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RESEARCH

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Estimation of Compressive Strength and Member Size of Steel Fiber Reinforced Concrete Using Stress Wave-Driven Nondestructive Test Methods

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Abstract

Among fiber-reinforced composites, steel fiber has been widely-used for concrete infrastructure such as silos, tunnels, specifically aiming at reducing the weight of concrete and enhancing its strength by overcoming the brittleness. However, there is still little known about appropriate quality management and applicability assessment for steel fiber composites. This study fills this knowledge gap by testing the possibility of maintenance through steel fiber concrete thickness estimation and assessing the applicability of the quality management instrument. To this end, this study utilizes two different stress wave-driven non-destructive test methods: ultrasonic pulse velocity and impact-echo methods. The ultrasonic pulse velocity method was employed to estimate the compressive strength of steel fiber reinforced concrete, while the impact-echo method was applied to estimate the thickness of various steel fiber reinforced concrete members. As a quality management factor of concrete, correlations between steel fiber mixing ratios and compressive strengths were experimentally explored and validated by error ratios for twenty-four specimens. The reliability was relatively high overall. The average error rate of all the specimens with steel fiber mixing ratios of 0, 0.75 and 1% was 3.36%. Accordingly, the results prove the applicability of the non-destructive test methods for building quality management.

Keywords: estimation, compressive strength, member size, steel fiber reinforced concrete, nondestructive test

1 Introduction

Bond strength is essential to securing the integration performance of concrete and reinforcing rods. Because the normal strength of concrete and reinforcing rods lack integration performance, high-strength concrete is generally used. One weakness of concrete is that despite its excellent durability, it lacks deformation capacity prior to the occurrence of cracks, and it involves a risk of brittle fracture after the occurrence of the cracks. In order to address this problem, research on fiber reinforced concrete has been conducted continually.

Among fiber-reinforced composites, steel fiber strengthens concrete and makes up for brittleness, which is a weakness of the concrete material. For this reason, steel fiber is used to reduce the weight of concrete in order to enhance its strength. While it is a recent trend to use steel fiber reinforced concrete for silos, tunnels, etc., there are few studies on its quality management and applicability assessment.

Nondestructive inspection refers to a defect detection technique for investigating the integrity, performance, and the status of defects without destroying the target structure. It can confirm the soundness and improve the reliability by applying the proper nondestructive inspection to each purpose. The nondestructive inspection can be applied to the design strength required by the hardened concrete in the new building, the life evaluation and the proper repair system for defects can be adopted

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through the diagnosis of the structure in the existing building, and the soundness evaluation of the member of the building in the remodeling building. In addition, the thickness of the member placed during construction supervision can be evaluated through nondestructive inspection to match the drawing, and in the case of a building where the drawing is lost, the thickness of the member can be measured through nondestructive inspection to prepare the drawing. Recently, the application of high performance and eco-friendly concrete has been expanded, and there is a lack of research on technology development and applicability evaluation to apply stress wave-based nondestructive inspection method. In case there is no information on the sizes of the column, slab, and beam members of the existing concrete structures, the estimation of the sizes of various members using the impact echo method can be applied to the regeneration of drawings for buildings whose structural drawings are lost and the maintenance of structures, etc.

This study applies the non-destructive test method, which is a quality management instrument, to assess the quality management and applicability of steel fiber reinforced concrete. The non-destructive test method is different from the ordinary destructive test method, which destructs or cuts off a member of a building to facilitate the inspection of the inside when a problem, such as crevice, heterogeneous substance, etc., occurs. This inspection method, however, examines defects, stress, characteristics, material change, integrity, etc., inside or outside a building by using radiation, ultrasound, electromagnetism, liquid, heat, light, etc., without changing or destructing its material properties or internal structures. It causes no destruction to materials. The non-destructive test method, however, may produce different results depending on the inspection type, instrument, and data analysis method. This study utilizes the two non-destructive test methods the ultrasonic pulse velocity method and the impact-echo method to derive the correlation between the steel fiber mixing ratio and compressive strength, which is a quality management factor of concrete, and to assess the applicability of the quality management instrument by calculating the error rate of steel fiber reinforced concrete size estimation.

2 Literature Review

Previous studies on the diagnosis of concrete structures using ultrasonic pulse velocity method and impact echo method have shown that, Hong and Cho (2006) aimed to examine ordinary concrete material inspection techniques by means of the impact echo method, which is a type of nondestructive test method, based on stress waves. Kim et al. (2007) focused on estimating the location of crevices and the compressive strength of ordinary concrete slabs by means of the impact-echo method and the surface-wave method. Kang et al. (2017) conducted an onsite applicability assessment to examine whether the method would be applicable to defect detection around the drain-pipe. Liu et al. (2017) proposed a way to distinguish crack echo and reinforced rod echo by using a phase spectrum. The correlation between the phase spectrum amplitude and the inclination in the echo frequency was examined. Benaicha et al. (2015) examined the correlation between steel fiber reinforced concrete and ultrasonic pulse velocity. In the nondestructive test on the extent of concrete hardening, the correlation between ultrasonic pulse velocity and concrete properties compressive strength, flexural strength, and elastic modulus by means of the ultrasonic pulse velocity method. Specimens were produced in a prism shape (10 cm × 10 cm × 40 cm) and a cylinder shape (16 cm × 32 cm). Thomas and Ramaswamy (2007) examined the mechanical properties of steel fiber reinforced concrete. A new empirical formula was proposed to predict the compression, tensile strength, and elastic modulus of SFRGC. Kim et al. (2016) examined flexural behavior characteristics of ultra-high-performance steel fiber reinforced concrete. It was verified that the proposed method to utilize steel fiber reinforced ultra-high-performance concrete and to perform flexural behavior modeling would be effective in predicting the flexural performance of a steel fiber reinforced concrete beam whose compressive strength is approximately 150 MPa. Choi et al. (2015) analyzed the relation between concrete compressive strength and tensile strength depending on the steel fiber mixing ratio. Domski (2016) examined the border between ordinary concrete and fiber reinforced concrete. While many researchers have conducted studies that utilize nondestructive test methods in order to evaluate the performance of ordinary concrete, there has been no significant research on quality management of steel fiber reinforced concrete in application of various non-destructive test methods.

3 Theoretical Background

Since the mid-1900s, research has been conducted to estimate compressive strength of concrete by means of non-destructive test methods, including the ultrasonic pulse velocity method (ASTM 597), the rebound hardness method, etc.

The ultrasonic pulse velocity method is utilized in such areas as medical diagnosis, structural steel inspection, etc. In these areas, molecules are small and highly dense and the density distribution is stable. The characteristics of wave motion spread are good enough to detect internal defects accurately. When applied to structures, however, the molecules of concrete are big and the density is not uniform. In this case, it is difficult to apply the ultrasonic pulse velocity method. Hence, it is essential to take into consideration various affecting elements for accurate estimation.

The ultrasonic pulse velocity method is applicable to inspecting the size and thickness of irregular specimens within a specimen, uniformity and corrosion of specimens, compressive strength, elastic modulus, etc., and the scope is expanding continually (Naik and Malhotra 1991). As to the basic principle of ultrasonic pulse velocity method operation, short and strong electric signals are sent to the converter and then the converter vibrates according to the resonance frequency. The vibration is transmitted to materials through the medium in contact, and then this is detected by the receiving converter at the opposite side. Depending on the arrangement of the transmitter and receiver, the ultrasonic pulse velocity method is classified to the direct type, indirect type, rectangular type, etc. When material properties are to be assessed by measuring the ultrasonic pulse speed, the level of measuring precision needs to be quite high. The longitudinal ultrasonic pulse velocity V inside an elastic body is calculated as follows:

$$\mathrm{V} = \sqrt{\frac{E}{\rho}\frac{(1-\nu)}{(1+\nu)(1-2\nu)}} \tag{1}$$

where E: dynamic elastic modulus, υ: Poisson's ratio, and ρ: density.

According to the theory of stress wave propagation, the propagation velocity of waves that is determined by the medium's material properties may be represented with Eq. 2 that is not related to wave kinds but the wavelength and frequency.

$$\mathrm{V} = \mathrm{f} \times \lambda \tag{2}$$

In other words, for heterogeneous materials such as concrete, the level of attenuation due to high frequency is significant, and thus it is inappropriate to increase the frequency. Details about the ultrasonic pulse velocity method are presented in KS F 2731 and ASTM C597-97.

It is possible to grasp the positions of boundaries or defects inside a medium by means of the impact-echo method (Sansalone and Carino 1989). If the dimensions of the concrete member are known, it is possible to estimate specific defects of concrete. When the propagation speed of compression wave is known, it is possible to grasp the position of the continuing surface inside a specimen by measuring the arrival time of reflected waves. In a domain time that is obtainable by collecting stress waves from a vibration source by means of an accelerometer, the records are converted into a frequency domain using the fast Fourier transform (FFT). As a result, the frequency of the first mode becomes that of the peak amplitude. Based on this data, it is possible to easily acquire the frequency of multiple reflections and to calculate the speed of compressive waves accordingly, the distance up to the reflective boundary of a plate structure, d; speed of compression waves: V_p, and resonance frequency: f. A possible approximate solution may be Eq. 3:

$$\mathrm{d} = \frac{V_p}{2f} \tag{3}$$

Among stress waves propagated through media upon elastic impact, body waves are propagated through the inside of a medium by the compression and tension of medium particles (P waves) or shear movements right and left or up and down (S waves). Surface waves (R waves) occur when a medium has a free surface similar to the ground surface. The particles of compressional waves (P waves) move forward and backward in a parallel direction of wave progress, causing bulk strain with no shear strain. Particles of shear waves (S waves) cause shear strain with no bulk strain. When displacement in an axial direction is restrained, the speed of compressive waves (v_p) is determined by Eq. 4 in consideration of the medium's elastic modulus and density.

$$v_p = \sqrt{\frac{M}{\rho}} = \sqrt{\frac{E(1-\nu)}{\rho(1+\nu)(1-2\nu)}} \tag{4}$$

where, M: constrained modulus, E: Young's modulus, ρ: density, and υ: Poisson's ratio.

4 Experimental Program: Correlation between Ultrasonic Pulse Velocity and Compressive Strength

The purpose of this study is to analyze the correlation between compressive strength and ultrasonic pulse velocity of steel fiber reinforced concrete according to the ages in order to confirm the quality control applicability of steel fiber reinforced concrete using nondestructive test method.

For design strength conditions of 24 MPa and 30 MPa, the ultrasonic pulse velocity of 5 different test specimens was measured at different aging points of 16 h, 20 h, 24 h,

Table 1 Test results (24 MPa)

Time (h)	Contents	
	Compressive strength (MPa)	Ultrasonic pulse velocity (m/s)
16	0.65	97.00
20	0.62	96.00
24	1.07	885.02
48	2.84	2261.66
72	6.38	2676.80
120	14.03	2946.10
168	19.29	3061.37
360	20.38	3342.47
672	23.50	3316.47

48 h, 72 h, 120 h, 168 h, 360 h, and 672 h as shown in Fig. 8a. A compressive strength test then followed, the measurements of which are presented in Tables 1, 2 and Figs. 1, 2, and 3.

In the experiment where the design strength was 24 MPa, the ultrasonic pulse velocity was 97.00 m/s at the aging point of 16 h, 96.00 m/s 20 h, 885.02 m/s 24 h, 2261.66 m/s 48 h, 2676.80 m/s 72 h, 2946.10 m/s 120 h, 3061.37 m/s 168 h, 3342.47 m/s 360 h, and 3316.46 m/s 672 h, respectively. As shown in Fig. 1, the wave velocity increased drastically from the aging point of 16 h to 72 h, and thereafter, it increased gradually up to the aging point of 672 h.

As shown in Fig. 2 as for compressive strength measurement, it was 2.71% of the design strength at the aging point of 16 h, 2.60% 20 h, 4.46% 24 h, 11.83% 48 h, 26.58% 72 h, 58.46% 120 h, 80.38% 168 h, 84.92% 360 h, and 97.92% 672 h, respectively.

Figure 3 shows that as for the correlation between compressive strength and wave velocity, as wave velocity increased, compressive strength increased accordingly. Estimation equations $y = 869.86 \ln(x) + 749.95,\ R^2 = 0.94$ was derived.

In the experiment where the design strength was 30 MPa, the ultrasonic pulse velocity was 96.80 m/s at the aging point of 16 h, 96.00 m/s 20 h, 400.55 m/s 24 h, 2366.44 m/s 48 h, 2840.04 m/s 72 h, 2978.40 m/s 120 h, 3090.73 m/s 168 h, 3317.00 m/s 360 h, and 3299.42 m/s 672 h, respectively. As shown in Fig. 4, the wave velocity increased drastically from the aging point of 16 h to 72 h, and thereafter, it increased gradually up to the aging point of 672 h. As shown in Fig. 5 as for compressive strength measurement, it was 2.06% of the design strength at the aging point of 16 h, 2.06% 20 h, 3.73% 24 h, 14.40% 48 h, 29.87% 72 h, 58.97% 120 h, 71.47% 168 h, 76.93% 360 h, and

Table 2 Test results (30 MPa)

Time (h)	Contents	
	Compressive strength (MPa)	Ultrasonic pulse velocity (m/s)
16	0.62	96.80
20	0.62	96.00
24	1.12	400.55
48	4.32	2366.44
72	8.96	2840.04
120	17.69	2978.40
168	21.44	3090.73
360	23.08	3317.00
672	22.50	3299.42

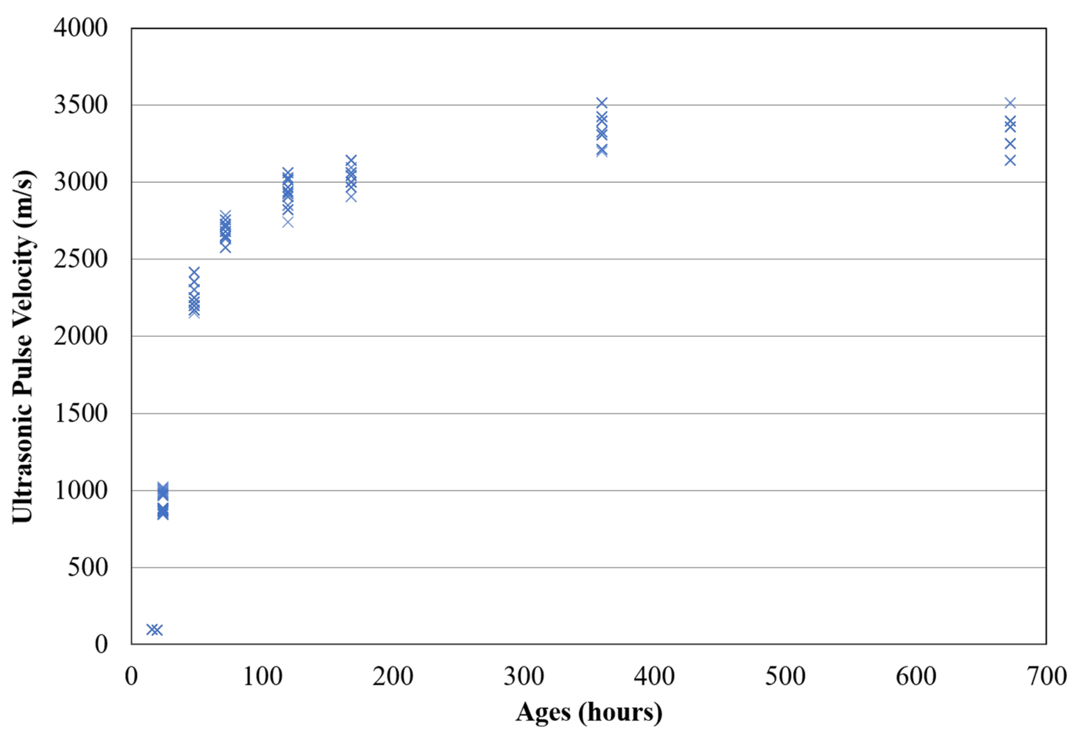


Fig. 1 Ultrasonic pulse velocity with ages (24 MPa)

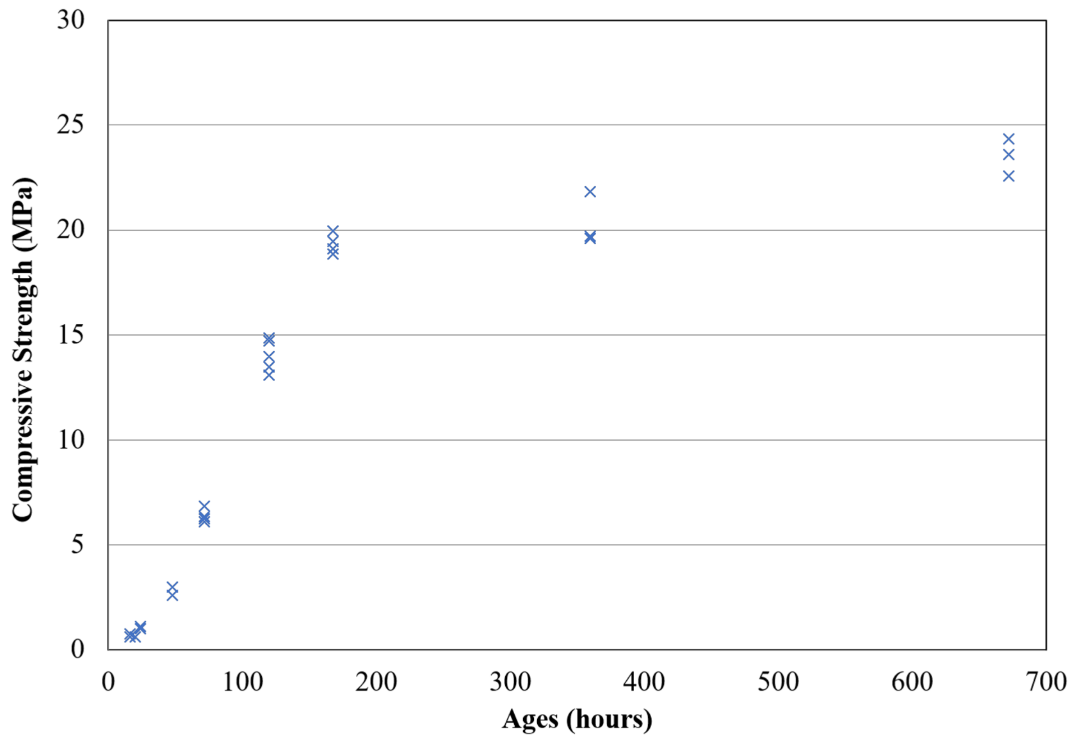


Fig. 2 Compressive strength with ages (24 MPa)

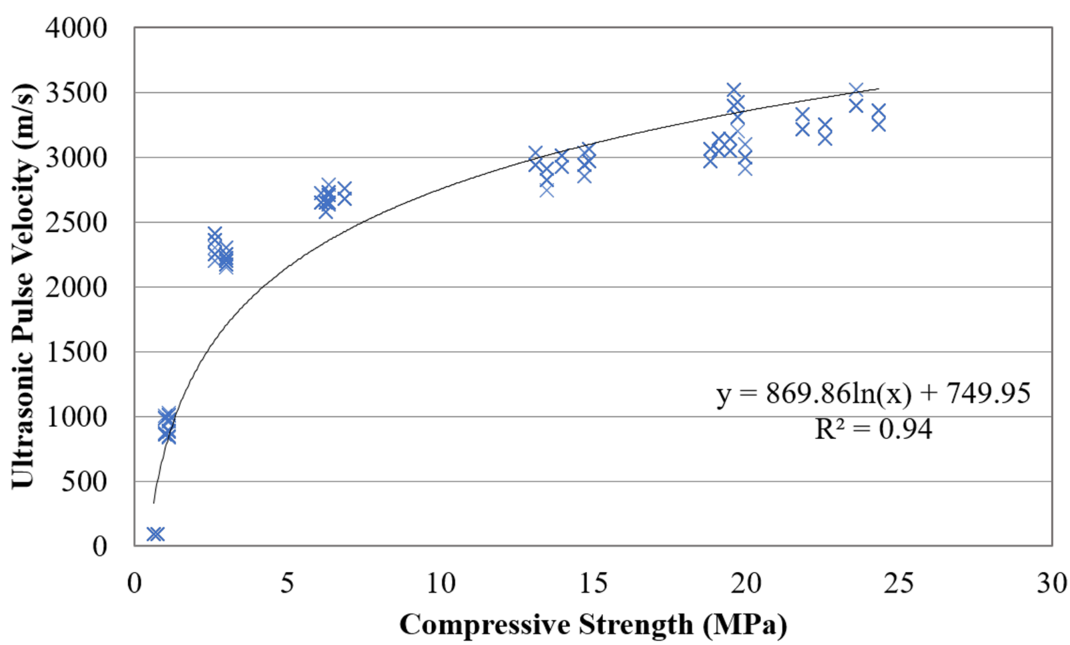


Fig. 3 Relation of ultrasonic pulse velocity and compressive strength (24 MPa)

75.00% 672 h, respectively. Figure 6 shows that as for the correlation between compressive strength and wave velocity, as wave speed increased, compressive strength increased accordingly. Estimation equations $y = 839.57 \ln(x) + 743.88$, $R^2 = 0.95$ was derived. As a result of comparison with existing experimental

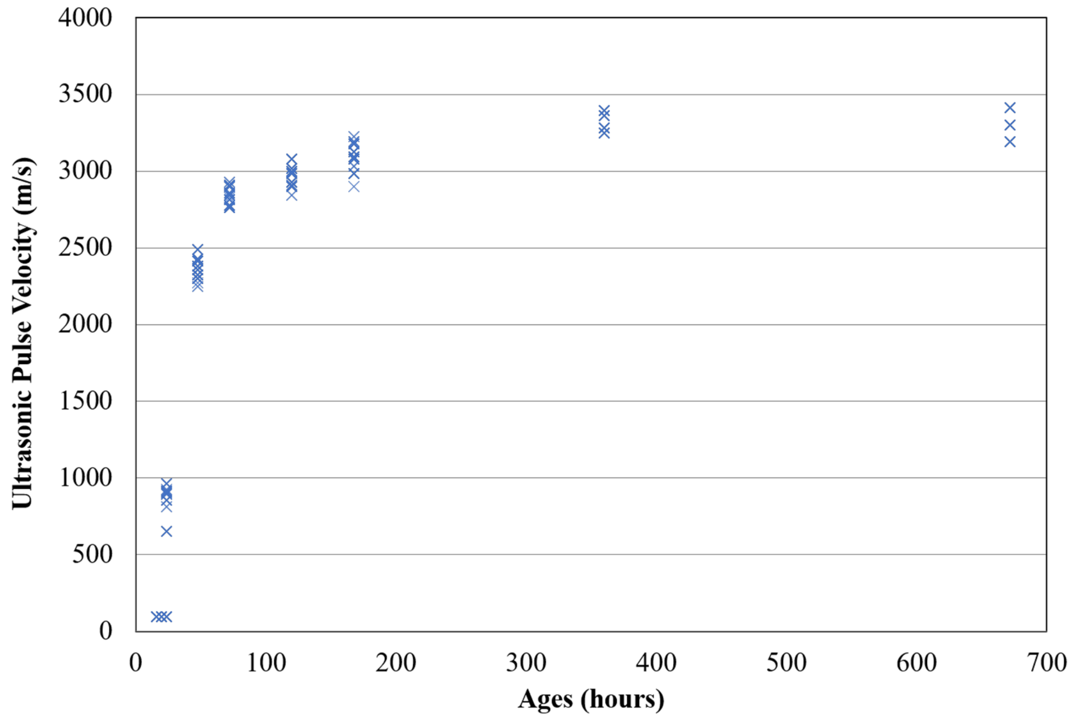


Fig. 4 Ultrasonic pulse velocity with ages (30 MPa)

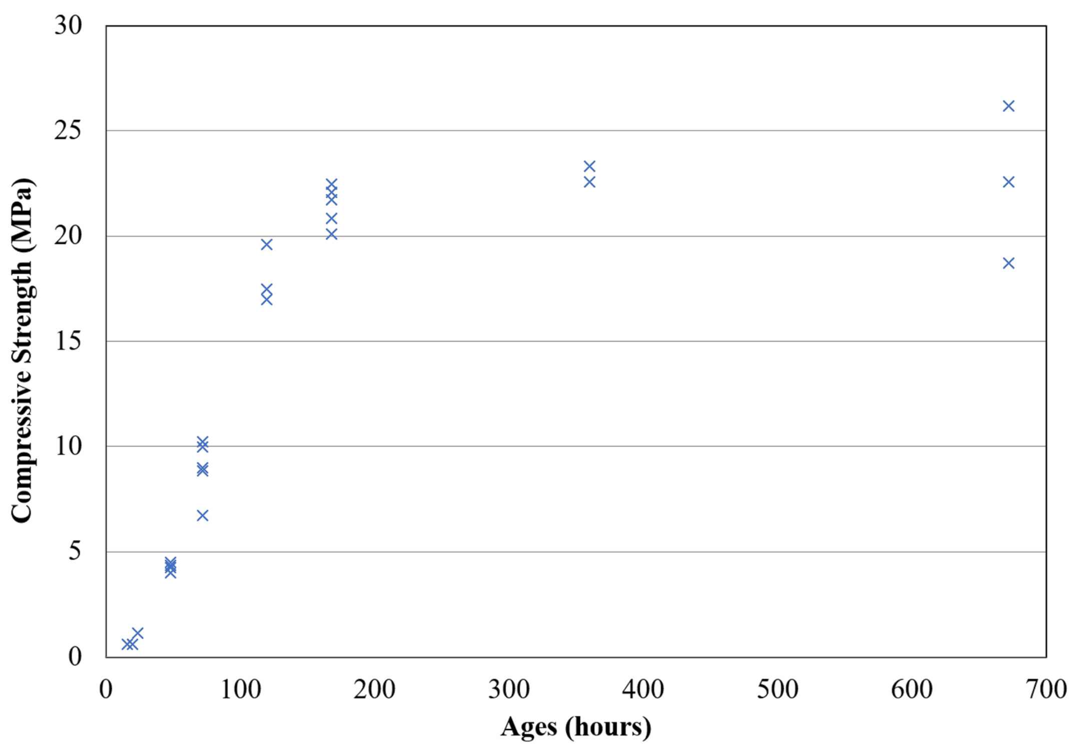


Fig. 5 Compressive strength with ages (30 MPa)

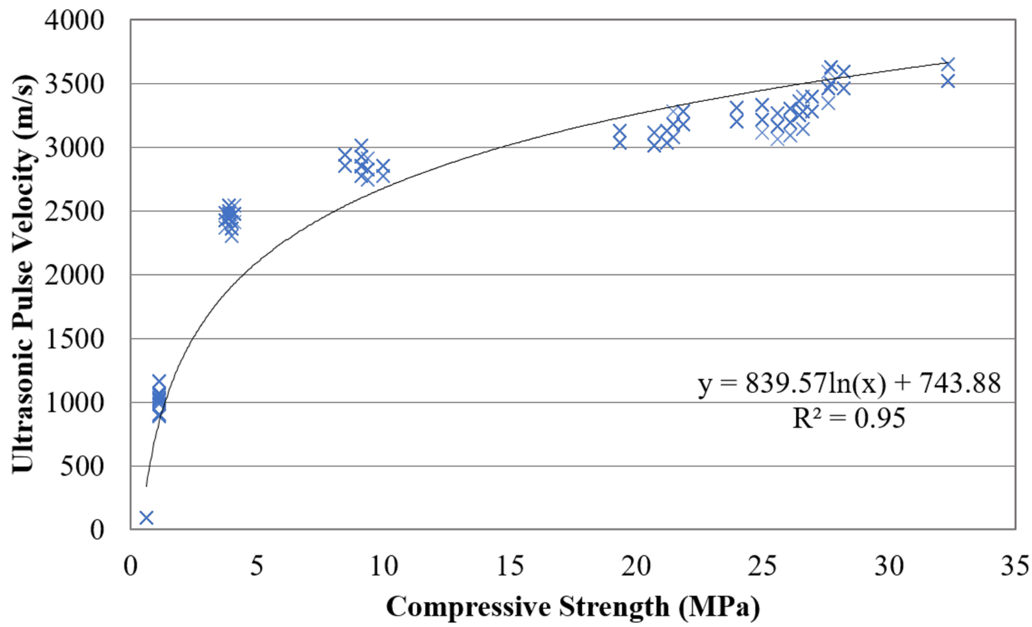


Fig. 6 Relation of ultrasonic pulse velocity and compressive strength (30 MPa)

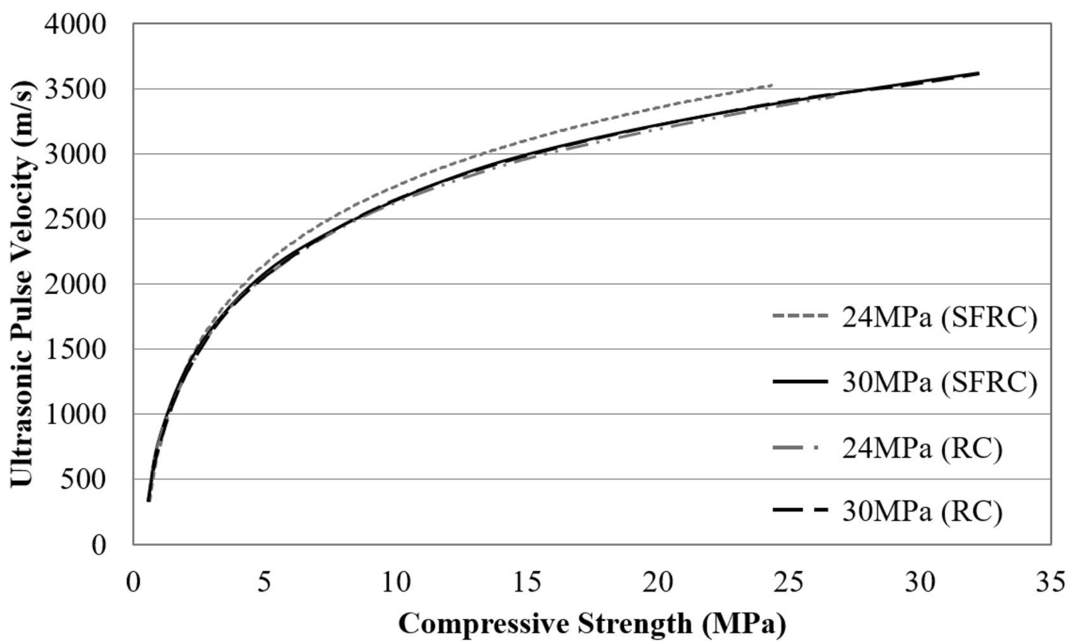
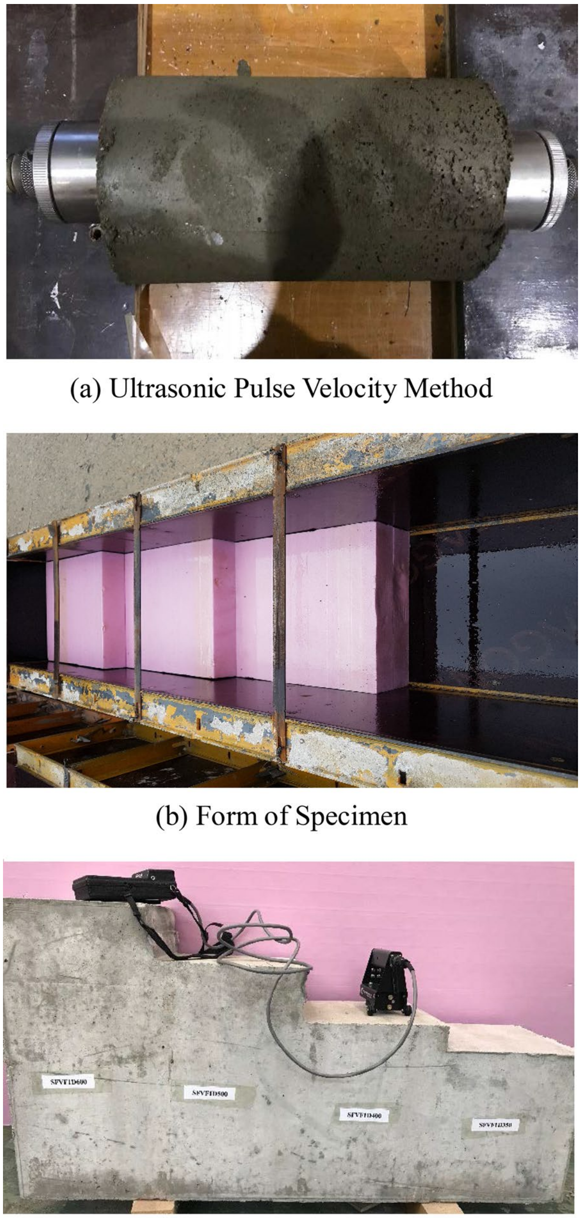


Fig. 7 Comparison of relation of ultrasonic pulse velocity and compressive strength

results (Hong and Kim 2018), the results are similar to those of concrete without steel fiber as shown in Fig. 7.

5 Experimental Program: Thickness Estimation of Steel Fiber Reinforced Concrete

Experiments were conducted to estimate the member size by setting various thicknesses of the steel fiber reinforced concrete using the nondestructive test method as shown in Fig. 8b.



(a) Ultrasonic Pulse Velocity Method

(b) Form of Specimen

(c) Specimen and Experiment

Fig. 8 Estimation of thickness of the SFRC

As part of the experimental study to examine the possibility of quality management through concrete thickness estimation in reference to the steel fiber mixing ratio, the thickness of each concrete member was estimated by means of the impact-echo method at random positions in application of variables as shown in Fig. 8c and Table 3. The thickness was estimated 3 times at each position in application of the variables, and the average value and the average error rate were calculated. Figure 9 and Table 4 show the results of thickness estimation depending on the steel fiber mixing ratio.

Table 3 Specimen list

Specimen name		Steel fiber volume fraction
SFVF0D600	SFVF0D400	0
SFVF0D500	SFVF0D350	
SFVF0S300	SFVF0S150	0
SFVF0S200	SFVF0S100	
SFVF0.75D600	SFVF0.75D400	0.75
SFVF0.75D500	SFVF0.75D350	
SFVF0.75S300	SFVF0.75S150	0.75
SFVF0.75S200	SFVF0.75S100	
SFVF1D600	SFVF1D400	1
SFVF1D500	SFVF1D350	
SFVF1S300	SFVF1S150	1
SFVF1S200	SFVF1S100	

SFVF steel fiber volume fraction/0, 0.75, 1%, *D* deep, *S* shallow

As for SFVF0 series specimens whose steel fiber mixing ratio was 0%, the thickness estimation error rate of SFVF0D600 was 2.85%; SFVF0D500 4.23%; SFVF0D400 5.32%; and SFVF0D350 4.71%, respectively. The average error rate of SFVF0D specimens was 4.28%. The thickness estimation error rate of SFVF0S300 was 2.81%; SFVF0S200 0.56%; SFVF0S150 6.92%; and SFVF0S100 1.25%, respectively. The average error rate of SFVF0S specimens was 2.86%. The average error rate of SFVF0 specimens was 3.57%, which indicates a relatively high level of reliability.

As for SFVF0.75 series specimens whose steel fiber mixing ratio was 0.75%, the thickness estimation error rate of SFVF0.75D600 was 2.62%; SFVF0.75D500 0.40%; SFVF0.75D400 2.28%; and SFVF0.75D350 1.76%, respectively. The average error rate of SFVF0.75D specimens was 1.77%. The thickness estimation error rate of SFVF0.75S300 was 0.00%; SFVF0.75S200 2.11%; SFVF0S150 1.41%; and SFVF0.75S100 3.23%, respectively. The average error rate of SFVF0.75S specimens was 1.69%. The average error rate of SFVF0.75 specimens was 1.73%, which indicates a relatively high level of reliability.

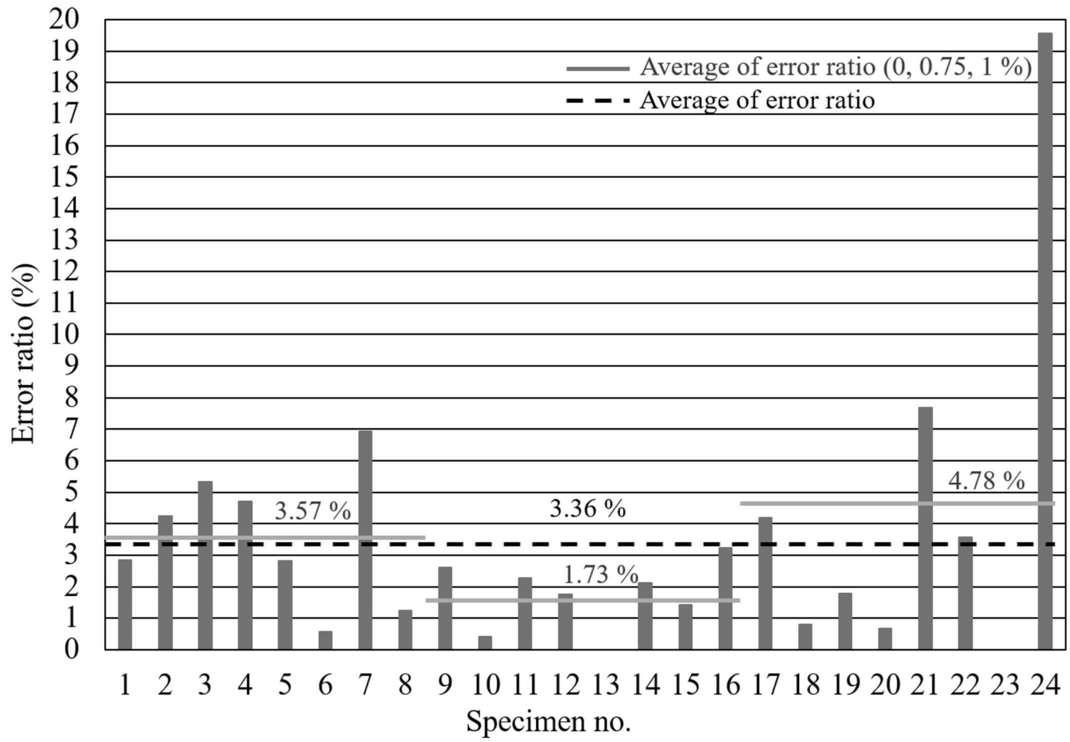


Fig. 9 Comparison of error ratio

As for SFVF1 series specimens whose steel fiber mixing ratio was 1%, the thickness estimation error rate of SFVF1D600 was 4.18%; SFVF1D500 0.81%; SFVF1D400 1.79%; and SFVF1D350 0.67%, respectively. The average error rate of SFVF1D specimens was 1.86%. The thickness estimation error rate of SFVF1S300 was 7.67%; SFVF1S200 3.57%; SFVF1S150 0.00%; and SFVF1S100 19.57%, respectively. The average error rate of SFVF1S specimens was 7.70%. The average error rate of SFVF1 specimens was 4.78%, which indicates a relatively high level of reliability. The average error rate of all the specimens whose steel fiber mixing ratio was 0, 0.75, or 1% was 3.36%, as shown in Fig. 9. Through these experiments, the possibility of quality management through steel fiber concrete thickness estimation was examined by means of non-destructive test methods.

6 Conclusion

This study verified the reliability of nondestructive test methods in the following way. Stress wave based nondestructive test methods ultrasonic pulse velocity method and impact echo method were applied to steel fiber reinforced concrete to examine the correlation between wave velocity and compressive strength of steel fiber reinforced concrete from the early age to the 28 days of age of steel fiber reinforced concrete.

1. Through these experiments, the possibility of maintenance through steel fiber concrete thickness estimation was examined by means of nondestructive test methods. The possibility of quality management was examined by estimating the compressive strength of steel fiber reinforced concrete from the early age to 28 days of age by means of the ultrasonic pulse velocity method, which is a type of nondestructive test method.
2. It was possible to estimate the thickness of various steel fiber reinforced concrete members by means of

Table 4 Experimental results

No.	Specimen name	Measure depth (mm)	Estimated depth (mm)			Average of estimated depth (mm)	Error ratio (%)	Average of error ratio (%)	
1	SFVF0D600	597	583	573	583	580	2.85	4.28	3.57
2	SFVF0D500	496	500	550	500	517	4.23		
3	SFVF0D400	395	402	388	417	374	5.32		
4	SFVF0D350	340	350	388	331	356	4.71		
5	SFVF0S300	285	273	281	276	277	2.81	2.86	
6	SFVF0S200	180	190	177	171	179	0.56		
7	SFVF0S150	130	121	124	119	121	6.92		
8	SFVF0S100	80	75	73	89	79	1.25		
9	SFVF0.75D600	610	594	594	594	594	2.62	1.77	1.73
10	SFVF0.75D500	504	489	500	528	506	0.40		
11	SFVF0.75D400	395	395	403	413	404	2.28		
12	SFVF0.75D350	340	342	354	342	346	1.76		
13	SFVF0.75S300	300	290	321	290	300	0.00	1.69	
14	SFVF0.75S200	190	190	205	187	194	2.11		
15	SFVF0.75S150	142	147	133	151	144	1.41		
16	SFVF0.75S100	93	103	93	91	96	3.23		
17	SFVF1D600	598	573	573	573	573	4.18	1.86	4.78
18	SFVF1D500	496	489	505	505	500	0.81		
19	SFVF1D400	392	381	392	381	385	1.79		
20	SFVF1D350	340	342	331	342	338	0.67		
21	SFVF1S300	300	330	340	300	323	7.67	7.70	
22	SFVF1S200	196	198	180	190	189	3.57		
23	SFVF1S150	145	147	141	147	145	0.00		
24	SFVF1S100	92	118	98	115	110	19.57		

SFVF steel fiber volume fraction/0, 0.75, 1%, *D* deep, *S* shallow

the impact echo method. The reliability was relatively high in general. The average error rate of all the specimens whose steel fiber mixing ratio were 0, 0.75 and 1% was 3.36%. The results verify the applicability as a building quality management method.

3. It is thought that when there is no information on the concrete thickness of an existing structure, the impact echo method can be utilized to estimate the thickness to restore the building drawings that have been lost and to maintain the structure.

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Authors' contributions
SH conceived and performed the experiments and analyzed the data and wrote the paper. SK supervised this project as a research director. Both authors read and approved the final manuscript.

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Availability of data and materials
All data is available to all of research community.

Competing interests
The authors declare that they have no competing interests.

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