5% has the highest value at 7 days and 28 days, 6.68 km/s and 6.34 km/s. At the SFRC-1.5%, the UPVs data have the highest value at 7 days, which is 5.89 km/s, and it was gradually decreasing although it is still in the excellent grade. It is because too much SFRC in the concrete makes it brittle. The higher frequency components of the pulse are smaller than the lower frequency components, and the pulse inception types are more rounded with greater distance travelled.

With the addition of fibers, the UPV of the SFRC drops. The SFRC develops voids and non-homogeneity, which significantly slows down the UPV test. The introduction of fibers affects the fluidity of the substance, making concrete less practical. In other words, steel fibers added causing the workability reduction and generating lack of homogeneity. At more fiber volume fractions, SFRC of compressive strength should decrease. However, if concrete’s workability is not improved, the increased fiber volume fractions will intensify the fiber bridging effect, resulting in a limited increase in compressive strength.

Table 10 - The grading of concrete quality at y-axis

Name	Ultrasonic Pulse Velocity (UPV) test, km/s			Concrete Quality (GRADE)		
	7 Days	14 Days	28 Days	7 Days	14 Days	28 Days
SFRC-0%	4.22	4.67	-	Excellent	Excellent	-
SFRC-0.5%	6.68	4.18	6.34	Excellent	Excellent	Excellent
SFRC-1.0%	4.11	4.48	4.90	Excellent	Excellent	Excellent
SFRC-1.5%	5.89	5.30	4.91	Excellent	Excellent	Excellent

3.2 Compressive Strength

Table 11 shows the compressive strength data on 7 days, 14 days, and 28 days with different steel fiber volumes. Overall, the highest value of compressive strength is SFRC-1.0%, 193.2 MPa at 14 days, SFRC-1.5%, 191.6 MPa at 14 days and SFRC-0.5%, 181.2 MPa at 28 days. The lowest compressive strength value is at control with 0% of steel fiber’s volume in the concrete mixture, 64.11 MPa at 14 days. The trend of these data shows an increase of compressive strength when steel fibers were added but limited at certain percentage than it began to drop, but still much higher strength than control specimen without the steel fiber.

Table 11 - Compressive strength test data

Name	Compressive Strength Test, MPa		
	7 Days	14 Days	28 Days
SFRC-0%	102.1	64.11	-
SFRC -0.5%	137.1	-	181.2
SFRC-1.0%	-	193.2	98.23
SFRC-1.5%	-	191.6	88.16

Fig. 4 displays the pattern of overall compressive strength value of the SFRC at 7, 14 and 28 days. Aside from incomplete data, SFRC-0.5% has an increasing pattern compared to SRFC-0%, SRFC-1.0% and SFRC-1.5%, though on day 7, they have the high value but eventually, as time goes by, it decreased gradually as the concrete lose its strength. The concrete takes a longer time to gains strength after casting. The rate of development of concrete compressive strength is faster during the first 28 days of casting and then slows down. Thus, it can be seen that the inclusion of steel fiber can increase the compressive strength but with certain volume fraction limitation and for this study, 1% steel fiber addition is the optimized percentage.

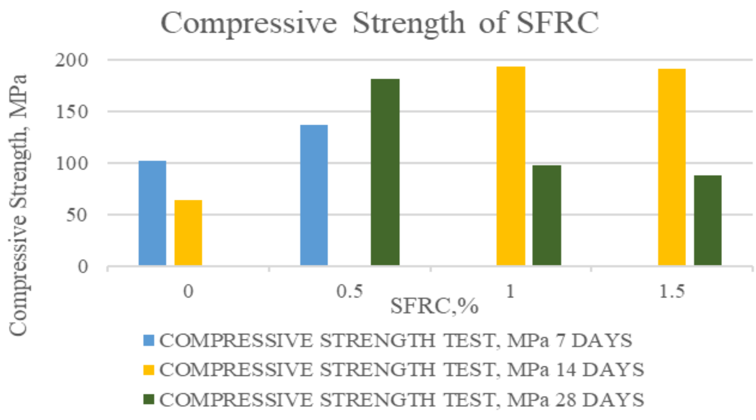

Fig. 4 - Compressive strength against Steel Fiber Reinforced Concrete (SFRC) at 7, 14 and 28 days

3.3 Correlation between Compressive Strength and UPV

The best fit correlation between compressive strength and UPV was determined by analyzing the experimental data statistically. Fig. 5 and Fig. 6 show the relationship between the compressive strength and UPV on both axes, the y-axis and the x-axis, at 28 days. In this study, non-linear model was adopted. Generally, the shorter the transit time, the higher the UPV value, as the sounds travel through the shortest distance.

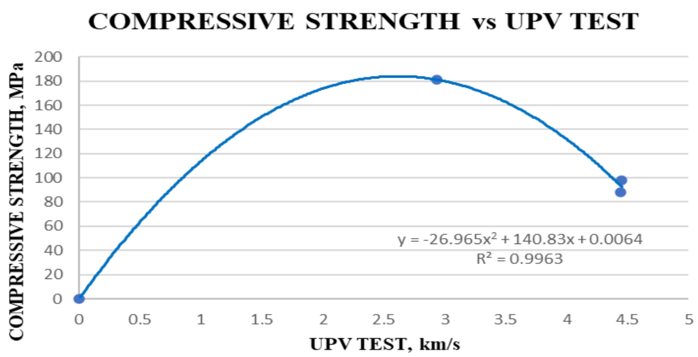

Fig. 5 - Steel Fiber Compressive Strength vs UPV test at x-axis

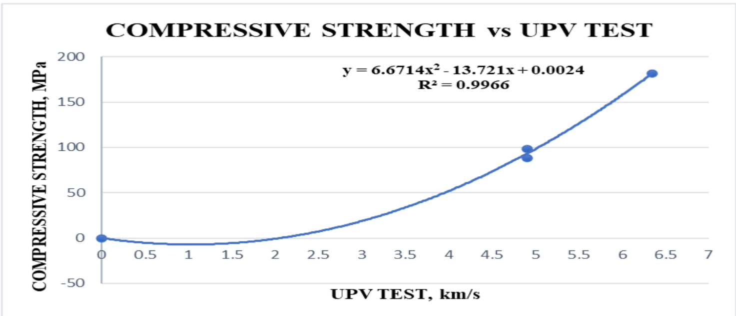

Fig. 6 - Steel Fiber Compressive Strength vs UPV test at y-axis

Fig. 5 and Fig. 6 results are from the correlation of compressive strength versus UPV test. As a whole, the higher the R-squared (also called regression coefficient), the better the model fits the data. The plotted data between compressive strength and UPV of tested specimens showed a high correlation with regression coefficient R-squared value of 0.9963 and 0.9966 from Fig. 5 and Fig. 6 respectively. The non-linear models show high regression coefficient of R-squared close to 1.00, which means the parameters are strongly correlated. Thus, these equations can be used and reliable to predict compressive strength based on UPV data for steel fiber volume up to 1.5%. The estimation of compressive strength by NDT is significant in reducing the number of specimens for compressive strength test.

The correlation equations obtained from both Figures are as follows:

$$y = -26.965x^2 + 140.83x + 0.0064 \quad (1)$$

$$y = 6.6714x^2 - 13.721x + 0.0024 \quad (2)$$

where, y = compressive strength, MPA and x= UPV, km/s.

4. Conclusions

It can be concluded that different volume of steel fiber affects the SFRC performance. The volume of the steel fiber added was at 0.50%, 1.0% and 1.5%. The samples were tested with a UPV test to determine the quality of the concrete. The higher the volume of the steel fiber, the higher the tendency of the concrete to be brittle. It affected the value of the UPV test as SFRC develops voids and non-homogeneity. At SFRC-1.5 %, the grading of concrete quality on the y-axis gradually falls, with values of 5.89 km/s at seven days, 5.30 km/s at 14 days, and 4.91 km/s at 28 days. Nevertheless, the grading is still considered excellent concrete quality based on BS1881.

The highest value of compressive strength is at SFRC-1.0% at 14 days which is 193.2 MPa, and it is gradually decreasing at 28 days which is 98.23 MPa. On the other hand, the lowest compressive strength value is in control (SFRC-0%) which is 64.11 MPa. The inclusion of steel fiber seems to increase the compressive strength but with volume fraction limitation. Thus, it can be concluded that percentage of steel fiber added, affect the strength of the tested concrete specimens and the optimized value of steel fiber added is at 1% in this study.

For the correlation between UPV and compressive strength data, the non-linear models show high regression coefficient of R-squared close to 1.00, in which can be considered as strongly correlated. Thus, the correlation equation obtained can be used to predict compressive strength based on UPV data for steel fiber volume fraction up to 1.5% of similar specimens. This estimation method is significant in reducing the number of specimens for compressive strength test.

Acknowledgement

The authors would like to acknowledge the financial support for this study from Ministry of Higher Education - Fundamental Research Grant Scheme of 600-IRMI/FRGS 5/3 (178/2019) and other supports from Institute for Infrastructure Engineering and Sustainable Management (IIESM), School of Civil Engineering and Research Management Centre (RMC), UiTM Shah Alam, Selangor. These supports are gratefully acknowledged.

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