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Evaluation of Compressive Strength of High Strength Concrete Using Ultrasonic Pulse Velocity Method for Diagnosis Platform

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Abstract.
Background/Objectives: The aim of this study was to evaluate the reliability of high strength concrete compressive strength estimation equations using the ultrasonic pulse velocity method.
Methods/Statistical analysis: The compressive strength test and the ultrasonic pulse velocity method were performed on standard high strength concrete specimens made (60, 70, 80MPa). Existing concrete compressive strength estimation equations were substituted into the results derived to examine the error rate between measured compressive strength and estimated compressive strength.
Findings: The reliability of high strength concrete compressive strength estimation equations proposed by previous studies was evaluated, and the estimation equations showed a wide range of mean error rates with a minimum of 1.5% and a maximum of 53.1%. A more reliable technique for estimating the compressive strength of high strength concrete would be necessary.
Improvements/Applications: By investigating the correlation between existing compressive strength estimation equations and compressive strength and ultrasonic pulse velocity of high strength concrete, a concrete compressive strength estimation technique with increased reliability can be proposed based on the nondestructive test method that minimizes the core tests.

Keywords: Evaluation, Compressive strength, High strength concrete, Ultrasonic pulse velocity method, Diagnosis platform

1. INTRODUCTION

An efficient system for early and regular structure evaluation is urgent to maintain structural safety, durability, and high performance level of infrastructures in each nation. Quality assurance of new structures during and after construction, reconstruction process, material characteristics as functions of time and environmental impact, and damage characterization are becoming increasingly serious[1]. Building safety diagnosis items include concrete compressive strength, cracking, and carbonation, and the concrete compressive strength is one of the most important factors among diagnostic items[2]. Concrete compressive strength estimation using non-destructive testing has been studied to understand the field applicability and increase the reliability because the strength is affected by environmental and material conditions. The nondestructive test method is preferred over the conventional compressive strength test because it can consistently maintain objects without damage and easily acquire data using one side of structures[3]. The nondestructive testing method is already used worldwide and has been standardized[4]. The nondestructive test method is an effective and very important tool for testing concrete quality of all construction works and concrete structures that accord with the purpose of the test, and the method has been studied and verified over decades[5].The first step is to prevent accidents in concrete buildings and come up with various means to prepare standards for precise safety diagnosis and nondestructive test method[6]. There are various nondestructive tests, including the rebound hardness method, ultrasonic pulse velocity method, and combined method. In particular, the ultrasonic pulse velocity method is a method of sending ultrasonic pulse to the specimen, analyzing energy and ultrasonic pulse propagation time of ultrasonic pulse reflected by discontinuity that exists on the inside, and accurately finding position and size of discontinuity[7]. This test applies to size and thickness of discontinuous specimen, uniformity of specimen, and corrosion. The application scope of the ultrasonic pulse velocity method is broadening to flow velocity measurement and concrete testing[8]. The ultrasonic pulse velocity method was originally developed to measure status and quality of concrete. However, as studies on the ultrasonic pulse velocity method continued, the relationship between concrete and ultrasonic pulse velocity or strength was examined[9]. The study trend was largely divided into estimation of compressive strength, crack, and rebar detection[10]. The ultrasonic pulse velocity method not only returns test results immediately but does not cause harm to human body like radiation and has an excellent ability to detect cracks on the surface[11]. Especially, this method has an advantage of showing less scattering and propagating to a far distance in an uneven medium because of a wide frequency domain that embraces the ultrasonic pulse domain, but the method requires professional knowledge due to the difficulty in interpreting measurement values[12]. Many previous studies were conducted on the estimation of compressive strength of high strength concrete using the ultrasonic pulse velocity method, but there is a lack of studies related to creation and systematization of databases[13]. With the development of construction technology, due to the urban concentration of the population, the construction project is gradually becoming high rise[14]. High strength concrete is frequently applied to skyscrapers and has been studied until recently[15]. The use of high strength concrete is increasing rapidly because high strength concrete contributes greatly to the reduction of self-weight and improvement of seismic performance due to reduced cross section of member. Also, high strength concrete structures are more economically feasible than steel structures and can reduce construction expenses. Researchers in many countries are conducting active research. However, strength of high strength concrete is defined differently according to the level of technology in each region or country and common usage domain[16]. As the usage of high strength concrete increases, users are required to build a diagnosis platform for safe structures. This study aims to evaluate the reliability of existing compressive strength estimation equations for high strength concrete using high strength concrete specimens by applying the ultrasonic pulse velocity method, which is one of the nondestructive test methods proposed by previous studies, to build a diagnosis platform.

2. REVIEW OF LITERATURE

Hong and Cho[17] estimated compressive strength of a concrete mock-up structure using the ultrasonic pulse velocity method and the rebound hardness method, calculated the relative error rate compared to an existing analysis method, and proposed an improved equation to reduce the relative error rate presented in Eq. (1). They mentioned that studies on strength estimation and applicable scope considering the curing condition and age are needed to apply the concrete compressive strength estimation equation based on the nondestructive test to actual concrete structures. The applicable scope of the estimation equation is from normal strength to high strength. In this study, the ultrasonic pulse velocity method and rebound hardness method were used to compare ultrasonic pulse velocity, rebound, and compressive strength and find out correlation with ultrasonic pulse velocity and rebound. Ultrasonic pulse velocity and rebound were used to propose a new compressive strength estimation equation. Reliability of the compressive strength estimation equation can be verified by the ultrasonic pulse velocity method and rebound hardness method using compressive strength of normal strength concrete, ultrasonic pulse velocity (V_P), and rebound (R). Relative error rate increased in high strength concrete. The experimental results showed the necessity for an estimation equation that can be applied to normal strength and high strength concrete. A new equation was derived from the results of the ultrasonic pulse velocity method and compressive strength experiment by performing regression analysis on the compressive strength relation according to ultrasonic pulse velocity. The compressive strength estimation equation using ultrasonic pulse velocity (V_P) was found to be as expressed in Eq. (1). This equation can be applied to normal strength and high strength concrete through relative error rate.

$$F_C = 0.0414 V_P{}^{4.5602} \tag{1}$$

Hisham Y. Qasrawi[18] verified the relationship between ultrasonic pulse velocity and crushing cube strength, and proposed Eq. (2). The applicable scope is 27.0~50MPa. Hisham Y. Qasrawi used both rebound hammer and ultrasonic pulse velocity methods, which are existing well-known methods that can be apply easily to conventional concrete structures and concrete specimens. Compared to the rebound method, the ultrasonic pulse velocity method seems to have high efficiency in estimating strength of concrete under work conditions, but Qasrawi mentioned that strength of concrete cannot be estimated reliably solely based on this method. Qasrawi explained that the result becomes similar to the true value in comparison to other methods if a combined method of ultrasonic pulse velocity and rebound hardness methods is used. The final results were compared to previous results, as well as actual results obtained from existing structure samples.

$$F_C = 36.72 V_P - 129.077 \tag{2}$$

Chang-hee Oh[19] proposed Eq. (3) to control the quality according to the ultrasonic pulse velocity method at the site. The applicable scope is 30.0~70.0MPa. Chang-hee Oh conducted a study to manufacture test specimens for ready-mixed concrete produced in Seoul and Gangwon regions and used at actual construction sites, measure the ultrasonic pulse velocity method and strength, and provide references for estimating strength of structures. In the estimation of compressive strength based on ultrasonic pulse velocity, water curing compressive strength became greater than air curing compressive strength as ultrasonic pulse velocity increased. The correlation between ultrasonic pulse velocity elastic modulus was higher than the correlation between ultrasonic pulse velocity and compressive strength.

$$F_C = (152 V_P - 383.9) \times 0.1 \tag{3}$$

Kim et al.[20] proposed Eq. (4) as a strength estimation equation based on the linear regression analysis of compressive strength using the ultrasonic pulse velocity method and rebound hardness test while considering the wet condition and measurement method of the high strength concrete surface. The ultrasonic pulse velocity method showed somewhat low correlation after 28 days compared to rebound hardness, but a high coefficient of determination was shown in the overall test results. The applicable scope is high strength concrete. Ultrasonic pulse velocity showed somewhat lower correlation compared to rebound hardness after 28 days, but it showed a high coefficient of determination for all experimental results. In addition, modification factors did not show any effects. Accordingly, the introduction of an age modification factor was determined to be inappropriate. However, an additional experiment can be carried out on long-term age to decide introduction. Also, the effect of function state was found to be negligible. If measured by the indirect method, an adequate way to convert into the direct method was to multiply by 1.046.

$$F_C = 50.491 V_P - 172.83 \tag{4}$$

Yun-gi Noh[21] divided the curing conditions into standard curing and air-dry curing, measured slump and air volume of unhardened concrete, measured compressive strength, rebound, and ultrasonic pulse velocity of hardened concrete at ages of 3, 7, 14, 28, 90, and 180 days, and proposed Eq. (5). Yun-gi Noh proposed a strength estimation equation appropriate for the circumstances in Korea by analyzing the correlation between concrete compressive strength and nondestructive test values using age, water-cement ratio, and curing condition as variables. Noh selected water-cement ratio (30, 40, 50, 60, 70%) and curing method (standard, air curing) as variables to estimate concrete compressive strength through the nondestructive measurement method. Air volume and slump values were identical, and specimens were divided according to age in days into 3, 7, 14, 28, 90, 180, and 365 days. Based on the test results, the degree of compressive strength increase was higher than air curing of rebound and standard curing of ultrasonic pulse propagation velocity. The strength estimation equation was prepared based on the test results, but adequate compensation was deemed as necessary. Also, air curing was found to show slowdown of ultrasonic pulse velocity compared to standard curing with increasing age. The difference in propagation velocity was caused by changes in function state due to dryness inside specimens.

$$F_C = (372.7V_P - 1250.2) \times 0.1 \tag{5}$$

Concrete compressive strength estimation equations proposed by the Architectural Institute of Japan (6), Materials Research Society of Japan (7), and KEPCO Research Institute (8) are as follows.

$$F_C = 21.5V_P - 62.0 \tag{6}$$

$$F_C = 10.4V_P - 11.9 \tag{7}$$

$$F_C = 33.91V_P - 110.7 \tag{8}$$

3. ULTRASONIC PULSE VELOCITY METHOD

The ultrasonic pulse velocity method is used to estimate the compressive strength of concrete from the path velocity of ultrasonic pulse passing through the middle of hardened concrete. Primary uses of the ultrasonic pulse velocity method include quality control of concrete structures, determination of time for formwork removal, and assistance on the estimation of precast concrete strength.

The principle of the ultrasonic pulse velocity method is as follows. Ultrasonic pulses (slow pulses of 20~200kHz) transmitted from the transmission terminal bonded to concrete moves inside concrete, and transit time is defined as the time taken to arrive at the receiving terminal on the opposite end. Path velocity is solved as shown in Eq. (9) by finding the distance between the two terminals. The ultrasonic pulse velocity method is based on the experiential fact that ultrasonic pulse velocity and compressive strength are correlated in concrete. According to previous study and test results, the appropriate strength range is about 10~60MPa. Methods of ultrasonic pulse exploration are classified into the direct method, angle beam method, and indirect method according to the arrangement of probes. Ultrasonic pulse velocity (longitudinal pulse) solved in the direct method is used to estimate strength, but ultrasonic pulse velocity can be measured by the indirect method (surface method) for any measurements that cannot apply the direct method at the site.

$$\text{Path Velocity } (V_p : Velocity) = \frac{Path\ Length}{Transit\ Time} \tag{9}$$

The principle of the ultrasonic pulse velocity method is to send short and strong electrical signals to the converter. When the converter vibrates according to the resonance frequency, vibrations of the converter are transmitted to concrete via the contact material and sensed by the receiving converter on the opposite side. Since the time taken for the pulse to arrive is recorded by an electrical device, ultrasonic pulse velocity can be solved if the distance traveled by the pulse is known. When the behavior of concrete is assumed to be an elastic behavior, the path velocity can be expressed as Eq. (10).

$$\mathrm{V} = \sqrt{\frac{E(1-\mu)}{\rho(1+\mu)(1-2\mu)}} \tag{10}$$

Here, V: ultrasonic pulse velocity, E: elastic modulus, ρ: density, and μ: Poisson's ratio.

As shown in Eq. (10), elastic modulus and density are the fundamental concrete components that affect ultrasonic pulse velocity. Pulse velocity is proportional to square root of elastic modulus and inversely proportional to square root of density. Moisture content and rebar are the factors that affect ultrasonic pulse velocity other than strength. Regarding the moisture content factor, ultrasonic pulse velocity is increased by about 5% when concrete is changed from dry state to saturated state. A compensation factor that accounts for the effect of rebar is proposed. Path velocity of the direct method and surface method fluctuates because of various causes, such as material type, mixing, and moisture content. Generally, path velocity has been experientially reported to be in the range of $V_d \approx 1.05\text{~}1.15V_i$. Here, V_d: ultrasonic pulse path velocity based on the direct method and V_i: ultrasonic pulse path velocity based on the indirect method.

In the case where the stress wave propagates along a medium, such as a cylinder, in which axial displacement is allowed, the non-constrained compression wave velocity (V_c) can be determined by Equation (11).

$$V_c = \sqrt{\frac{E}{\rho}} \tag{11}$$

where, V_c: Compression Wave velocity (m/s)

The secondary wave, in contrast to the primary wave, causes shear deformation and does not cause volume deformation. The direction of the medium particle movement is perpendicular to the propagation direction. The secondary wave velocity (V_s) is determined by the shear modulus and density of the medium, as shown in Equation (12).

$$V_s = \sqrt{\frac{G}{\rho}} \tag{12}$$

where,
V_s: Secondary wave velocity (m/s)
$G = \frac{E}{2(1+v)}$: Shear modulus (MPa)

If the correlation between the ultrasonic pulse velocity and the compressive strength is found, the reliability of the compression strength estimation can be improved by considering various variables that affect the compressive strength. However, there can be a problem in the reliability when estimating strength only using ultrasonic pulse velocity as such factors are unknown for actual structures. Among ultrasonic pulse velocity test methods, there are three types of arrangement for sender and receiver, including the direct method, semi-direct method, and indirect method. Since the semi-direct method and indirect method still have problems in reliability, the pulse velocity test is carried out by the direct method. This method estimates strength of concrete by arranging each probe on the opposite face of concrete and measuring transmission time. Since there must be no gap between the probe and test surface, gaps are generally filled using grease. Space in between should be made as thin as possible for testing. Nondestructive strength of concrete according to ultrasonic pulse differs according to material quality, gap, crack, and rebar placement. Therefore, the focus should be placed on material defect and construction status over concrete strength measurement. This test can measure density of the evaluated material, elasticity, homogeneity, existence of gap or hollow, chemical damage, degradation from aging, and carbonation phenomenon, and can be applied to testing of concrete strength and measurement of crack depth.

Table 1 : Factors Influencing Ultrasonic Pulse Velocity Method

Concrete Mixtures	Coarse	mixed ratio
		max size of coarse aggregate
		unit weight
	Cement	mixed ratio
		type
	etc	Fly ash
		Water-/cement ratio
And so on		age
		arrangement of bar
		crack

Factors that affect ultrasonic pulse propagation velocity of concrete are as presented in Table 1. Water content in concrete has a large effect on velocity of sound, and velocity increases as if concrete is in damp state. Velocity of sound has been reported to increase by about 50~60m/sec for every 1% of increase in water content. In the case of long-term ages of three months or longer, velocity of sound does not increase as much as the increase of concrete strength. If strength does not increase much, velocity of sound can decline. Influential factors include changes in water content inside concrete and formation of microcracks. When configurating the correlation between ultrasonic pulse velocity and compressive strength, reliability of compressive strength can be increased by considering various factors that influence compressive strength. However, as such factors are often unknown in actual structures, a problem can occur in reliability if strength is estimated solely based on ultrasonic pulse velocity. If major conditions are similar, the correlation between sound velocity and strength becomes consistent and strength can be estimated to some degree. Therefore, when estimating concrete strength using the ultrasonic pulse velocity method, various factors have different effects on strength estimation. It would be desirable to reflect such factors on strength estimation in order to enhance the accuracy of strength estimation.

4. MATERIALS AND METHODS

Four standard specimens with design compressive strength of 60, 70, and 80MPa were manufactured, and the ultrasonic pulse velocity method and compressive strength test were performed to evaluate the reliability of existing compressive strength estimation equations for high strength concrete using the ultrasonic pulse velocity method. The ultrasonic pulse velocity method was carried out in accordance with ASTM C 597 and KS F 2731. Ultrasonic pulse velocity was measured 20 times on high strength concrete using Pundit Lab operating instructions, as shown in Figure 1. The compressive strength test was carried out in accordance with KS F 2405. Compressive strength was measured using the Universal Testing Machine (UTM), as shown in Figure 2.

5. RESULTS AND DISCUSSION

The results of the ultrasonic pulse velocity method and compressive strength test on 60MPa concrete are presented in Table 2. The mean ultrasonic pulse velocity of the HC60S1 specimen was 5,279.7m/s, and compressive strength was 91.6MPa. The mean ultrasonic pulse velocity of the HC60S2 specimen was 5,281.9m/s, and compressive strength was 88.0MPa. The mean ultrasonic pulse velocity of the HC60S3 specimen was 5,258.7m/s, and compressive strength was 87.6MPa. The mean ultrasonic pulse velocity of the HC60S4 was 5,258.2m/s, and compressive strength was 67.6MPa.

Figure 1. Ultrasonic pulse velocity method

Figure 2. Compressive strength test

Table 2: Standards for ultrasonic pulse velocity method

No	Specimen name	Ultrasonic pulse velocity (m/s)				Ultrasonic pulse velocity Average (m/s)	Compressive strength (MPa)
1	HC60S1	5.291	5.291	5.300	5.291	5.279.7	91.6
		5.254	5.263	5.254	5.263		
		5.263	5.282	5.291	5.282		
		5.297	5.263	5.291	5.282		
		5.263	5.291	5.291	5.291		
2	HC60S2	5.263	5.282	5.291	5.282	5.281.9	88.0
		5.282	5.291	5.282	5.263		
		5.282	5.282	5.282	5.291		
		5.263	5.282	5.291	5.291		
		5.282	5.282	5.291	5.282		
3	HC60S3	5.245	5.254	5.263	5.254	5.258.7	87.6
		5.245	5.254	5.282	5.254		
		5.282	5.254	5.254	5.282		
		5.245	5.254	5.245	5.263		
		5.254	5.254	5.282	5.254		
4	HC60S4	5.245	5.263	5.254	5.254	5.258.2	67.6
		5.254	5.282	5.263	5.245		
		5.245	5.254	5.263	5.254		
		5.282	5.254	5.263	5.254		
		5.282	5.254	5.245	5.254		

The results of the ultrasonic pulse velocity method and compressive strength test on 70MPa concrete are presented in Table 3. The mean ultrasonic pulse velocity of the HC70S1 specimen was 5,339.6m/s, and compressive strength was 83.3MPa. The mean ultrasonic pulse velocity of the HC70S2 specimen was 5,348.2m/s, and compressive strength was 100.2MPa. The mean ultrasonic pulse velocity of the HC70S3 specimen was 5,325.9m/s, and compressive strength was 98.3MPa. The mean ultrasonic pulse velocity of the HC70S4 specimen was 5,349.2m/s, and compressive strength was 84.9MPa.

Table 3: Standards for ultrasonic pulse velocity method

No	Specimen name	Ultrasonic pulse velocity (m/s)				Ultrasonic pulse velocity Average (m/s)	Compressive strength (MPa)
1	HC70S1	5300	5,338	5,319	5,348	5,339.6	83.3
		5319	5,357	5,357	5,348		
		5357	5,348	5,338	5,357		
		5319	5,348	5,319	5,338		
		5357	5,319	5,348	5,357		
2	HC70S2	5338	5,348	5,357	5,319	5,348.2	100.2
		5348	5,338	5,357	5,348		
		5348	5,357	5,357	5,348		

		5348	5,357	5,338	5,348		
		5357	5,348	5,357	5,348		
3	HC70SE1	5282	5,310	5,291	5,300	5,325.9	98.3
		5300	5,319	5,348	5,329		
		5357	5,348	5,338	5,386		
		5338	5,300	5,348	5,300		
		5348	5,338	5,300	5,338		
4	HC70SE2	5357	5,338	5,300	5,338	5,349.2	84.9
		5386	5,348	5,357	5,348		
		5300	5,348	5,357	5,357		
		5386	5,348	5,348	5,348		
		5357	5,348	5,357	5,357		

The results of the ultrasonic pulse velocity method and compressive strength test on 80MPa concrete are presented in Table 4. The mean ultrasonic pulse velocity of the HC80S1 specimen was 5,425.1m/s, and compressive strength was 92.2MPa. The mean ultrasonic pulse velocity of the HC80S2 specimen was 5,427.6m/s, and compressive strength was 93.8MPa. The mean ultrasonic pulse velocity of the HC80S3 specimen was 5,433.0m/s, and compressive strength was 95.0MPa. The mean ultrasonic pulse velocity of the HC80S4 specimen was 5,433.0m/s, and compressive strength was 95.3MPa.

Table 4: Standards for ultrasonic pulse velocity method

No	Specimen name	Ultrasonic pulse velocity (m/s)				Ultrasonic pulse velocity Average (m/s)	Compressive strength (MPa)
1	HC80S1	5,386	5,386	5,415	5,415	5,425.1	92.2
		5,435	5,435	5,435	5,435		
		5,435	5,435	5,415	5,435		
		5,435	5,415	5,435	5,435		
		5,435	5,415	5,435	5,435		
2	HC80S2	5,435	5,415	5,435	5,435	5,427.6	93.8
		5,386	5,415	5,435	5,435		
		5,415	5,435	5,435	5,435		
		5,435	5,435	5,415	5,435		
		5,435	5,415	5,435	5,435		
3	HC80SE1	5,435	5,425	5,435	5,435	5,433.0	95.0
		5,445	5,435	5,435	5,415		
		5,435	5,435	5,445	5,435		
		5,415	5,435	5,415	5,435		
		5,445	5,435	5,435	5,435		
4	HC80SE2	5,435	5,445	5,415	5,435	5,433.0	95.3
		5,435	5,435	5,445	5,435		
		5,415	5,425	5,435	5,435		
		5,435	5,445	5,445	5,435		
		5,415	5,425	5,435	5,435		

The results of estimating compressive strength of high strength concrete specimens using the ultrasonic pulse velocity method and the results of estimating with existing compressive strength estimation equations are presented in Table 5.

Table 5: Experimental results

Specimen	UPV (m/s)	Compressive Strength (MPa)	Estimated compressive strength (MPa)							
			(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
			Error Ratio (%)							
			(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
60	5,270	83.7	81.0	51.3	42.9	68.0	93.3	64.4	71.4	41.7
			11.2	37.9	48.0	17.6	26.9	22.0	16.0	49.5
70	5,341	91.7	86.1	52.8	43.6	70.4	96.9	67.1	74.1	42.8
			8.1	42.0	52.1	22.6	9.0	26.3	18.7	53.0

80	5,430	94.1	92.8	54.7	44.6	73.4	101.3	70.3	77.4	44.2
			1.5	41.8	52.7	22.0	7.6	25.3	17.8	53.1
Average of error ratio	-	-	6.9	40.6	51.0	20.7	10.8	24.5	17.5	51.9
Existing Compressive Strength Estimation Equation	(1) $F_C = 0.0414V_P{}^{4.5602}$					Hong and Cho				
	(2) $F_C = 21.5V_P - 62.0$					Architectural institute of japan				
	(3) $F_C = 10.4V_P - 11.9$					Materials Research Society of japan				
	(4) $F_C = 33.91V_P - 110.7$					KEPCO Research institute of Technology				
	(5) $F_C = 50.491V_P - 172.83$					Kim et al				
	(6) $F_C = 36.72V_P - 129.077$					Qasrawi				
	(7) $F_C = (372.7V_P - 1250.2) \times 0.1$					Roh Yoon-gi				
	(8) $F_C = (152V_P - 383.9) \times 0.1$					Changhee Oh				

The error rate between measured compressive strength and estimated compressive strength of the 60MPa specimen is shown in Figure 3. The error rate was found to be 11.2% for Eq. (1), 37.9% for Eq. (2), 48% for Eq. (3), 17.6% for Eq. (4), 25.9% for Eq. (5), 22% for Eq. (6), 16% for Eq. (7), and 49.5% for Eq. (8). The equations showed a wide range of error between 11.2%~49.5%.

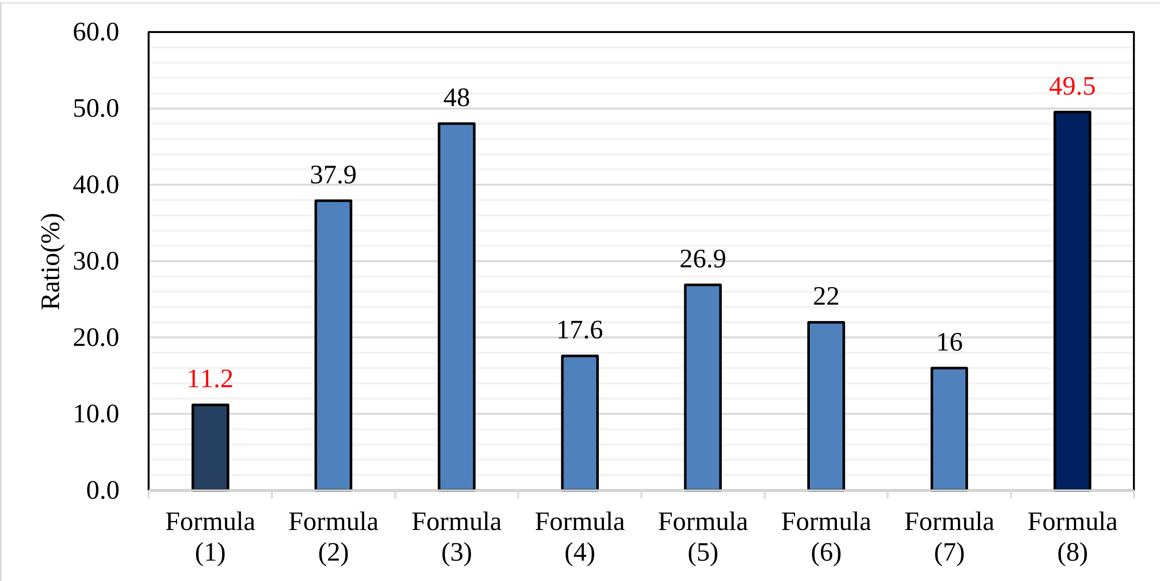

Figure 3. 60MPa

The error rate between measured compressive strength and estimated compressive strength of the 70MPa specimen is shown in Figure 4. The error rate was found to be 8.1% for Eq. (1), 42% for Eq. (2), 52.1% for Eq. (3), 22.6% for Eq. (4), 9% for Eq. (5), 26.3% for Eq. (6), 18.7% for Eq. (7), and 53% for Eq. (8). The equations showed a wide range of error between 8.1%~53%.

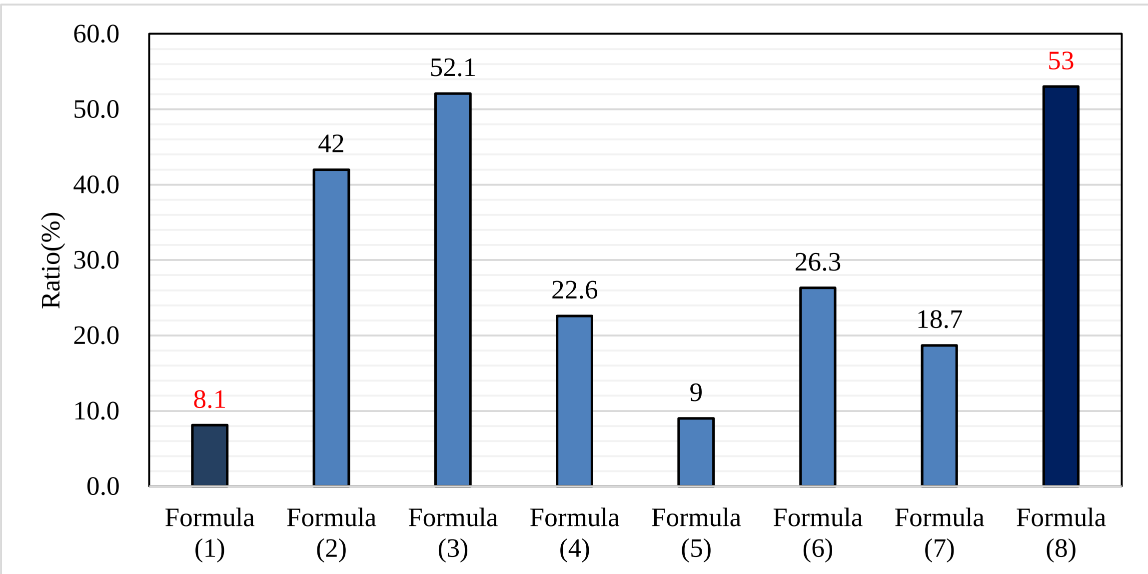

Figure 4. 70MPa

The error rate between measured compressive strength and estimated compressive strength of the 80MPa specimen is shown in Figure 5. The error rate was found to be 1.5% for Eq. (1), 41.8% for Eq. (2), 52.7% for Eq. (3), 22% for Eq. (4), 8.6% for Eq. (5), 25.3% for Eq. (6), 17.8% for Eq. (7), and 53.1% for Eq. (8). The equations showed a wide range of error between 1.5%~53.1%.

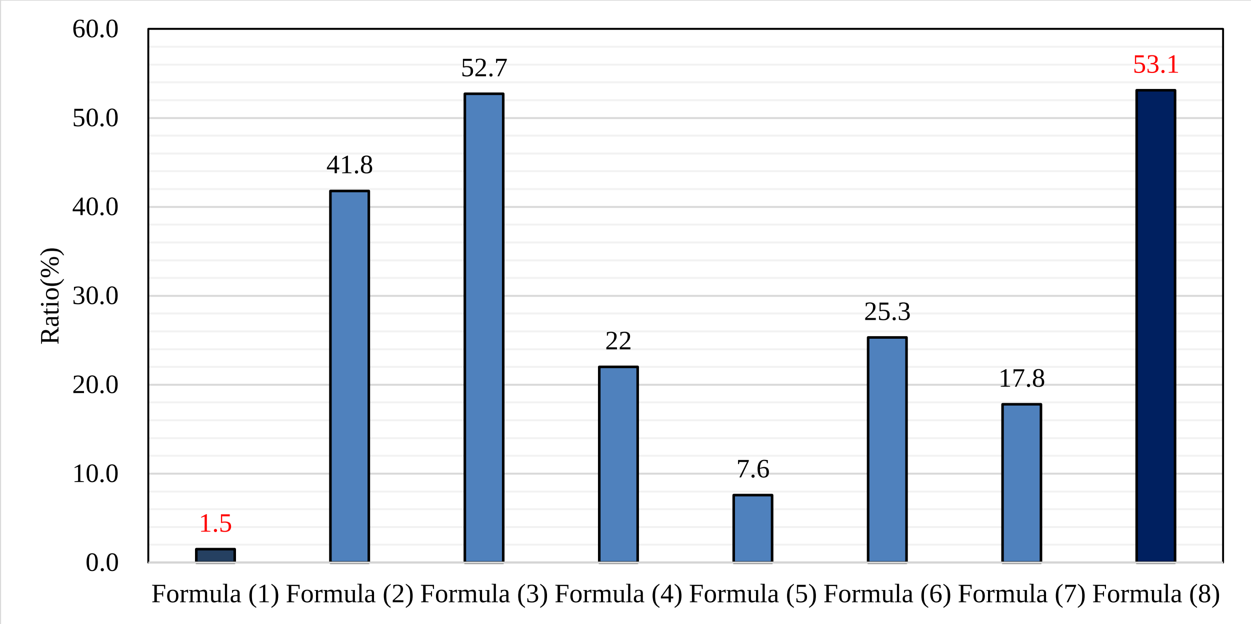

Figure 5. 80MPa

The mean error rate for each of the existing equations proposed is presented in Figure 6. The mean error rate was 6.9% for Eq. (1), 40.6% for Eq. (2), 51.0% for Eq. (3), 20.7% for Eq. (4), 10.8% for Eq. (5), 24.5% for Eq. (6), 17.5% for Eq. (7), and 51.9% for Eq. (8). The equations showed a wide range of error between 6.9%~51.9%.

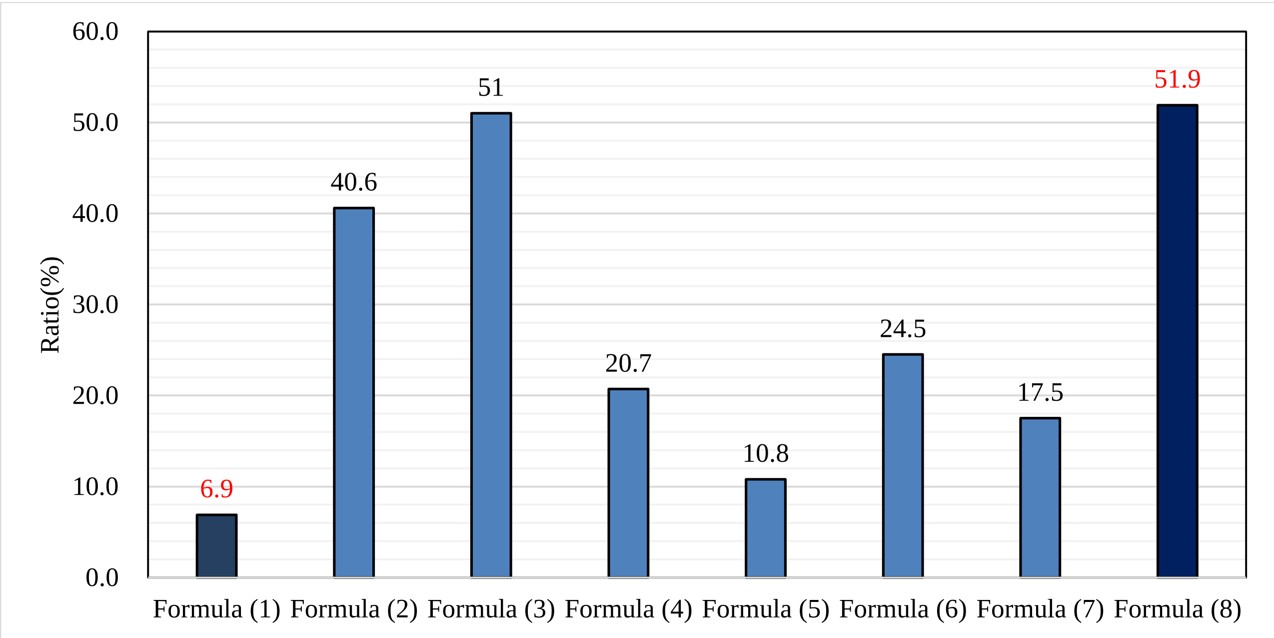

Figure 6. Average of error ratio

6. CONCLUSION

The conclusion of evaluating the estimated reliability of high strength concrete compressive strength to build a diagnostic platform is as follows. If a structure that uses high strength concrete is diagnosed, the error rate of the compressive strength estimation equation using the ultrasonic pulse velocity method varies between 1.5%-53.1%. Based on the correlation between existing compressive strength estimation equations and compressive strength and ultrasonic pulse velocity of high strength concrete, a compressive strength estimation technique for high strength concrete that can increase the reliability of the nondestructive test method that minimizes the core tests would be necessary.

7. ACKNOWLEDGMENT

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