applied sciences

MDPI

Article

Evaluation of Condition of Concrete Structures Using Ultrasonic Pulse Velocity Method

Seonguk Hong [1], **Sangki Yoon** [2], **Jonghyun Kim** [2], **Changjong Lee** [2], **Seunghun Kim** [2] **and Yongtaeg Lee** [2,*]

1 Department of Architecture, Woosuk University, 66 Daehakro, Jincheoneup, Jincheongun, Chungcheong bukdo 27841, Korea; suhong@woosuk.ac.kr
2 Department of Architectural Engineering, Hanbat National University, 125 Dongseodero, Yuseonggu, Daejeon 34158, Korea; looter2000@nate.com (S.Y.); klhoppaklh@naver.com (J.K.); changjong1229@hanmail.net (C.L.); kimsh@hanbat.ac.kr (S.K.)
* Correspondence: ytlee@hanbat.ac.kr; Tel.: +82-42-821-1127

Received: 16 December 2019; Accepted: 14 January 2020; Published: 19 January 2020

check for updates

Abstract: The purpose of this study is to estimate the compressive strength according to the age of the concrete structure using ultrasonic pulse velocity method. If the correlation between the ultrasonic pulse velocity and the compressive strength according to the age is derived, the compressive strength of the early age of the concrete structure can be estimated at the new construction site and the compressive strength of the existing structure can be estimated at the remodeling construction site. Concrete structural specimens were constructed with 123 specimens by setting 9 parameters based on the design compressive strength of 24, 30, 40 MPa at 16, 20, 24, 48, 72, 120, 168, 360, 672 h. For the calculation of the average ultrasonic velocity according to the age of concrete, it is carried out according to KS F 2731, ASTM C597 and ACI 228-2R, and the concrete compressive strength is carried out according to KS F 2405. From correlation between ultrasonic pulse velocity and compressive strength, this experiment suggests compressive strength estimation equation. The proposed estimation equation confirmed that it is possible to estimate the compressive strength of concrete according to its age using nondestructive test methods.

Keywords: evaluation; condition; concrete structures; compressive strength; ultrasonic pulse velocity method

1. Introduction

Structural safety diagnosis examines the safety and durability of an existing structure using destructive and nondestructive testing as well as visual observation and analysis. Nondestructive testing methods are widely used because they do not damage structures during the evaluation of their condition [1–3]. In addition, when the condition of concrete structures is evaluated, it is necessary to estimate the compressive strength through various methods for a diagnosis at the time of maintenance after construction, as well as for quality control during construction. Here, the focus is on diagnostic methods that use nondestructive testing methods suitable for examining the condition of a target building without damaging or destroying it. Moreover, many studies are being conducted on the evaluation of their applicability. Most of the previous studies conducted nondestructive testing for more than 28 days of age and examined quality control related to the concrete compressive strength at early ages, which is urgently required at construction sites [4–6]. However, these studies are scarce. Meeting the human desire to live in safe and convenient buildings as well as in cities is an important requirement of the current times. It would be desirable if there were no factors that threaten safety; however, various unexpected problems do occur in buildings. Under the premise of providing people with happiness and welfare through building safety, it is extremely important to establish a method of estimating the strengths of materials more accurately using nondestructive testing methods related to safety diagnosis. This is the first step of various methods to prevent accidents in concrete buildings and establish standards on precision safety diagnosis for buildings or for nondestructive testing methods.

The ultrasonic pulse velocity method estimates the compressive strength of concrete by measuring the ultrasonic pulse velocity from the pulse passing time between the transmitter and receiver at certain distances in a concrete structure, as described in ASTM C597-09 and KS F 2731. The ultrasonic pulse velocity can be used for evaluating concrete quality factors such as the elastic modulus, crack depth, and internal defects, and is applied by obtaining a correlation between the ultrasonic pulse velocity and the compressive strength.

This study proposes a compressive strength estimation equation from the correlation between the ultrasonic pulse velocity and the compressive strength according to the age of the concrete by applying the ultrasonic pulse velocity method, which is one of the nondestructive testing methods. Thus, the equation ultimately provides important data for establishing standards. The proposed concrete compressive strength estimation equation is expected to provide information on formwork removal at new construction sites by estimating the compressive strength of concrete structures at early ages. Further, it enables the quality control of materials at remodeled construction sites by accurately estimating the concrete compressive strength of the existing structures. Concrete specimens were fabricated to achieve the purpose of this study. Then, compressive strength testing and a nondestructive testing experiment were conducted using the specimens. In the experiment, a concrete compressive strength estimation equation was proposed by applying the ultrasonic pulse velocity method, one of the nondestructive testing methods, to identify the compressive strength estimation accuracy according to the age of the concrete structure. A total of 123 concrete specimens were fabricated by setting nine variables based on the ages of 16, 20, 24, 48, 72, 120, 168, 360, and 672 h for the designed strengths of 24, 30, and 40 MPa. To calculate the average ultrasonic pulse velocity according to the age of the concrete, an experiment was performed in accordance with KS F 2731, ACI 228-2R, and ASTM C 597-16. The concrete compressive strength testing was conducted in accordance with KS F 2405. Based on this, a method of evaluating the compressive strength estimation for concrete structures using the nondestructive testing method was established.

2. Literature Review

Studies on nondestructive testing methods for concrete structures began in the 1930s and increased in the 1970s when flaws were detected in unhardened concrete. In England, BS 1881 part 4 and part 5, which were standards on concrete testing methods for strength and others, were published, and BS 1881 part 201, which provided guidelines on the use of nondestructive testing for hardened concrete, was published in the 1980s. In the 2000s, standards on core testing, rebound hardness, and ultrasonic pulse velocity measurement were announced. In the U.S., an ACI 228 strength evaluation report with 38 papers on the standards of nondestructive evaluation and measurement area was published in the 1980s [1]. Based on this report, many studies have been conducted on the application of nondestructive testing methods to the diagnosis of concrete structures [2,3,7,8].

The representative previous studies on nondestructive testing methods can be summarized beginning with the most recent as follows. In 2018, Panedpojaman and Tonnayopas (2018) conducted research on estimating the residual compressive strength of concrete after a fire using the concrete surface hardness [9]. Hong et al. (2016) and Hong and Cho (2006) conducted research on estimating the thickness of concrete as well as the defect locations inside a slab for concrete structures using the ultrasonic pulse velocity method and impact echo method [10,11]. In 2014, Azari, Nazarian and Yuan (2014) conducted research on the benefits of combining the impact echo method and the method of ultrasonic surface waves [4]. In 2013, Bogas et al. (2013) identified the difference between lightweight aggregate and normal aggregate using the ultrasonic pulse velocity method and proposed an estimation equation for predicting the compressive strength of concrete [12], and Furuich (2013) describes a fundamental uncertainty analysis for a flowrate measurement in a pipe using an ultrasonic Doppler velocity profile method and an evaluation of the estimated uncertainty by an actual flow calibration [13]. In 2011, Roh (2011) conducted research on estimating the corrosion of rebar in concrete walls using a self-potential survey method and infrared thermographic technique [14]. Baek et al. (2005) conducted research on a method of estimating the rebar corrosion level using infrared thermography data [15]. There are many other studies (Nadepour et al. (2017), Sabbag and Uyanik (2017), François Saint-Pierre et al. (2016), Nadepour et al. (2016) and Ghosh et al. (2018)) but most of these studies were conducted for a concrete age of 28 days or more, and the studies on quality control related to the compressive strength of concrete at early ages are insufficient [5–7,16,17].

3. Ultrasonic Pulse Velocity Method

Structural safety diagnosis examines the status of the members in an existing structure for safety, durability, and usability using destructive and nondestructive testing as well as visual observation, measurement, and analysis. Nondestructive testing methods are used for the safety diagnosis of buildings. The definition of nondestructive testing methods includes a wide range. First, nondestructive testing refers to a diagnosis that does not deform concrete and other specimens by the test itself. Second, the test refers to methods that do not degrade the function of the structures. For example, core testing is also involved in the range of nondestructive testing. Third, the test refers to a diagnosis that causes less damage to structures than core testing.

For the construction management of structures and the judgment of durability of existing structures, it is necessary to be aware of the strength and condition of the structures. For structures under construction, typically, the compressive strengths of concrete specimens fabricated on site are checked. However, it is not possible to estimate accurate strength using the concrete of a structure and the concrete of a specimen; differences exist between on-site conditions (such as placing, compaction, and curing) and laboratory conditions. Therefore, measuring the compressive strength of the concrete of a structure in a nondestructive manner to secure accurate data is important. It is difficult to apply nondestructive evaluation to concrete because large uncertainties arise from differences in skill levels in the processes of concrete mixing, pouring, and curing; thus, related studies are being conducted constantly. Currently, the American Society of Testing Materials (ASTM) and International Standard Organization (ISO) are performing standardization work based on the research results for nondestructive testing methods. Nondestructive evaluation methods can be applied to various areas including concrete. Moreover, owing to advances in technology, new nondestructive evaluation methods have been developed.

The ultrasonic pulse velocity method estimates the compressive strength of concrete by measuring the ultrasonic pulse velocity from the pulse passing time between the transmitter and receiver at certain distances in a concrete structure, as described in ASTM C597-16 and KS F 2731. The ultrasonic pulse velocity can be used for evaluating concrete quality factors such as the elastic modulus, crack depth, and internal defects, and is applied by obtaining a correlation between the ultrasonic pulse velocity and the compressive strength. As ultrasound is affected by many factors owing to the non-uniform and nonspecific concrete density, estimating the accurate compressive strength of concrete using ultrasound alone is difficult in many cases. However, if the major conditions are similar, estimate the strength to a certain degree is possible because of the correlation between ultrasound and strength. ASTM C597-16 deals with a method of measuring the propagation velocity of the ultrasonic pulse in the longitudinal direction of concrete; it specifically indicates that stress waves are not applied to other types of radio waves. It also establishes appropriate safety and healthcare implementation standards and discusses the evaluation of the applicability of the management limit before use.

In the ultrasonic pulse velocity method, a short and strong electrical signal is transmitted to the transducer to make it vibrate according to the resonance frequency. The vibration of the transducer is transferred to the concrete by the contact medium and detected by the receiving transducer on the opposite side. As the time between the generation and arrival of the wave is recorded by the electrical equipment, the wave velocity can be obtained if the distance traveled by the wave is known. Assuming the behavior of concrete to be elastic, the propagation velocity of the wave can be expressed as Equation (1).

$$V_p = \sqrt{\frac{M}{\rho}} = \sqrt{\frac{E(1-v)}{\rho(1+v)(1-2v)}} \quad (1)$$

where,

V_p: Velocity (m/s)
M: Constrained modulus (MPa)
E: Young's modulus (MPa)
ρ: Density (kg/m^3)
v: Poisson's ratio

As can be seen from Equation (1), the fundamental components of concrete that affect the wave velocity are the elastic modulus and density. The wave velocity is proportional to the square root of the elastic modulus and inversely proportional to the square root of the density. Factors affecting the wave velocity other than the strength are the water content and rebar. As for the water content, when concrete is changed from the dried state to the saturated state, the wave velocity increases by approximately 5%. As for rebar, correction factors of 0.9 and 0.8 for the measured ultrasonic pulse velocity are proposed for perpendicular and parallel cases to the wave path, respectively. When a stress wave is propagated along a medium with the cylindrical shape in which axial displacement is allowed, the rod-wave velocity (V_c) can be determined by Equation (2).

$$V_c = \sqrt{\frac{E}{\rho}} \quad (2)$$

As opposed to the P wave, the S wave causes only shear deformation without volume deformation, and the direction of the medium particle motion is perpendicular to the propagation direction. The velocity of the S wave (V_s) in Equation (3) is determined by the shear elastic modulus and density of the medium.

$$V_s = \sqrt{\frac{G}{\rho}} \quad (3)$$

where $G = \frac{E}{2(1+v)}$: Shear elastic modulus (MPa)

The medium particles of Rayleigh waves propagating along the surface of a semi-infinite medium show their behavior in the form of a retrograde ellipse, and the behavior is opposite to the propagation direction of the wave on top of the ellipse. The velocity of the R wave (V_R) in Equation (4) is a function of Poisson's ratio and can be obtained from the velocity of the S wave.

$$V_R = \frac{0.83 + 1.12v}{1+v} V_s \quad (4)$$

The ultrasonic pulse velocity method comprises direct, indirect, and angle beam methods according to the placement of the transmitter and receiver. The direct method is the most reliable one. When the characteristics of materials are evaluated by measuring the ultrasonic pulse velocity, the measurement accuracy must be very high. This means that testing equipment capable of generating appropriate pulses and accurately measuring the transit time through the tested material must be used. When the path lengths of pulses in a material are measured, the pulse velocity can be calculated using Equation (5).

$$\text{Pulse velocity} = \frac{\textit{Path length}}{\textit{Transit time}} \quad (5)$$

The typical equipment used for testing includes a pair of flexible data port channel (FDPC) platforms for recording and analyzing the original velocity, and receiver transducers (54 kHz) for displaying the pulse velocity energy detected by the receiver. In the ultrasonic pulse velocity method inspection source, the receiver (54-kHz resonant transducer concrete) compressional wave and the ultrasonic pulse are included when transferring the distance known through waves, concrete, or wood. The signal is recorded by the computer, which is capable of amplifying, filtering, and viewing the signal. The computer also records the execution time and voltage amplitude. The pulse velocity is calculated by dividing the pulse path length by the transit time in concrete. The number shown on the measuring instrument represents the velocity passing from the transmitting transducer (Tx) to the receiving transducer (Rx) when Tx and Rx are located at the appropriate positions on the surface of a member, and it is the value for the earliest pulse.

4. Experiment

The purpose of this study is to estimate the compressive strength of concrete using the ultrasonic pulse velocity method, one of the nondestructive testing methods, for compressive strength estimation according to the age of a concrete structure. As such, 123 concrete specimens were fabricated, as shown in Figure 1, by setting nine variables based on the ages of 16, 20, 24, 48, 72, 120, 168, 360, and 672 h for the designed strengths of 24, 30, and 40 MPa using the mixing design shown in Table 1.

Figure 1. Concrete curing and concrete cylinder mold.

Table 1. Mix ratio of concrete.

Designed Strength 24 MPa: Mix Ratio (kg/m^3)					
Cement	**Water**	**Fine Aggregate**	**Crushed Sand**	**Coarse Aggregate**	**High-Performance AE Reducing Agent**
314	166	619	267	931	2.51
W/B		52.9%	S/a		49%
Designed Strength 30 MPa: Mix Ratio (kg/m^3)					
Cement	**Water**	**Natural Sand**	**Crushed Sand**	**Coarse Aggregate**	**High-Performance AE Reducing Agent**
383	170	557	240	948	3.06
W/B		44.4%	S/a		45.9%
Designed Strength 40 MPa: Mix Ratio (kg/m^3)					
Cement	**Water**	**Natural Sand**	**Crushed Sand**	**Coarse Aggregate**	**High-Performance AE Reducing Agent**
465	160	532	230	944	3.72
W/B		34.4%	S/a		44.9%

To calculate the average ultrasonic pulse velocity in concrete at early ages, the ultrasonic pulse velocity was measured 20 times at the center of the specimens, as shown in Figure 2, using ultrasonic pulse velocity measuring equipment from Olson in the U.S. in accordance with the standards of KS F 2731 and ACI 228-2R based on the ages of 16, 20, 24, 48, 72, 120, 168, 360, and 672 h. For the compressive strength of concrete, the experiment was performed in accordance with KS F 2405, as shown in Figure 3.

Figure 2. Experiment of ultrasonic pulse velocity method.

Figure 3. Testing method for compressive strength of molded concrete cylinders.

The top surfaces of the specimens were polished using a grinder for testing the compressive strength. The compressive strength was calculated after measuring the maximum load using a digital universal testing machine (UTM). The results of the experiment conducted for the 123 fabricated specimens to estimate the compressive strength of concrete using the ultrasonic pulse method are as follows. For the designed strength of 24 MPa, the ultrasonic pulse velocity in each specimen was measured at the ages of 16, 20, 24, 48, 72, 120, 168, 360, and 672 h, and compressive strength testing was conducted. The measurement results are listed in Table 2. The measured ultrasonic pulse velocity for the designed concrete compressed strength of 24 MPa was 96.4 m/s at 16 h of age, 709.8 m/s at 20 h, 1005.3 m/s at 24 h, 2300.1 m/s at 48 h, 2703.5 m/s at 72 h, 2988.8 m/s at 120 h, 3131.9 m/s at 168 h, 3382.6 m/s at 360 h, and 3381.1 m/s at 672 h. Figure 4 shows the ultrasonic pulse velocity according to age. As shown in the Figure 4, the wave velocity sharply increased from 16 to 72 h of age. It slowly increased to 120 h and then maintained a very slow increasing tendency up to 672 h.

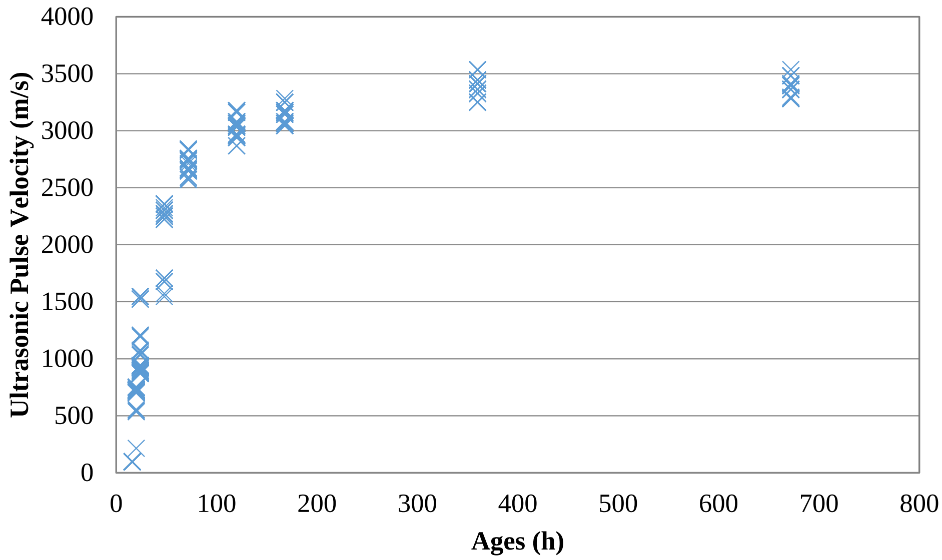

Figure 4. Ultrasonic pulse velocity with age (24 MPa).

Table 2. Experiment results.

Age (h)	Ultrasonic Pulse Velocity (m/s)										Aver.	Compressive Strength (MPa)	Aver.
16	97	96	97	96	96	97	96	97	96	96	96.40	0.62	0.62
	97	96	97	96	96	97	96	97	96	96			
	97	96	97	96	96	97	96	97	96	96		0.62	
	97	96	97	96	96	97	96	97	96	96			
	97	96	97	96	96	97	96	97	96	96		0.62	
	97	96	97	96	96	97	96	97	96	96			
	97	96	97	96	96	97	96	97	96	96		0.62	
	97	96	97	96	96	97	96	97	96	96			
	97	96	97	96	96	97	96	97	96	96		0.62	
	97	96	97	96	96	97	96	97	96	96			
20	549	537	735	535	729	724	751	707	729	719	709.83	0.75	0.75
	555	714	746	702	724	724	751	707	751	707			
	719	719	751	707	724	724	751	707	724	719		0.75	
	214	719	746	702	729	724	751	707	751	712			
	719	719	746	702	724	724	751	707	714	719		0.75	
	724	719	751	707	724	724	746	702	746	707			
	724	724	751	702	729	724	751	702	724	724		0.75	
	719	724	751	702	729	724	751	702	751	707			
24	891	1207	925	917	871	900	1207	942	1063	871	1005.27	0.87	0.92
	900	1031	933	917	879	900	1523	942	925	879			
	900	1523	933	1075	879	900	1546	942	925	879		1.00	
	891	1042	933	925	871	900	1546	942	925	879			
	900	1042	942	917	879	900	1546	942	934	871		1.00	
	891	1546	942	925	879	900	1207	942	925	879			
	900	1546	933	925	879	900	1546	942	934	879		0.87	
	900	1192	942	925	871	900	1523	942	925	879			
	900	1546	942	925	871	900	1523	942	934	879		0.87	
	900	1064	942	925	879	900	1546	942	925	871			

Table 2. *Cont.*

Age (h)	Ultrasonic Pulse Velocity (m/s)										Aver.	Compressive Strength (MPa)	Aver.
48	2357	2250	1706	2272	2302	2357	2250	1677	2272	2357	2176.86	2.99	2.77
	2357	2302	1706	2222	2302	2357	2250	1706	2272	2357			
	2302	2250	1706	2272	2302	2357	2302	1677	2222	2357		2.99	
	2357	2302	1706	2222	2302	2302	2250	1706	2222	2357			
	2302	2302	1706	2222	2302	2357	2302	1677	2272	2357		2.62	
	2357	2250	1706	2272	2302	2357	2250	1677	2325	2357			
	2302	2302	1706	2272	2357	2302	2302	1706	2272	2357		2.37	
	2302	2250	1706	2222	2357	2357	2250	1677	2272	2357			
	2302	2250	1706	2272	2302	2302	2250	1546	2272	2357		2.87	
	2357	2302	1706	2272	2357	2302	2302	1571	2272	2302			
72	2662	2572	2838	2750	2736	2592	2572	2757	2750	2736	2703.51	5.86	6.06
	2662	2572	2757	2675	2662	2662	2648	2838	2750	2736			
	2662	2572	2838	2750	2736	2662	2648	2757	2750	2662		5.98	
	2662	2572	2757	2828	2662	2662	2572	2757	2750	2736			
	2662	2648	2838	2750	2736	2662	2648	2838	2750	2714		6.36	
	2592	2648	2757	2750	2736	2662	2648	2757	2750	2736			
	2662	2572	2757	2828	2736	2592	2648	2757	2750	2662		6.24	
	2662	2572	2838	2675	2736	2662	2648	2838	2675	2736			
	2662	2648	2838	2750	2736	2662	2572	2757	2750	2736		5.86	
	2736	2648	2757	2750	2662	2662	2572	2757	2750	2736			
120	3062	2969	3078	3031	2954	3062	3062	3177	2939	2954	2988.83	11.98	13.20
	3163	2969	3177	2939	2867	3062	3062	3078	293.9	2954			
	3161	2969	3078	3031	2867	3062	2969	3078	3031	2954		12.85	
	3161	2969	3177	2939	2954	3062	3062	3078	3031	3046			
	3062	3062	3078	3031	2867	3062	2969	3177	3031	3046		14.22	
	3062	2969	3177	3031	2954	3062	3062	3177	3031	3046			
	3062	3062	3078	3031	2954	3161	2969	3177	3031	2954		13.60	
	3161	3062	3177	3031	3046	3062	3062	377	3031	2954			
	3062	3062	3078	3031	3046	3062	3062	3177	3031	2954		13.35	
	3062	3062	3177	2939	2954	3062	3062	3177	2939	2954			
168	3062	3078	3145	3078	3046	3062	3078	3250	3177	3046	3131.91	14.35	17.79
	3062	3177	3145	3078	3046	3062	3177	3250	3177	3046			
	3161	3177	3145	3177	3046	3161	3078	3250	3078	3046		19.09	
	3062	3177	3250	3177	3046	3161	3078	3145	3078	3046			
	3161	3177	3145	3177	3046	3062	3078	3145	3177	3046		17.84	
	3161	3177	3145	3177	3046	3062	3177	3250	3177	3046			
	3062	3177	3250	3078	3046	3062	3177	3145	3078	3046		18.72	
	3062	3177	3145	3177	3046	3161	3177	3145	3283	3145			
	3062	3177	3250	3177	3046	3161	3177	3250	3177	3046		18.97	
	3161	3177	3145	3177	3145	3062	3177	3250	3177	3145			

Table 2. *Cont.*

Age (h)	Ultrasonic Pulse Velocity (m/s)										Aver.	Compressive Strength (MPa)	Aver.
	3362	3446	3413	3362	3327	3535	3250	3327	3413	3362		19.96	
	3362	3327	3413	3250	3327	3535	3250	3446	3413	3250			
	3362	3327	3413	3362	3446	3413	3250	3446	3413	3446		21.34	
360	3250	3446	3535	3250	3327	3413	3362	3446	3413	3446	3382.57		20.59
	3362	3327	3535	3362	3446	3413	3362	3327	3535	3413		20.46	
	3250	3327	3413	3362	3327	3413	3250	3446	3535	3413			
	3410	3362	3396	3410	3482	3283	3410	3482	3283	3410		23.08	
	3410	3482	3396	3293	3362	3283	3410	3362	3283	3410			
	3410	3362	3283	3410	3362	3396	3410	3362	3396	3482		21.84	
672	3293	3362	3283	3293	3482	3283	3410	3362	3396	3482	3381.12		22.17
	3410	3362	3283	3410	3482	3283	3410	3482	3283	3283		21.59	
	3410	3482	3396	3410	3362	3283	3537	3482	3283	3396			

Figure 5 shows the concrete compressive strength according to age. As shown in the Figure 5, the concrete compressive strength was 2.58% of the designed strength at 16 h of age, 3.3% at 20 h, 3.83% at 24 h, 11.54% at 48 h, 25.25% at 72 h, 55.00% at 120 h, 74.13% at 168 h, 85.79% at 360 h, and 92.38% at 672 h. In particular, it was found that the compressive strength increased as the age increased. Figure. 6 shows the correlation between the ultrasonic pulse velocity and the compressive strength. The Figure 6 shows that there is a certain correlation between the ultrasonic pulse velocity and the compressive strength.

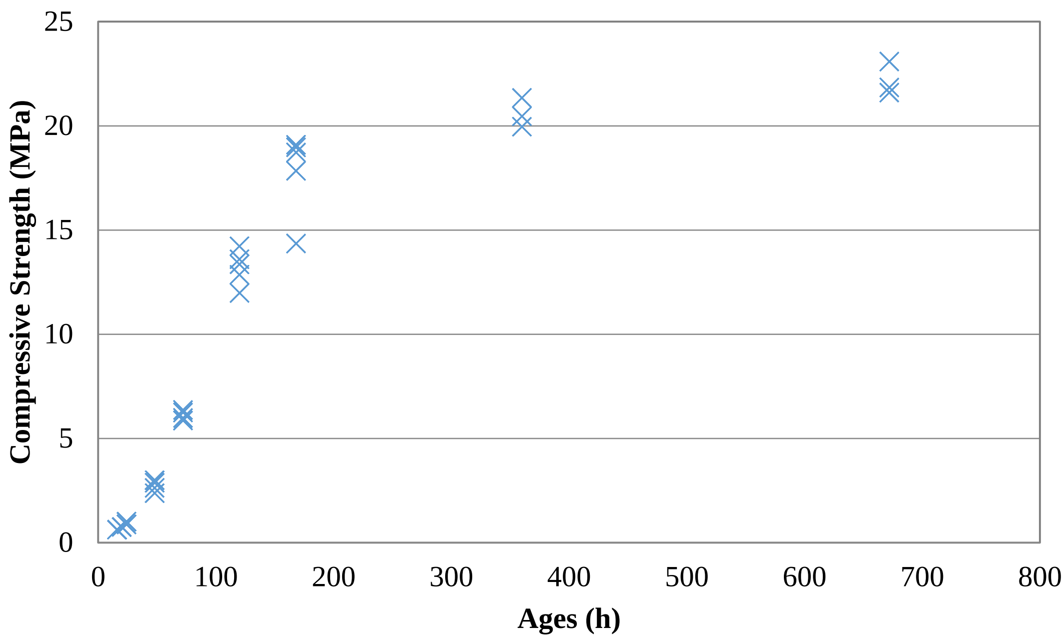

Figure 5. Compressive strength with age (24 MPa).

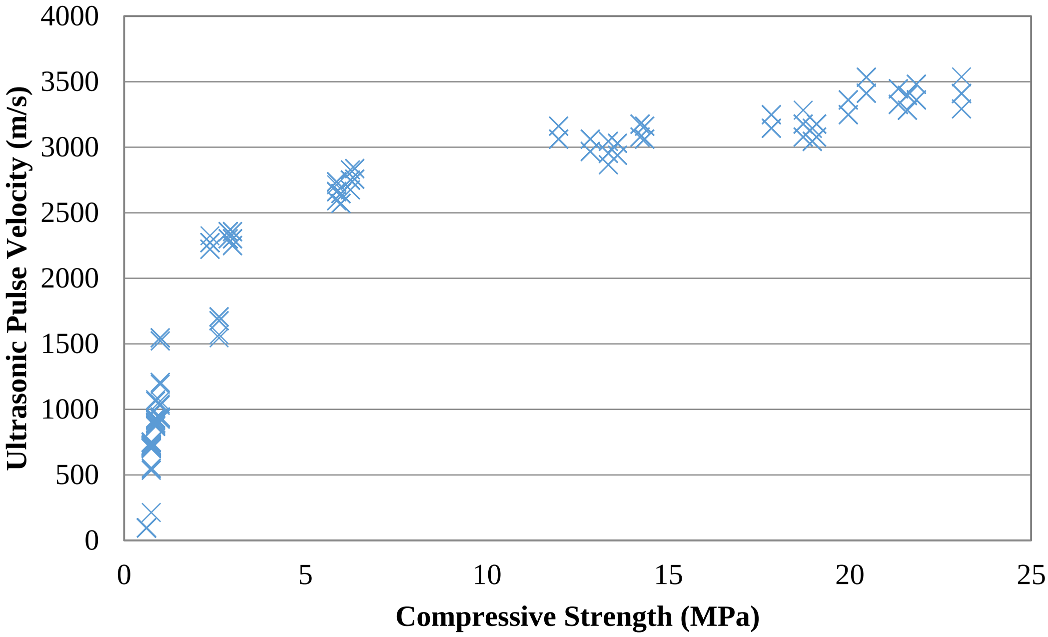

Figure 6. Relationship of ultrasonic pulse velocity and compressive strength (24 MPa).

For the designed concrete compressed strength of 30 MPa, the ultrasonic pulse velocity in each specimen was measured at the ages of 16, 20, 24, 48, 72, 120, 168, 360, and 672 h, and compressive strength testing was conducted. The measurement results are listed in Table 3. The measured ultrasonic pulse velocity was 96.4 m/s at 16 h of age, 96.0 m/s at 20 h, 1010.03 m/s at 24 h, 2451.8 m/s at 48 h, 2867.2 m/s at 72 h, 3118.3 m/s at 120 h, 3240.3 m/s at 168 h, 3529.8 m/s at 360 h, and 3389.2 m/s at 672 h. Figure 7 shows the ultrasonic pulse velocity according to age. As shown in the Figure 7, the wave velocity sharply increased from 16 to 72 h of age. It slowly increased to 120 h and then maintained a very slow increasing tendency up to 672 h. Figure 8 shows the concrete compressive strength according to age. As shown in the figure, the concrete compressive strength was 2.07% of the designed strength at 16 h of age, 2.07% at 20 h, 3.73% at 24 h, 13.07% at 48 h, 30.67% at 72 h, 69.70% at 120 h, 84.70% at 168 h, 92.77% at 360 h, and 95.40% at 672 h. In particular, the compressive strength increased as the age increased.

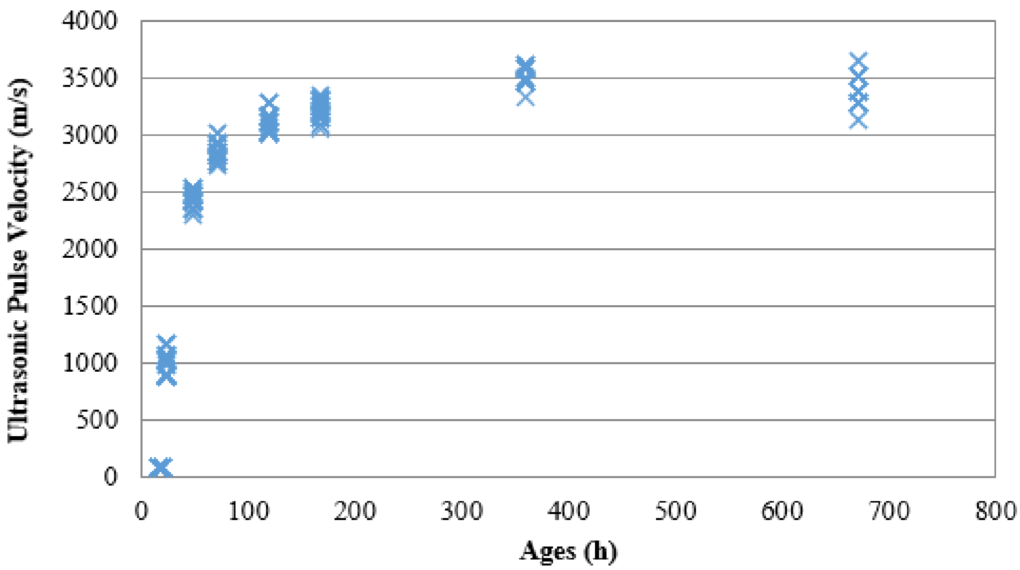

Figure 7. Ultrasonic pulse velocity with age (30 MPa).

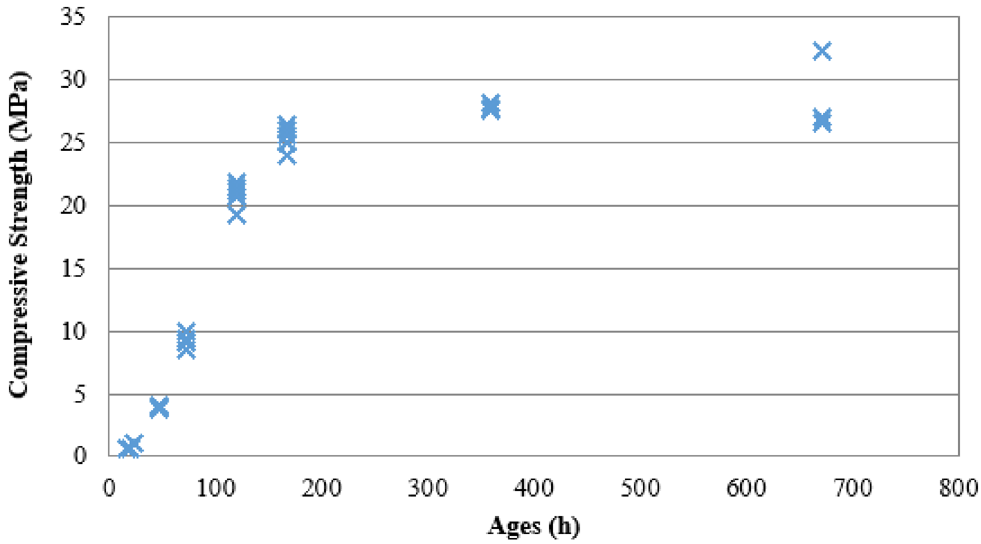

Figure 8. Compressive strength with age (30 MPa).

Table 3. Experiment results (30 MPa).

Age (h)	Ultrasonic Pulse Velocity (m/s)										Aver.	Compressive Strength (MPa)	Aver.
16	97	96	97	96	96	97	96	97	96	96	96.40	0.62	0.62
	97	96	97	96	96	97	96	97	96	96			
	97	96	97	96	96	97	96	97	96	96		0.62	
	97	96	97	96	96	97	96	97	96	96			
	97	96	97	96	96	97	96	97	96	96		0.62	
	97	96	97	96	96	97	96	97	96	96			
	97	96	97	96	96	97	96	97	96	96		0.62	
	97	96	97	96	96	97	96	97	96	96			
	97	96	97	96	96	97	96	97	96	96		0.62	
	97	96	97	96	96	97	96	97	96	96			
20	96	96	96	96	96	96	96	96	96	96	96.00	0.62	0.62
	96	96	96	96	96	96	96	96	96	96			
	96	96	96	96	96	96	96	96	96	96		0.62	
	96	96	96	96	96	96	96	96	96	96			
	96	96	96	96	96	96	96	96	96	96		0.62	
	96	96	96	96	96	96	96	96	96	96			
	96	96	96	96	96	96	96	96	96	96		0.62	
	96	96	96	96	96	96	96	96	96	96			
	96	96	96	96	96	96	96	96	96	96		0.62	
	96	96	96	96	96	96	96	96	96	96			
24	1069	888	1157	1036	900	1069	896	1164	904	908	1009.95	1.12	1.12
	1058	1005	1164	1025	1020	1069	888	1164	1025	908			
	1047	995	1164	1025	908	1069	985	1164	1025	908		1.12	
	1069	896	1164	1015	908	1058	888	1164	1036	908			
	1069	888	1164	1025	900	1069	896	1164	904	908		1.12	
	1058	995	1164	896	908	1069	896	1164	1036	908			
	1069	896	1164	1015	908	1069	896	1164	1036	908		1.12	
	1069	896	1164	904	908	1069	896	1164	1025	900			
	1069	896	1164	896	908	1069	896	1164	1025	908		1.12	
	1069	896	1164	896	900	1069	995	1164	1025	908			

Table 3. *Cont.*

Age (h)	Ultrasonic Pulse Velocity (m/s)										Aver.	Compressive Strength (MPa)	Aver.
48	2426	2475	2475	2414	2439	2426	2475	2475	2357	2439	2451.78	3.74	3.92
	2426	2475	2538	2302	2439	2426	2475	2475	2357	2500			
	2369	2475	2538	2357	2439	2426	2475	2538	2357	2439		4.12	
	2369	2475	2538	2357	2439	2426	2475	2538	2357	2500			
	2426	2538	2475	2414	2439	2426	2475	2538	2414	2439		3.87	
	2426	2475	2538	2357	2439	2487	2475	2475	2414	2500			
	2426	2475	2475	2302	2439	2426	2414	2538	2414	2500		3.99	
	2426	2475	2538	2302	2439	2487	2475	2538	2357	2500			
	2487	2475	2538	2357	2439	2487	2538	2538	2414	2439		3.87	
	2426	2475	2538	2414	2500	2487	2475	2538	2357	2439			
72	2842	2771	2823	2852	2852	2926	2771	2742	2852	2939	2867.16	9.11	9.21
	2926	2852	2823	2852	2939	2926	2852	2823	2852	2939			
	2926	2852	2909	2771	2939	3015	2852	2823	2771	2939		9.98	
	2926	2852	2823	2852	2852	2926	2852	2823	2852	2852			
	2842	2852	2823	2771	2939	3015	2771	2742	2852	2852		9.36	
	2926	2852	2823	2852	2939	2926	2852	2823	2852	2852			
	2926	2771	2823	2852	2939	3015	2852	2742	2852	2939		9.11	
	2926	2852	2823	2852	2939	2926	2852	2823	2771	2852			
	3015	2852	2823	2771	2939	3015	2852	2823	2852	2939		8.48	
	3015	2852	2823	2852	2939	2926	2852	2909	2771	2852			
120	3078	3177	3031	3031	3015	3177	3177	3031	3129	3015	3118.27	21.46	20.91
	3177	3177	3031	3129	3015	3177	3283	3129	3129	3112			
	3177	3283	3129	3129	3112	3177	3177	3129	3129	3015		21.84	
	3078	3177	3031	3129	3015	3177	3283	3031	3031	3015			
	3177	3177	3129	3129	3015	3177	3177	3129	3129	3015		19.34	
	3177	3177	3031	3129	3015	3177	3283	3129	3031	3015			
	3177	3177	3031	3129	3015	3283	3283	3031	3031	3112		21.21	
	3177	3283	3031	3129	3015	3078	3177	3031	3129	3015			
	3177	3283	3129	3129	3015	3177	3283	3031	3031	3112		20.71	
	3078	3177	3129	3031	3112	3177	3283	3031	3031	3015			
168	3200	3112	3250	3062	3193	3200	3216	3362	3161	3300	3240.31	23.96	25.41
	3310	3216	3250	3266	3093	3200	3216	3250	3161	3193			
	3310	3327	3250	3161	3093	3310	3327	3362	3266	3300		24.96	
	3310	3216	3250	3161	3300	3310	3216	3362	3161	3193			
	3200	3327	3250	3161	3191	3310	3216	3250	3161	3300		26.45	
	3310	3327	3250	3161	3300	3310	3327	3250	3161	3193			
	3200	3216	3250	3266	3193	3200	3327	3362	3266	3300		25.58	
	3200	3327	3250	3266	3193	3200	3216	3250	3161	3300			
	3200	3327	3250	3161	3193	3310	3327	3250	3161	3193		26.08	
	3200	3216	3250	3161	3300	3200	3327	3250	3161	3300			

Table 3. *Cont.*

Age (h)	Ultrasonic Pulse Velocity (m/s)										Aver.	Compressive Strength (MPa)	Aver.
360	3464	3464	3629	3592	3464	3500	3592	3464	3629	3592	3529.82	28.20	27.83
	3464	3464	3629	3592	3464	3500	3592	3344	3629	3464			
	3464	3464	3629	3592	3464	3500	3592	3464	3500	3464		27.58	
	3464	3344	3500	3592	3464	3629	3592	3592	3500	3464			
	3464	3464	3629	3464	3464	3629	3592	3464	3629	3500		27.70	
	3592	3464	3629	3592	3464	3629	3592	3464	3629	3629			
672	3517	3283	3283	3517	3283	3145	3648	3396	3283	3648	3389.20	32.32	28.62
	3517	3396	3283	3648	3283	3283	3517	3396	3283	3517			
	3517	3283	3283	3517	3283	3283	3517	3396	3396	3396		26.95	
	3517	3283	3283	3517	3396	3283	3517	3396	3396	3283			
	3517	3396	3283	3517	3396	3283	3648	3396	3283	3283		26.58	
	3517	3396	3283	3517	3396	3145	3517	3283	3145	3283			

Figure 9 shows the correlation between the ultrasonic pulse velocity and the compressive strength. As shown in the Figure 9, there is a certain correlation between the ultrasonic pulse velocity and the compressive strength. For the designed concrete compressed strength of 40 MPa, the ultrasonic pulse velocity in each specimen was measured at the ages of 16, 20, 24, 48, 72, 120, 168, 360, and 672 h, and compressive strength testing was conducted. The measurement results are listed in Table 4. The measured ultrasonic pulse velocity was 96.4 m/s at 16 h of age, 96.0 m/s at 20 h, 1570.9 m/s at 24 h, 2543.5 m/s at 48 h, 2952.5 m/s at 72 h, 3157.6 m/s at 120 h, 3321.9 m/s at 168 h, 3474.6 m/s at 360 h, and 3455.7 m/s at 672 h. Figure 10 shows the ultrasonic pulse velocity according to age. As can be seen in the Figure 10, the wave velocity sharply increased from 16 to 72 h of age. It slowly increased to 120 h and then maintained a very slow increasing tendency up to 672 h.

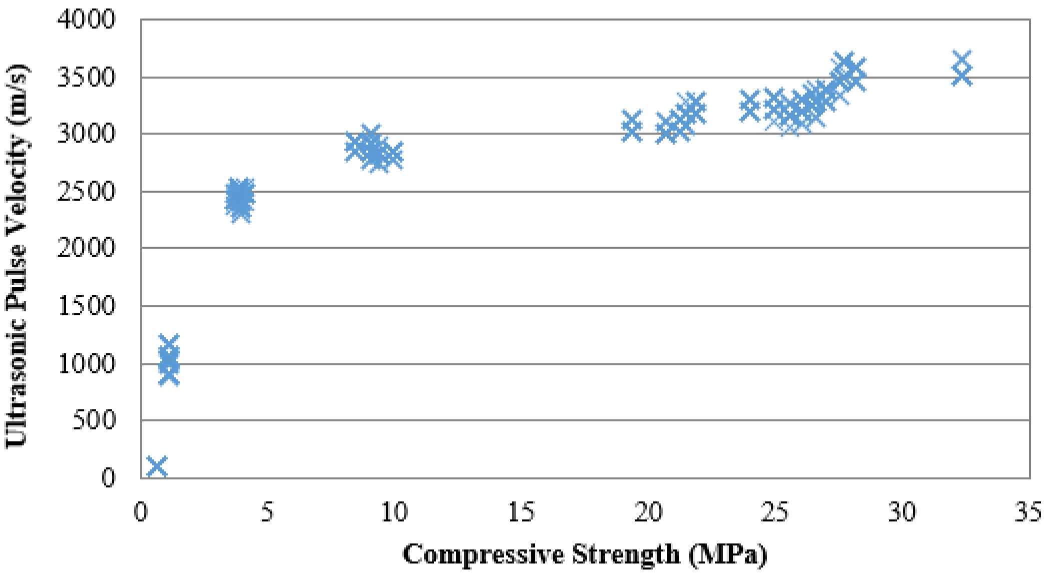

Figure 9. Relationship between ultrasonic pulse velocity and compressive strength (30 MPa).

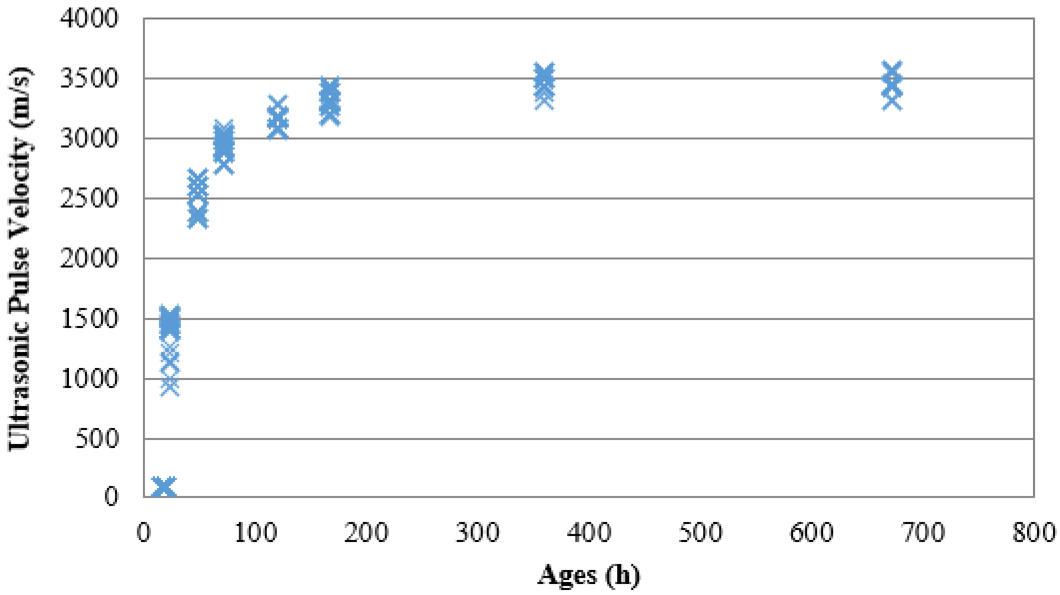

Figure 10. Ultrasonic pulse velocity with age (40 MPa).

Figure 11 shows the concrete compressive strength according to age. As shown in the Figure 11, the concrete compressive strength was 1.55% of the designed strength at 16 h of age, 1.55% at 20 h, 2.80% at 24 h, 16.05% at 48 h, 38.33% at 72 h, 69.43% at 120 h, 83.85% at 168 h, 85.38% at 360 h, and 85.48% at 672 h. These results indicate that the compressive strength increased as the age increased. Figure 12 shows the correlation between the ultrasonic pulse velocity and the compressive strength. The Figure 12 shows that there is a certain correlation between the ultrasonic pulse velocity and the compressive strength.

Table 4. Experiment results (40 MPa).

Age (h)	Ultrasonic Pulse Velocity (m/s)										Aver.	Compressive Strength (MPa)	Aver.
16	97	96	97	96	96	97	96	97	96	96	96.40	0.62	0.62
	97	96	97	96	96	97	96	97	96	96			
	97	96	97	96	96	97	96	97	96	96		0.62	
	97	96	97	96	96	97	96	97	96	96			
	97	96	97	96	96	97	96	97	96	96		0.62	
	97	96	97	96	96	97	96	97	96	96			
	97	96	97	96	96	97	96	97	96	96		0.62	
	97	96	97	96	96	97	96	97	96	96			
	97	96	97	96	96	97	96	97	96	96		0.62	
	97	96	97	96	96	97	96	97	96	96			
20	96	96	96	96	96	96	96	96	96	96	96.00	0.62	0.62
	96	96	96	96	96	96	96	96	96	96			
	96	96	96	96	96	96	96	96	96	96		0.62	
	96	96	96	96	96	96	96	96	96	96			
	96	96	96	96	96	96	96	96	96	96		0.62	
	96	96	96	96	96	96	96	96	96	96			
	96	96	96	96	96	96	96	96	96	96		0.62	
	96	96	96	96	96	96	96	96	96	96			
	96	96	96	96	96	96	96	96	96	96		0.62	
	96	96	96	96	96	96	96	96	96	96			

Table 4. *Cont.*

Age (h)	Ultrasonic Pulse Velocity (m/s)										Aver.	Compressive Strength (MPa)	Aver.
24	1414	1449	1401	1507	1149	1414	1515	1421	1530	1136	1570.92	1.12	1.12
	1000	1492	1421	1485	1470	1394	1492	1442	1530	1515			
	1394	1492	1442	1507	1449	1207	1515	1421	1507	1449		1.12	
	933	1492	1442	1507	1492	1414	1515	1421	1530	1492			
	925	1492	1421	1507	1449	1394	1515	1421	1507	1515		1.12	
	1414	1270	1421	1530	1470	1414	1515	1442	1530	1492			
	1394	1492	1421	15074	1136	1414	1515	1463	1507	1449		1.25	
	1414	1492	1421	1530	1136	1414	1492	1421	1530	1515			
	1394	1515	1442	1530	1470	1414	1515	1442	1507	1492		1.00	
	1414	1492	1421	1530	1515	1414	1515	1421	1507	1470			
48	2605	2605	2538	2538	2325	2605	2675	2605	2538	2325	2543.53	7.49	6.42
	2605	2675	2538	2605	2380	2605	2675	2605	2605	2325			
	2538	2605	2605	2538	2380	2605	2675	2538	2538	2380		7.24	
	2605	2675	2605	2538	2380	2538	2675	2605	2538	2380			
	2538	2675	2605	2605	2380	2538	2675	2605	2538	2380		6.49	
	2605	2675	2538	2605	2380	2538	2675	2538	2605	2325			
	2605	2675	2538	2538	2325	2605	2675	2605	2538	2325		5.99	
	2538	2675	2605	2605	2325	2538	2605	2605	2538	2325			
	2605	2605	2605	2538	2380	2538	2605	2605	2538	2380		4.87	
	2538	2605	2538	2538	2325	2538	2675	2538	2605	2325			
72	2984	2887	2926	3031	3030	2984	2785	2926	3031	3030	2952.45	15.10	15.33
	2984	2785	3015	2939	2941	2897	2785	2926	2939	2941			
	2984	2887	3015	3031	2941	2984	2887	3015	2939	2941		16.10	
	3078	2887	3015	3031	2941	2894	2785	2926	2939	3030			
	2984	2785	2926	2939	2941	2984	2887	3015	2939	3030		13.48	
	2984	2887	2926	2939	2941	2984	2887	3015	3031	2941			
	2984	2785	3015	2939	3030	2984	2887	2926	3031	3030		16.35	
	2897	2887	3015	2939	3030	2984	2785	3015	3031	2941			
	2897	2887	3015	2939	3030	3078	2887	3015	2939	3030		15.60	
	2984	2785	3015	3031	2941	2984	2785	3015	3031	2941			
120	3093	3161	3177	3177	3093	3193	3062	3177	3177	3093	3157.61	27.45	27.77
	3193	3161	3177	3177	3093	3193	3161	3177	3177	3193			
	3093	3062	3177	3177	3093	3193	3161	3078	3283	3093		28.07	
	3193	3161	3177	3177	3093	3193	3161	3177	3283	3193			
	3093	3062	3078	3283	3093	3193	3161	3078	3177	3093		27.45	
	3093	3161	3078	3177	3193	3193	3161	3177	3177	3193			
	3193	3161	3078	3177	3193	3193	3161	3078	3283	3093		28.07	
	3193	3161	3078	3283	3093	3093	3161	3177	3177	3193			
	3093	3161	3177	3177	3093	3193	3161	3177	3177	3193		27.83	
	3193	3161	3177	3177	3193	3193	3161	3078	3177	3193			

Table 4. *Cont.*

Age (h)	Ultrasonic Pulse Velocity (m/s)										Aver.	Compressive Strength (MPa)	Aver.
168	3316	3300	3266	3316	3209	3316	3193	3379	3316	3209	3321.93	32.57	33.54
	3316	3193	3378	3316	3316	3431	3300	3379	3316	3316			
	3316	3300	3379	3316	3209	3431	3300	3379	3316	3209		33.94	
	3316	3193	3379	3316	3316	3431	3300	3266	3316	3316			
	3431	3300	3379	3316	3316	3431	3300	3379	3431	3316		33.69	
	3431	3300	3379	3316	3209	3431	3413	3266	3431	3209			
	3316	3300	3379	3316	3209	3316	3300	3379	3431	3316		33.94	
	3316	3300	3379	3316	3209	3316	3300	3379	3431	3209			
	3316	3300	3266	3431	3316	3316	3300	3266	3316	3316		33.57	
	3316	3300	3379	3431	3316	3431	3300	3266	3316	3209			
360	3500	3431	3431	3500	3553	3431	3500	3431	3431	3379	3474.60	36.06	34.15
	3500	3553	3431	3500	3553	3431	3500	3553	3431	3500			
	3500	3431	3431	3500	3553	3316	3500	3431	3431	3553		33.94	
	3500	3431	3431	3500	3553	3431	3379	3553	3316	3553			
	3500	3553	3431	3500	3431	3431	3500	3553	3431	3431		32.44	
	3500	3431	3431	3500	3553	3431	3500	3553	3431	3553			
672	3316	3431	3448	3431	3431	3571	3316	3431	3448	3431	3455.70	39.55	34.19
	3431	3431	3571	3431	3553	3448	3316	3553	3571	3431			
	3431	3431	3571	3431	3553	3571	3431	3431	3448	3431		31.44	
	3316	3431	3448	3431	3431	3448	3431	3553	3448	3431			
	3431	3431	3448	3431	3553	3448	3316	3431	3448	3448		31.57	
	3431	3431	3571	3431	3431	3571	3431	3431	3571	3571			

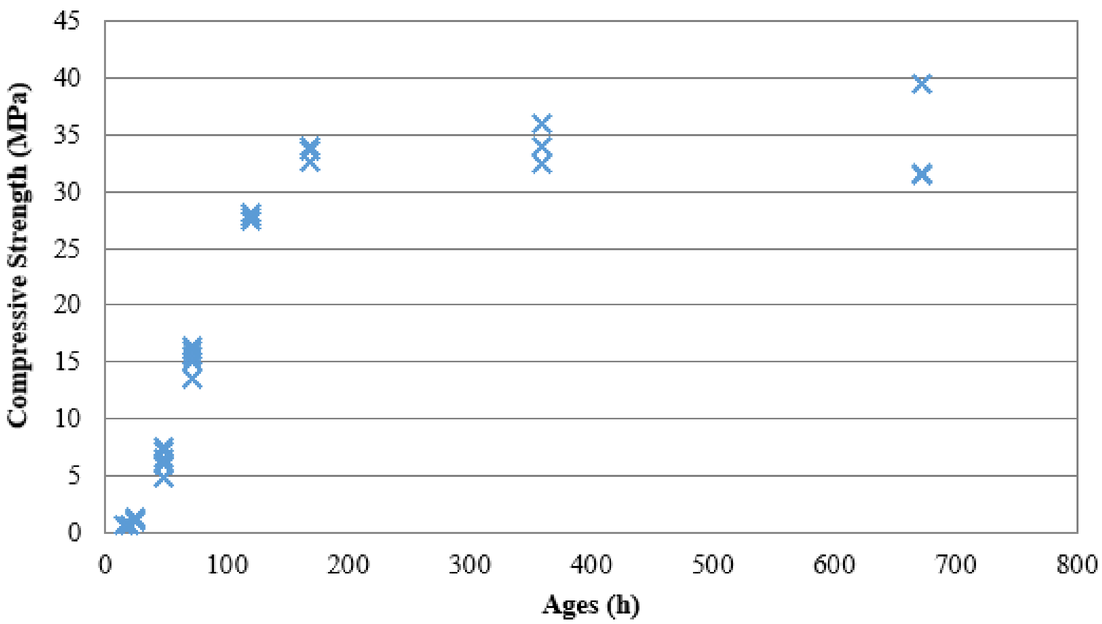

Figure 11. Compressive strength with age (40 MPa).

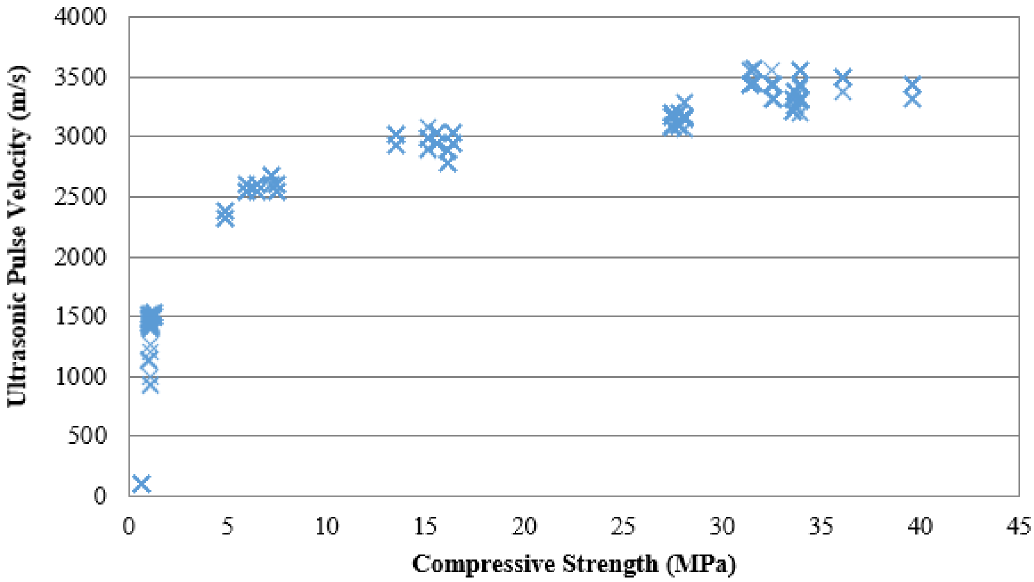

Figure 12. Relationship of ultrasonic pulse velocity and compressive strength (40 MPa).

5. Discussion

Based on the experiment results, this study attempted to estimate the compressive strengths of concrete structures by identifying the correlation between the concrete compressive strength and the ultrasonic pulse velocity according to age. Figure 13 shows the correlation between the ultrasonic pulse velocity and the compressive strength derived from the 123 concrete specimens fabricated by setting nine variables based on the ages of 16, 20, 24, 48, 72, 120, 168, 360, and 672 h for the designed strengths of 24, 30, and 40 MPa. From the derived correlation, a concrete compressive strength estimation equation is proposed as Equation (6).

$$y = 832.75\ln(x) + 844.9,\ R^2 = 0.94 \quad (6)$$

where
x: concrete compressive strength (MPa)
y: ultrasonic pulse velocity (m/s)

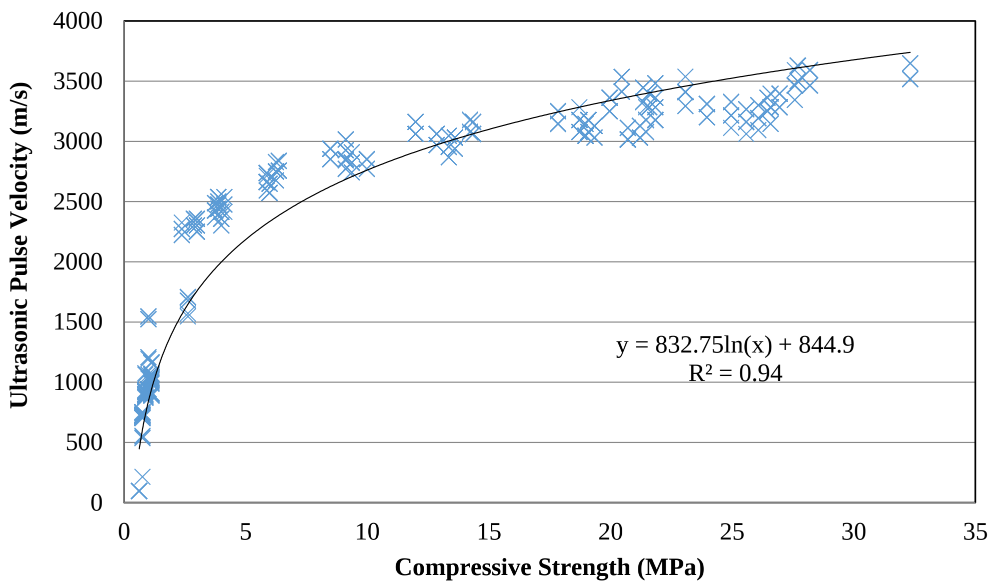

Figure 13. Estimation equation of compressive strength.

6. Conclusions

The purpose of this study was to estimate the compressive strength of concrete using the ultrasonic pulse velocity method, one of the nondestructive testing methods, for compressive strength estimation according to the age of the concrete. To achieve this purpose, a total of 123 concrete specimens were fabricated by setting nine variables based on the ages of 16, 20, 24, 48, 72, 120, 168, 360, and 672 h for the designed strengths of 24, 30, and 40 MPa. An experiment was performed to estimate the compressive strength of concrete according to its age. From the experiment, the following conclusions were obtained:

For the designed strengths of 24, 30, and 40 MPa, the ultrasonic pulse velocity in each specimen sharply increased from 16 to 72 h of age. It slowly increased to 120 h and then maintained a very slow increasing tendency up to 672 h. As a result of measuring the compressive strength, the average compressive strength was 2.07% of the designed strength at 16 h of age, 2.25% at 20 h, 3.21% at 24 h, 13.55% at 48 h, 31.42% at 72 h, 64.71% at 120 h, 80.89% at 168 h, 87.98% at 360 h, and 91.09% at 672 h. From the analysis of the correlation between the ultrasonic pulse velocity and the compressive strength, a concrete compressive strength estimation equation was proposed as Equation (6). The proposed estimation equation confirmed that it is possible to estimate the compressive strength of concrete according to its age using nondestructive testing methods. In particular, the proposed estimation equation is expected to be helpful in preventing problems caused by formwork removal by providing construction sites with valuable information at early ages of the concrete.

Author Contributions: S.H., S.Y., C.L., and J.K. conceived and performed the experiments and analyzed the data and wrote the paper. Y.L. and S.K. supervised this project as a research director. All authors have read and agreed to the published version of the manuscript.

Funding: National Research Foundation of Korea (NRF) funded by the Ministry of Education. Award Number: NRF-2017R1A2B2009743 (Recipient: Yongtaeg Lee, Ph.D).

Acknowledgments: This research was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education (NRF-2017R1A2B2009743).

Conflicts of Interest: The authors declare no conflict of interest.

References

1. ACI 228.2R. *Nondestructive Test Methods for Evaluation of Concrete in Structures*; American Concrete Institute: Farmington Hills, MI, USA, 2013.
2. ASTM C 597. *Standard Test Method for Pulse Velocity through Concrete*; American Society for Testing and Materials: West Conshohocken, PA, USA, 2016.
3. ASTM C 1383. *Standard Test Method for Measuring the P-wave Speed and the Thickness of Concrete Plates Using the Impact Echo Method*; American Society for Testing and Materials: West Conshohocken, PA, USA, 2015.
4. Azari, H.; Nazarian, S.; Yuan, D. Assessing sensitivity of impact echo and ultrasonic surface wave methods for nondestructive evaluation of concrete structures. *Constr. Build. Mater.* **2014**, *71*, 384–391. [CrossRef]
5. Sabbag, N.; Uyanık, O. Prediction of reinforced concrete strength by ultrasonic velocities. *J. Appl. Geophys.* **2017**, *141*, 13–23. [CrossRef]
6. Ghosh, R.; Sagar, S.P.; Kumar, A.; Gupta, S.K.; Kumar, S. Estimation of geopolymer concrete strength from ultrasonic pulse velocity using high power pulser. *J. Build. Eng.* **2018**, *16*, 39–44. [CrossRef]
7. Naderpour, H.; Rafiean, A.H.; Fakharian, P. Compressive strength prediction of environmentally friendly concrete using artificial neural networks. *J. Build. Eng.* **2016**, *16*, 213–219. [CrossRef]
8. Pal, P. Dynamic Poisson's ratio modulus of elasticity of pozzolana Portland cement concrete. *Int. J. Eng. Technol. Innov.* **2019**, *9*, 131–144.
9. Panedpojaman, P.; Tonnayopas, D. Rebound hammer test to estimate compressive strength of heat exposed concrete. *Constr. Build. Mater.* **2018**, *172*, 387–395. [CrossRef]
10. Hong, S.U.; Lee, Y.T.; Kim, S.H.; Lee, C.S. Estimation of Thickness of Concrete Structures using the Impact Echo Method and Ultrasonic Pulse Velocity Method. *Archit. Res.* **2016**, *18*, 179–184. [CrossRef]

11. Hong, S.U.; Cho, Y.S. A Study on the Damage Detection of Concrete Structures using Impact Echo Method based on Stress Waves. *J. Archit. Inst. Korea* **2006**, *22*, 11–18.
12. Bogas, J.A.; Gomes, M.G.; Gomes, A. Compressive strength evaluation of structural lightweight concrete by non-destructive ultrasonic pulse velocity method. *Ultrasonics* **2013**, *53*, 962–972. [CrossRef] [PubMed]
13. Furuichi, N. Fundamental uncertainty analysis of flow rate measurement using the ultrasonic Doppler velocity profile method. *Flow Meas. Instrum.* **2013**, *33*, 202–211. [CrossRef]
14. Roh, Y.S. Corrosion Level Measurement Technique for RC Wall Reinforcement Using Non-Destructive Test Methods. *J. Korean Soc. Nondestruct. Test.* **2011**, *31*, 24–31.
15. Baek, I.K.; Cho, S.H.; Chung, L. Non-destructive Measurement Method of Reinforcement Corrosion Level by Infrared Thermography Data. *J. Archit. Inst. Korea* **2005**, *21*, 3–10.
16. Naderpour, H.; Rafiean, A.H.; Fakharian, P. Analytical and genetic programming model of compressive strength of eco concretes by NDT according to curing temperature. *Constr. Build. Mater.* **2017**, *144*, 195–206.
17. Saint-Pierre, F.; Philibert, A.; Giroux, B.; Rivard, P. Concrete Quality Designation based on Ultrasonic Pulse Velocity. *Constr. Build. Mater.* **2016**, *125*, 1022–1027. [CrossRef]