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Estimation of Compressive Strength of High Strength Concrete Using Non-Destructive Technique and Concrete Core Strength

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Abstract: Estimating the compressive strength of high strength concrete (HSC) is an essential investigation for the maintenance of nuclear power plant (NPP) structures. This study intends to evaluate the compressive strength of HSC using two approaches: non-destructive tests and concrete core strength. For non-destructive tests, samples of HSC were mixed to a specified design strength of 40, 60 and 100 MPa. Based on a dual regression relation between ultrasonic pulse velocity (UPV) and rebound hammer (RH) measurements, an estimation expression is developed. In comparison to previously published estimation equations, the equation proposed in this study shows the highest accuracy and the lowest root mean square error (*RMSE*). For the estimation of compressive strength using concrete core specimens, three different concrete core diameters were examined: 30, 50, and 100 mm. Based on 61 measured compressive strengths of core specimens, a simple strength correction factor is investigated. The compressive strength of a concrete core specimen decreases as the core diameter reduces. Such a relation is associated with the internal damage of concrete cores and the degree of coarse aggregate within the core diameter from the extracting process of the cores. The strength estimation expressions was formulated using the non-destructive technique and the core strength estimation can be updated with further test results and utilized for the maintenance of NPP.

Keywords: high strength concrete; nuclear power plant; estimation of compressive strength; Nondestructive test; dual regression; concrete core; strength correction factor

1. Introduction

Nuclear power plants (NPPs) have been promoted as a green power source because they are a stable supply of electricity and diminish greenhouse gases relative to other power sources. Recently, environmental events like earthquakes or typhoons have threatened the safety of NPPs; there has already been a big disaster at the Fukushima Daiichi NPP in Japan. Even though there is a serious risk of radiation, increasing the use of NPPs is regarded as a common strategy to satisfy the enormous need for electricity in the future.

One possible way of preventing the disastrous leakage of radiation from NPP failure is to build stronger plants, by using innovative materials such as high strength concrete (HSC). In South Korea, one of the more proactive nations in the research and development of NPP facilities, innovative research associated with high strength concrete has been consistently performed; since 2010, researchers have strived to achieve a target concrete compressive strength of 42 MPa at 28 days [1]. Increasingly, NPPs are being constructed using HSC, which naturally creates a need for an appropriate maintenance method for NPPs. After all, during the NPP service life the structural condition should be monitored by investigating the compressive strength of concrete. One of the main techniques for the estimating compressive strength of concrete is to apply a non-destructive test (NDT) [2,3]. Another possible strength-assessing method is the core strength test, which is a partially destructive test.

Two significant non-destructive methodologies for estimating the compressive strength of concrete are the rebound hammer (RH) test and the ultrasonic pulse velocity (UPV) method. These estimating methods are simple and effective. Thus, they have been used to estimate concrete compressive strength since 1960 [4,5]. Recently, research on a new estimating equation for NDTs has been carried out [6–8]. For NDT methods, it was reported that the rebound or ultrasonic velocity could be substantially impacted by void condition, age and the humidity of the concrete [9]. Accordingly, large or small variations can exist in the estimation results and a statistical approach should be employed to develop the estimation equation. Due to its simplicity and practicality, most of the approaches for estimating the compressive strength of concrete are usually based on the statistical regression method. This is widely used because it can obtain a simple, deterministic equation from the tested data. Previous studies have pointed out that using the multiple linear regression method [10–12] and the combined method [13–15] in combination with ultrasonic pulse velocity and rebound hammer values (or including other influencing factors) can provide more accurate and reliable prediction of the compressive strength of concrete. Another advanced approach, using an artificial neural network can effectively improve the reliability of the estimating result by excluding the out of data [16]. Even though there have been many research efforts that aimed to estimate the strength of high strength concrete, few of the proposed equations use data from the rebound hammer test and ultrasonic pulse velocity method [17]. Thus, there is still not enough experimental data for estimating the compressive strength of HSC that is stronger than 40 MPa.

The core strength test is a partially destructive test that extracts the core specimen from the massive concrete member. For normal strength concrete, some in situ core tests were carried out [18,19]. However, such tests are rare for high strength concrete members. Because there are still hazard problems during the extracting process of the cores, some codes like ASTM and British Standards (BS) strongly recommend a minimum core diameter of 100 mm, satisfying the condition that the diameter of the core is at least three times larger than the maximum coarse aggregate size in the concrete mixture [20,21]. For a few special cases, some standards allow smaller diameters, down to 50 mm [22,23]. Having a smaller core size than that of standard specimen (Φ100 × 200) is a very useful and practical way to estimate the compressive strength of concrete without causing possibly serious damage to concrete members during the extraction process of the cores. It can also save on the in situ drilling time due to the high strength of concrete. Moreover, a smaller core is much more appropriate for high reinforced concrete members (such as nuclear power plant structures), in which the reinforcement space is relatively narrow. When the core is extracted from the concrete member, a correction factor should be examined as compared with the compressive strength of standard concrete specimens with a cylinder or cube type. The correction factor is mainly affected by varying the slenderness ratio (Length/Diameter). For a core size of 46 and 69 mm, the mixed strength decreased by around 70% as equal to 14 and 24 MPa with a maximum coarse aggregate of 22 mm at 28 days [24]. Another study found that the maximum aggregate size and the slenderness ratio increases as the core strength decreases [25]. Microcore strength tests were conducted on concrete with a compressive strength ranging from 20 to 50 MPa, using a core diameter of 28 mm and the strength reduction showed up to 79% [26]. For high strength concrete, one significant study reported that the core strength was about 95% of the total cylinder strength in concrete with 20 MPa compressive strength, whereas in 50 MPa concrete, the core strength was about 85% of the total cylinder strength [27]. For the special case of concrete with very high compressive strength, around 120 MPa, the discrepancy was between 72% and 85% of the standard cylinder specimen for cores with diameters between 25 and 100 mm [28]. In contrast with concrete cylinders, core strength tests can result in somewhat large variation in the prediction of the strength. In order to guarantee the applicability of the core strength test for testing high strength concrete, further investigation on correction factor is needed. In particular, comparing core specimens (including small-size core specimens) with the standard cylinder strength of the concrete should be investigated.

This study proposes two methods for evaluating the compressive strength of HSC for the maintenance of NPP structures. One method is to use non-destructive techniques such as UPV and RH. The other is the partially destructive, concrete core strength test. The mix proportions of the HSC are designed to result in strengths of 40, 60, and 100 MPa, and three different core diameters are examined: 30, 50, and 100 mm. The compressive strength test of the concrete cylinder and core was carried out at 28 days and the correlation relationship between the tested and predicted strength using NDT was investigated. The estimation equation for the HSC cylinder was statistically obtained using a double linear regression method for better accuracy of prediction and superior validation. Furthermore, the strength correction factor between the cylinder and core (including small-size cores) specimen is examined.

2. Research Significance

This study proposes an estimation equation for high strength concrete with a compressive strength over 40 MPa. To improve prediction accuracy, the equation is based on a multivariable regression model of the NDT data from the ultrasonic pulse velocity and the rebound number. This equation can be useful in estimating strength for the maintenance of NPP structures made of high strength concrete. Besides, this study investigates the correlation factors between concrete cylinders and core specimens including specimens with diameters smaller than 100 mm. By using smaller core specimens, a reasonable strength estimation of high strength concrete NPP members is possible while minimizing partial destruction during practical testing.

3. Experimental Program

3.1. Materials

The cement used in this study was Ordinary Portland Cement (OPC) with a bulk density of 3150 kg/m^3, produced by Ssangyong Cement Co. of Busan, South Korea. Normal weight coarse and fine aggregates were used to form ready mixed concrete (RMC). A blend of natural white, crushed sand was used as the fine aggregate. The bulk densities of the fine (sand) and coarse (20 mm limestone) aggregate were 2610 and 2690 kg/m^3, respectively. The maximum size of the coarse aggregate was 20 mm. In order to complete the high strength concrete mixing, two types of mineral admixture such as fly ash and silica fume were used in the mixing design.

3.2. Concrete Mixing

Table 1 presents the three different mix proportions of the concrete used in this study. The specific compressive strength of the concrete at 28 days was specified to be 40, 60, or 100 MPa. The fundamental approach for obtaining high strength is to have a low water to cement ratio. For high strength concrete (up to 100 MPa), high pozzolan ingredients were added to the mixing design. These additives can the effect of delaying concrete strengthening, by delaying the full hydration reaction. The water to cement ratio varied from 0.43 to 0.27 as the target strength increased. Slump was set to 150 $\pm$ 20 mm. After several trial mixtures, the optimum dosage of the admixture was finally determined. Class F fly ash meeting ASTM C 618 [29] was used in all mix proportions. In a special case, silica fume with high pozzolanic properties was used only in mix 3, which resulted in the highest compressive strength of concrete in this study.

Table 1. Mix proportions of concrete (unit: kg/m^3).

Mix Types	f_c' (MPa)	W/B (%)	S/a (%)	Water	Cement	Sand		Gravel	Fly-Ash	Silica Fume	AE [a]
Mix 1	40	38.5	52	160	374	358	537	849	42	-	3.74
Mix 2	60	31	51	165	479	328	492	809	53	-	4.52
Mix 3	100	21	46.5	165	613	189	440	743	79	94	14.93

[a] air-entraining admixture.

3.3. *Experimental Test*

3.3.1. Compressive Strength Test

The compressive strength test was carried out using a universal test machine (UTM) by Dong-Ah Co. (Yangsan-city, South Korea) with 1000 kN capacity in compliance with ASTM C39M [30]. The type of concrete cylinder specimen had dimensions of Φ100 × 200 mm. For core specimens, the length of the entire core specimen was cut to result in a slenderness of 2.0 prior to the destructive test. The compressive strength was automatically measured by a data acquisition system.

3.3.2. Rebound Hammer Test (RHT)

The rebound hammer test was carried out using a shmidt hammer by Proceq Co. (Zurich, Switzerland) also known as a Schmidt Hammer. This is a well-known NDT technique and is widely used for evaluating the compressive strength of concrete, based on the surface hardness of the concrete. A hammer impact was applied on to the side surface of the cylinder specimen, which was vertically restrained with 10% of the ultimate load of the compressive strength test (Figure 1a). This approach is quite useful because it makes sure that the cylinder specimen is fastened horizontally against the impact load of the hammer. The impact angle is zero (purely horizontal). A previous study has employed this method when applying a rebound hammer test to a concrete specimen. The impacts were applied to twenty points around the perimeter of the concrete cylinder then averaged, excluding the data points that exceeded a value 20% above or below the average.

(**a**) (**b**)

Figure 1. Non-destructive test for the concrete cylinder specimen. (**a**) Rebound hammer test; (**b**) Direct ultrasonic pulse velocity method.

3.3.3. Ultrasonic Pulse Velocity Method (UPVM)

Ultrasonic Pulse Velocity Method (UPVM) uses the relationship between travel length (L) and time (T) of an ultrasonic pulse wave. The measurement is made using a transmitter and receiver. Evidently, less faults inside the concrete results in a high speed of the UP, whereas more faults (caused by pores, cracks or poor quality) reduces the UPV. Ultrasonic velocity is affected by the choice of measuring type such as the direct or indirect method. Indirect UPVM is usually used for in situ measurements and a calibration factor of 1.05 between direct and indirect UPVM was employed in a previous study [31]. The BS 1881–203 (1986) [32] suggests that the effect of steel reinforcement bars occurs parallel to direction of the pulse path. For a/L, where a is the concrete cover and L is the length of the ultrasonic pulse path, the influence of the reinforcement becomes negligible when a/L reaches 0.2 to 0.25. In case where a/L is under 0.2, Equation (1) is employed to correct the influence of steel reinforcement on the ultrasonic pulse velocity. In this study, direct UPVM was employed to measure the concrete cylinders and core specimens as shown in Figure 1b. UPVM was conducted three times for each cylinder specimen and the data was averaged to give the representative value.

$$T = \frac{L}{V_s} + 2a\sqrt{\frac{V_s^2 - V_c^2}{V_s V_c}} \quad (1)$$

where,
V_c = ultrasonic pulse velocity in the plain concrete
V_s = ultrasonic pulse velocity in the steel

3.3.4. Core Strength Test

For the core strength test, this study considers the standard size of the core to be 100 mm in diameter and 200 mm in length, which is same size as the concrete cylinder. In general, conducting a core strength test using specimens above the standard size may cause harmful damage to the constructed concrete members, due to the partial destruction of concrete and steel reinforcement, which occurs when the spacing of the reinforcement is not sufficiently large to avoid hitting the core drill bit.

According to an inspection manual [33], smaller core strength tests (with diameters less than 100 mm) are allowed in the estimation of the compressive strength of concrete. However, this is only permitted when the maximum aggregate size is less than 10 mm. As concrete core size decreases, the possibility of damage to the concrete members is minimized. It is quite important for the maintenance of a critical facility such as NPP.

In order to investigate the compressive strength effect due to variation in the core size, square concrete blocks without steel rebar were fabricated with a target strength of either 40, 60 or 100 MPa. Their geometry was 600 mm long, 600 mm wide and 200 mm thick, as shown in Figure 2. They were cured under the same conditions as the concrete cylinder specimens. The concrete core diameters used in this study were 100, 50, and 30 mm and their slenderness (Length/Diameter) was fixed at 2.0.

(**a**)

(**b**)

Figure 2. Fabrication of concrete cylinder specimens and concrete block for a core strength test. (**a**) Complete of test specimens; (**b**) Extracting process of the cores.

4. Non-Destructive Test Results and Comparisons

4.1. Experimental Results and Strength Prediction of Concrete Cylinder

After finishing water curing under a constant temperature and humidity for 28 days, the compressive strength tests were conducted using a 1000 kN UTM. The compressive strength of the concrete cylinder was measured by averaging nine separate cylinder specimens for each mix design (Table 2 summarizes the compressive strength results). The test results of mix 1 and mix 2 show a compressive strength of 53.1 and 66.2 MPa, respectively, and they exceeded their intended mixed design strength at 28 days. Mix 3, however, did not reach the intended mixed design strength of 100 MPa but stopped at 68.6 MPa, (a strength level of 69%). This phenomenon may be due to the pozzolanic reaction with high pozzolan ingredients; the strength occurrence was somewhat delayed until the full hydration reaction was completed.

Table 2. Measured compressive strength of concrete cylinder according to the case of mix proportion.

Mix Types	f_c' (MPa)	Average (MPa)
Mix 1	52.3, 53.8, 52.2, 52.9, 54.5	53.1
Mix 2	62.4, 70.4, 61.9, 73.8, 60.2, 65.7, 65.0, 69.8	66.2
Mix 3	64.4, 65.3, 67.8, 66.2, 76.8	68.6

Figure 3 shows the relationship between the tested compressive strength and the strength predicted by the ultrasonic pulse velocity and rebound hammer tests. For high strength concrete, UPV ranged between 4.5 and 5.0, for a concrete with a compressive strength ranging from 50 to 80 MPa. The relatively high speed of the UPV is due to the high level of density in high strength concrete. The results of the rebound hammer test presented wider scatter of hammer values, even though the predicted strength range was same as that predicted by UPV. This discrepancy might be caused by predicting the compressive strength from the surface impact of the concrete specimen. This is because the surface is not regular and the impact test is largely depended on the testing workability.

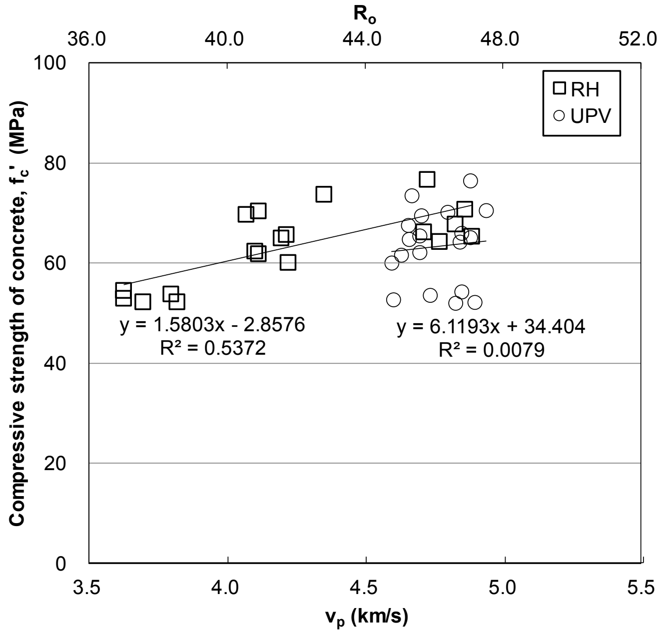

Figure 3. Relationship between tested compressive strength of concrete cylinder and predicted by the non-destructive test.

For better accuracy and practicability, multivariable linear regression analysis (MRA) was employed as a statistical approach. MRA intends to simultaneously certify two or more independent influencing parameters. The general MRA equation is given in Equation (2), which the dependent variable being a linear equation of more than an independent variable.

$$Y = a + b_1 X_i + b_2 X_j + \ldots b_k X_n \pm e \tag{2}$$

where,
Y = dependent variable
a = Y intersect
$b_{1,2,..k}$ = slopes related with $X_{i,j,\ldots n}$
$X_{i,j,\ldots n}$ = values of independent variables
e = error

In order to evaluate the degree of accuracy for the prediction equations, the root mean square error (*RMSE*) value was employed. When two data sets, for example, one set is from the observed or tested value and the other is the theoretical calculation or prediction, are compared, root means square can serve a measure how far on average the error is from 0. The standard deviation indicates the variability of the difference, where the *RMSE* is meaningful measure of the error. The common expression of *RMSE* is introduced in Equation (3).

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(X_i - x_i)^2} \tag{3}$$

where,
X_i = tested compressive strength of concrete (MPa)
x_i = predicted compressive strength of concrete (MPa)
n = number of specimens

Based on a multiple regression analysis, this study suggests a dual variable regression equation for estimating the compressive strength of high strength concrete in practical applications (see Equation (4)). Table 3 summarizes the comparison results between the tested and predicted compressive strength of concrete obtained from single and dual linear regression expressions. As a result, *RMSE* values of 4.9 obtained by the dual linear regression equation was closer to the tested strength values, compared to the *RMSE* value of the single linear regression equation for UPV (7.3) and RH (5.0). The discrepancy in *RMSE* between the single and dual linear regression is somewhat small. However, it is possible that the *RMSE* will increase when the number of datasets increases. The previous literature review found that the number of influencing factors is deeply related to improving the accuracy of predicting the compressive strength of concrete. In any case, a dual linear regression must have better prediction accuracy than a single linear regression approach. Figure 4 plots Equation (4) and the experimental results.

$$f'_c = 38.7055 - 9.5194 \times v_P + 1.6678 \times R_o \tag{4}$$

where,
f'_c = estimated compressive strength of concrete cylinder at 28 days
v_p = ultrasonic pulse velocity (km/s)
R_0 = rebound hammer value

Table 3. Experimental results and estimated compressive strength for non-destructive tests.

Specimen Number	Experimental Results			Estimated Strength (MPa)		
	f_c' (MPa)	v_p (km/s)	R_0	Single Regression by v_p	Single Regression by R_0	Dual Regression by v_p and R_0
1-1	52.3	4.89	37.6	64.3	56.5	54.8
1-2	53.8	4.73	38.4	63.3	57.7	57.7
1-3	52.2	4.82	38.6	63.9	58.1	57.1
1-4	52.9	4.60	37.0	62.5	55.6	56.6
1-5	54.5	4.84	37.0	64.0	55.6	54.3
2-1	62.4	4.69	40.8	63.1	61.6	62.1
2-2	70.4	4.79	40.9	63.7	61.8	61.3
2-3	61.9	4.63	40.9	62.7	61.8	62.9
2-4	73.8	4.66	42.8	62.9	64.8	65.7
2-5	60.2	4.59	41.8	62.5	63.1	64.6
2-6	65.7	4.69	41.7	63.1	63.0	63.6
2-7	65.0	4.65	41.6	62.9	62.8	63.7
2-8	69.8	4.70	40.6	63.2	61.2	61.6
3-1	64.4	4.83	46.2	64.0	70.1	69.6
3-2	65.3	4.87	47.1	64.2	71.6	70.9
3-3	67.8	4.65	46.6	62.9	70.8	72.1
3-4	66.2	4.84	45.7	64.0	69.4	68.8
3-5	76.8	4.87	45.8	64.2	69.5	68.7
3-6	70.8	4.93	46.9	64.6	71.3	70.0

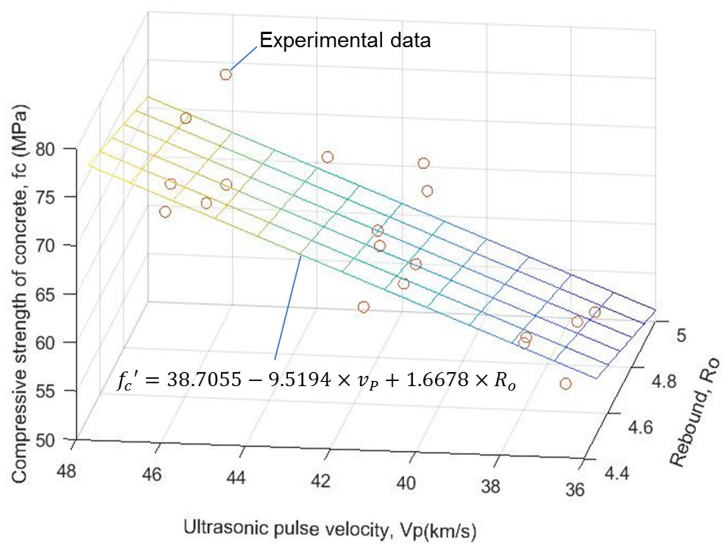

Figure 4. Relationship between tested compressive strength of concrete cylinder and predicted by the non-destructive test.

4.2. Comparison with Previous Equations

To validate the accuracy of the formula suggested in this study, the estimated compressive strength of concrete results from the suggested formula were compared with those of other considered formulas for UPV or RH (as summarized in Tables 4 and 5). The expression types are classified as 1st and 2nd polynomial, power or exponential. The compressive strength of concrete ranged from 20 to 100 MPa, however, most of the tested strength is limited to high strength concrete exceeding 40 MPa.

Figure 5 presents a summary of the test to predicted ratio for the average compressive strength of concrete. The results indicate that most of the considered formulas are conservative in their predictions of the compressive strength of high strength concrete, based on data from the UPV and RH methods. These results can give safer prediction but may be impractical with respect to the factor of safety resulting from the strength evaluation. Consequently, the formula suggested by the dual linear regression expression showed the best accordance with the test results. Tables 6 and 7 include the analysis results in terms of *RMSE*. Figure 6 plots the entire comparison, revealing which formula has the smallest *RMSE*, thus showing the highest accuracy in the prediction of the compressive strength of high strength concrete. With the exception of the formulas of Kim and Kwon, most of the considered formulas presented relatively large *RMSE*. Consequently, the estimation equation suggested in this study showed the lowest *RMSE* among the considered formulas. This proves that the dual linear regression expression used in this study can give a good prediction for the strength evaluation of HSC by combining two significant influencing factors: measured UPV and RH.

Table 4. Previous equations for the rebound hammer test.

References	Regression Formula (MPa)	Strength Limit (MPa)	Expression Types
AIJ [4]	$f'_c = 0.73R_0 + 10.0$	45	1st polynomial
Ali-benyahia [34]	$f'_c = -15.034 + 0.9874R_o$	21.9	1st polynomial
Atici [10]	$f'_c = 3.34exp^{0.0598R_0}$	36.4	Exponential
Kim [35]	$f'_c = 1.267R_0 + 9.7868$	60	1st polynomial
Kwon [36]	$f'_c = 2.59R_0 - 51.5$	65	1st polynomial
Mohammed [37]	$f'_c = 9.5879exp^{0.0384R_0}$	40	Exponential
Qasrawi [13]	$f'_c = 1.353R_0 - 17.393$	42	1st polynomial
Rashid [38]	$f'_c = -0.08R_0^2 + 8.37R_0 - 157.54$	52	2nd polynomial
Willetts [39]	$f'_c = 0.00935R_0^2 + 0.8R_0 - 12.06$	-	2nd polynomial

Table 5. Previous equations for the ultrasonic pulse velocity method.

References	Regression Formula (MPa)	Strength Limit (MPa)	Expression Types
AIJ [4]	$f'_c = 21.5V_p - 62$	45	1st polynomial
Ali-benyahia [34]	$f'_c = 0.6401V_p^{2.5654}$	21.9	Power
Atici [10]	$f'_c = 0.0316exp^{1.3V_p}$	36.4	Exponential
Del Rio [40]	$f'_c = e^{[(-5.4 \pm 0.8)+(0.00185 \pm 0.00018)V_p]}$	34.0	Exponential
Khan [17]	$f'_c = 0.5208V_p^5$	100	Power
Kim [10]	$f'_c = 50.163V_p - 178.2$	60	1st polynomial
Najim [11]	$f'_c = 0.0136V_p - 21.34$	50	1st polynomial
Qasrawi [13]	$f'_c = 32.72V_p - 129.077$	42	1st polynomial
Rashid [38]	$f'_c = 38.05V_p^2 - 316.76V_p + 681.62$	52	2nd polynomial
Trtnik et al [16]	$f'_c = 0.854exp^{1.2882V_p}$	50	Power

Table 6. Comparison results of compressive strength of concrete by rebound hammer test.

References	Test/Predicted	Standard Deviation	Root Mean Square *
AIJ [4]	1.6	0.13	23.6
Ali-benyahia [34]	2.4	0.21	37.5
Atici [10]	1.5	0.21	22.4
Kim [35]	1.0	0.08	5.1
Kwon [36]	1.1	0.11	8.7
Mohammed [37]	1.3	0.12	15.9
Qasrawi [13]	1.6	0.13	24.6
Rashid [38]	1.2	0.09	12.4
Willetts [39]	1.7	0.16	25.9
Dual linear regression	1.0	0.08	4.9

* calculated by using the results in Table 3.

Table 7. Comparison results of compressive strength of concrete by ultrasonic pulse velocity method.

Reference	Test/Predicted	Standard Deviation	Root Mean Square *
AIJ [4]	1.6	0.20	29.5
Ali-benyahia [34]	1.8	0.23	24.5
Atici [10]	4.2	0.72	48.7

Table 7. *Cont.*

Reference	Test/Predicted	Standard Deviation	Root Mean Square *
Del Rio [40]	2.2	0.47	34.4
Khan [17]	0.7	0.11	32.2
Kim [10]	1.1	0.15	9.3
Najim [11]	1.9	0.26	30.4
Qasrawi [13]	1.5	0.17	21.5
Rashid [38]	2.4	0.41	37.9
Trtnik et al [16]	1.8	0.30	28.7
Dual linear regression	1.0	0.08	4.9

* calculated by using the results in Table 3.

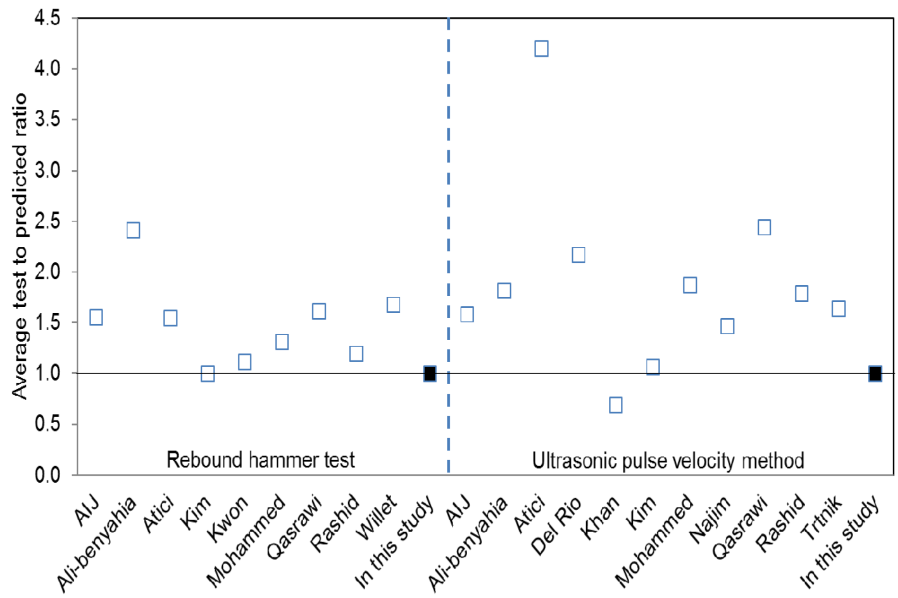

Figure 5. Ratio of the measured strength to the estimated strength.

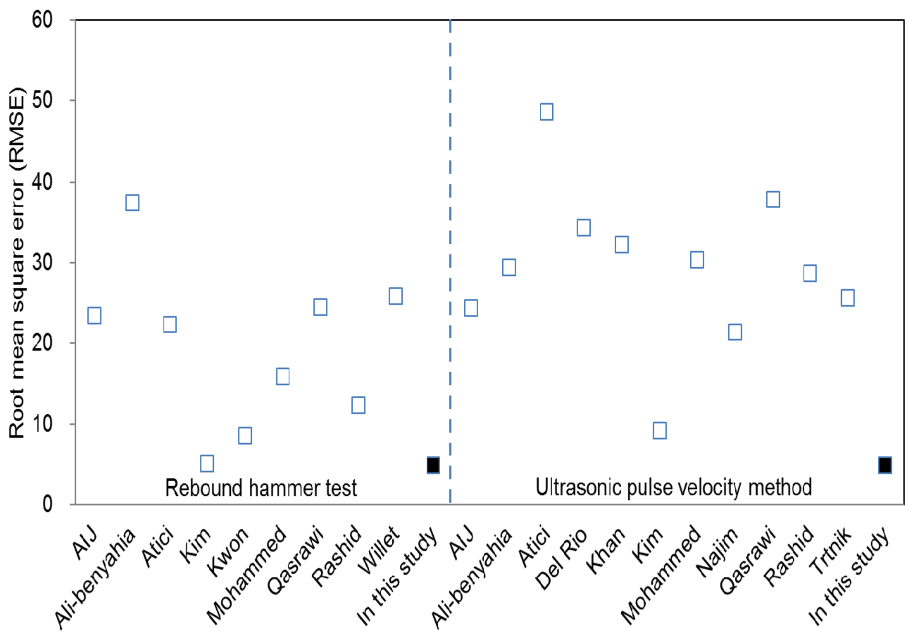

Figure 6. Root mean square error of the compressive strength of concrete.

5. Strength Correction Factor for Concrete Core Strength

For the maintenance of concrete strength evaluation, the concrete core specimen is generally considered to be the direct representative specimen for evaluating the compressive strength of concrete within an in situ structural member. According to the specifications British Standard Institution (BSI) [21], International Union of laboratories and Experts in Construction Materials, Systems and Structures (RILEM) [5] and Architectural Institute of Japan (AIJ) [4] for NDT, a non-destructive test is recommended for estimating the compressive strength of concrete members, based on the correlation of the strength obtained by core strength tests. One of the most significant concerns in using a core specimen is that it is easily damaged by the high speed drill bit during the extracting process of the cores [41]. The core strength test essentially partially damages the target concrete member. A concrete core diameter of 100 mm is generally used, however, the practical concrete core size is usually limited by the installation of internal reinforcement, such as pre-stressed tendon. Another limitation is the position where the core concrete can be extracted from: it is necessary to minimize partial damage in parts of the member where the stresses concentrate. In these conditions, a smaller core size specimen is a useful option, because it is causes much less partial damage so that the structural integrity of concrete member can be guaranteed after the extracting process of the cores. The use of a small-size core specimen must be quite effective in the maintenance of NPP structures made of HSC. When estimating the compressive strength of HSC using a small-size core specimen, the strength correction factor between the smaller diameter specimen and the 100 mm concrete cylinder should be evaluated.

Figure 7 shows the three diameters of core specimen that were evaluated in this study. Concrete core specimens were obtained from a square concrete block without steel reinforcement. The block is 600 mm long, 600 mm wide and 200 mm thick, as previously shown in Figure 2.

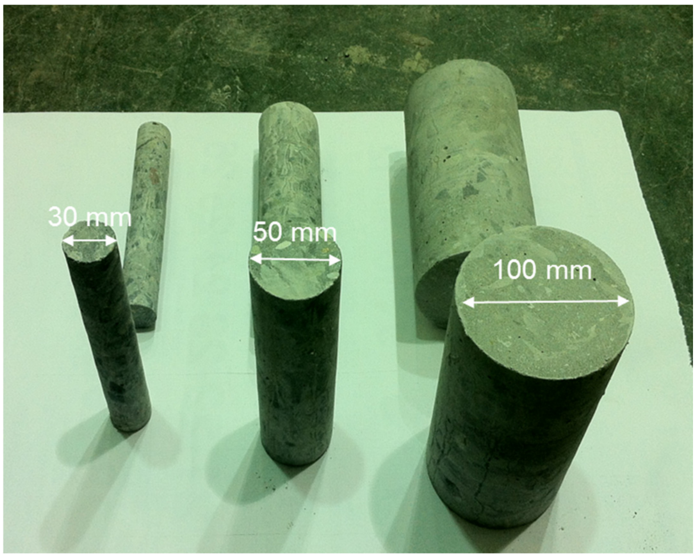

Figure 7. Extracted core specimens for diameter of 30, 50, 100 mm.

Table 8 summarized compressive core strength of concrete according to the mix types and core diameters. Considering that the maximum size of the coarse aggregate is 20 mm, a minimum core size of 30 mm is reasonable for investigating the compressive strength of concrete using a compressive test. As the diameter size of the specimen decreases, the compressive strength of the core specimens also decreases.

Table 8. Compressive core strength of concrete according to the mix types and core diameters.

Mix Type	Concrete Block No.	f_{core} (MPa)		
		30 mm	**50 mm**	**100 mm**
Mix 1	1	44.7, 31.6	56.3, 45.0, 51.0	48.9, 51.7
-	2	52.8, 38.6	67.3, 46.2	62.3, 56.9
-	3	32.8, 39.8	36.9, 37.1, 38.2	57.1, 48.4, 54.7
-	Average	40.1	47.3	54.3
Mix 2 *	1	36.2, 31.3	32.0, 32.1	46.4, 53.6
-	2	40.7, 37.0	42.5	35.0, 33.3, 40.1
-	3	39.9, 41.6	37.5, 35.3, 40.1	32.4, 35.8, 44.8
-	Average	37.8	36.6	40.2
Mix 3	1	49.8, 94.8	43.8	55.3, 54.3
-	2	80.3, 50.3	55.8, 67.7, 54.0	78.7, 76.2
-	3	42.7, 41.9, 55.3	44.9, 42.9, 44.5	54.2, 58.8
-	Average	59.3	50.5	62.9

* Mix 2 is not included for the evaluation of strength correction factor.

This trend is in agreement with previous research, including an observed higher coefficient of variation (COV) [25]. This strength discrepancy is deeply related with degree of coarse aggregate. Coarse aggregate is the source that enables excellent interlocking mechanisms within concrete members. For instance, 25 mm diameter coarse aggregate is usually used for concrete mixing. If the concrete core diameter decreases to below 25 mm, the probable chance of having 25 mm aggregate within the core specimen also decreases. Accordingly, the estimated compressive strength of the concrete core specimen must be lower, as there is less coarse aggregate to resist against the compressive loading. The minimum size of the core diameter will have to be appropriately determined by considering the maximum coarse aggregate used in the target concrete structures for core strength tests.

Figure 8 exhibits the strength correction factor between concrete core specimens and the 100 mm standard concrete cylinder. For 100 mm specimens, the strength correction factor between the core and cylinder ranged from 0.92 to 1.02. However, the 30 and 50 mm core specimens had lower evaluated strength than those of the concrete cylinder specimens. One possible reason for the strength reduction is that water particles inside the concrete are gradually eliminated due to drying and proceeding hydration mechanism so that a number of micro voids remain. These pores within the structure may develop a critical damage interface. Once the drill bit penetrates the concrete member, the high speed rotating impact deeply affects the damage acceleration of concrete around the pores then the integrity of concrete worsens compared to the standard concrete cylinder. There are a few research data on strength correction factors between the concrete core and the standard cylinder, and also few data on high strength concrete. Because of the uncertainty in the strength evaluation of the specimens obtained from the extracting process of the cores, the strength correction factors between the concrete core and the standard cylinder should be further investigated, and an empirical strength relationship needs to be researched for the maintenance of high strength concrete structures. From Figure 8, as the concrete strength went to mix 1, the average strength ratio was increased. Thus, the damage in extracting core may be reduced rather than that of stronger specimen of mix 3. This can be explained that higher power and rotating speed is needed for mix 3 specimens so it may affect even more damages inside concrete.

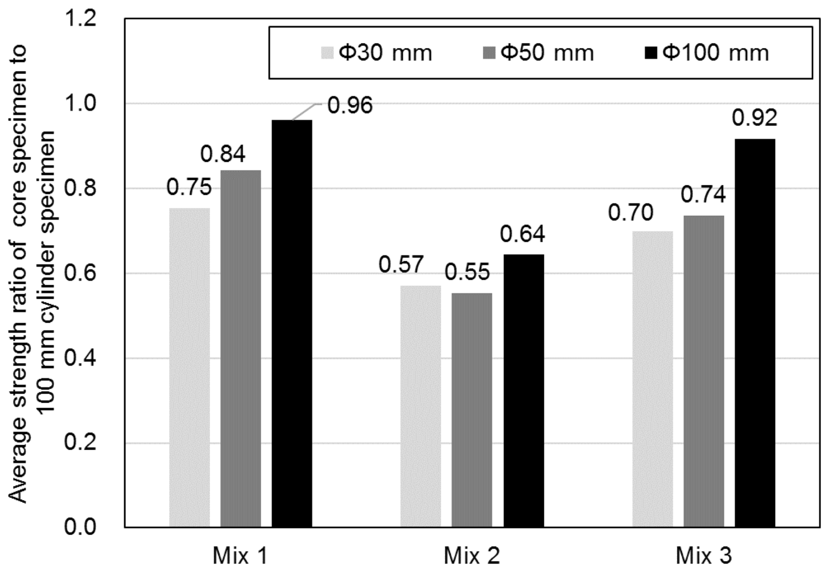

Figure 8. Compressive core strength of concrete and strength ratio for the three types of mix proportions.

Figure 9 classifies the average compressive strength according to the three different core diameters used in this study. Core specimens made from mix 2 exhibited out of strength results, which might be caused by some problems in the extracting process. Figure 10 shows the average strength correction factor (γ) defined as the ratio of the core strength (f_{core}) to the cylinder specimen strength (f_c'). Mix 2 specimens were excluded when calculating this strength correction factor, due to the reason stated above. Therefore, the strength correction factor is obtained by following expression as $\gamma = f_{core}/f_c'$. The average γ was obtained as 0.73 for 30 mm, 0.79 for 50 mm, and 0.94 for 100 mm. The γ equation can simply convert the compressive strength of concrete core specimens to the compressive strength of the concrete cylinders at 28 days. This correlation equation is convenient to use, without needing destructive data on the in situ concrete cylinder, and the strength correction factor can be continuously updated as the tested dataset increases. This equation can be used, in combination with smaller in situ core specimens, as a maintenance strategy for evaluating the designed compressive strength of high strength concrete within NPP structures.

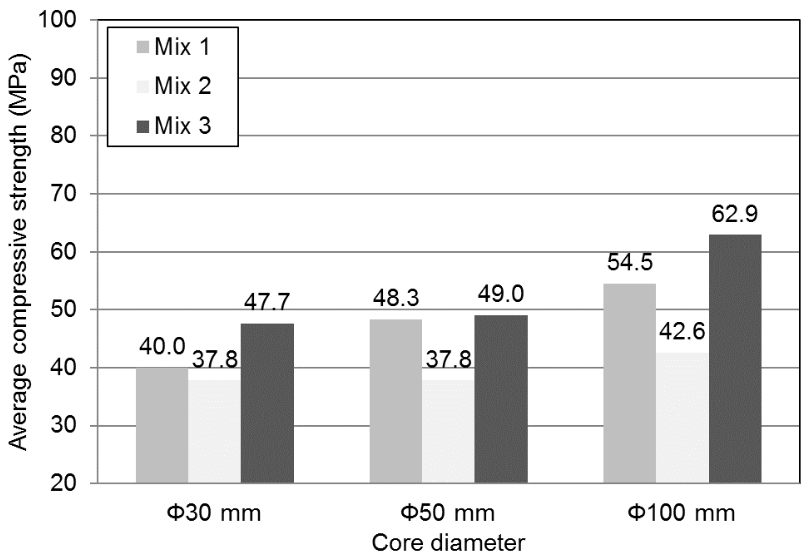

Figure 9. Compressive strength of concrete according to the diameters of 30, 50, 100 mm.

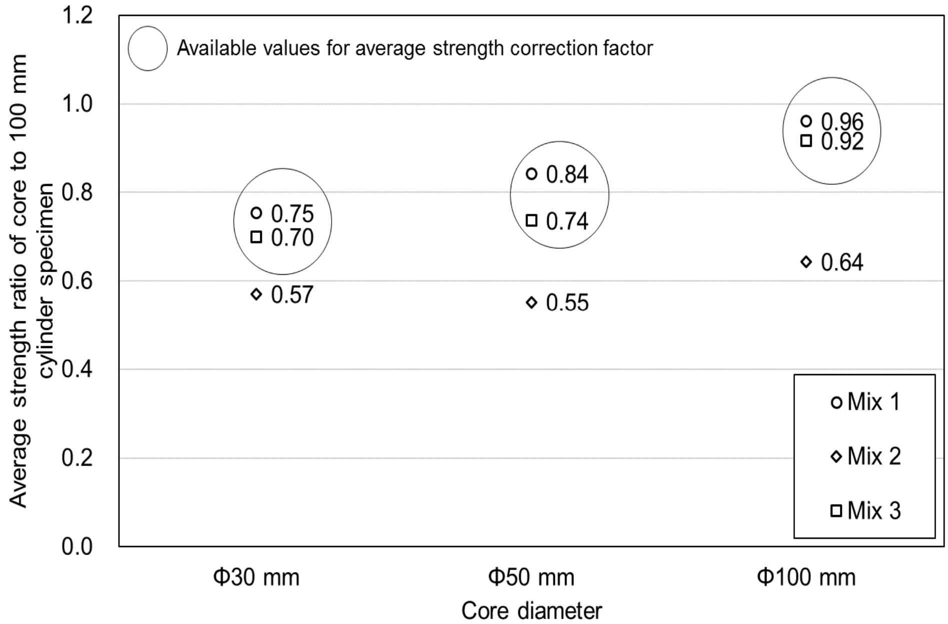

Figure 10. Average strength ratio for core specimens according to core diameter.

6. Conclusions

This study investigated the compressive strength of the high strength concrete and suggested the estimation equation for non-destructive tests and core strength tests. The conclusions are as follows:

1. In this study, the compressive strength of high strength concrete (greater than 40 MPa) was evaluated and an estimation equation was suggested that uses a dual regression approach in conjunction with rebound hammer tests and the ultrasonic pulse velocity method. In comparison to previous formulas, the proposed estimation equation showed the highest accuracy and the lowest *RMSE* in predicting compressive strength. Thus, the formula suggested in this study can be effectively used to estimate the compressive strength of a high strength concrete member.
2. Analytical comparison of the concrete core and cylinder specimen revealed that the compressive strength of the concrete core specimen was lower than that of the concrete cylinder. This must be due to the inherent damage caused during the extracting process of the cores, and the lower amount of coarse aggregates within the specimen. Thus, the strength correction factor of high strength concrete should be further researched using more experimental tests or damage image processing. Smaller-sized concrete core specimens can be reasonably used to estimate the compressive strength of concrete with minimum destructive damage to high strength concrete members.
3. This study investigated a strength correction factor (γ) that converts the compressive strength of concrete core specimens to the compressive strength of the concrete cylinder at 28 days. The strength factor conversion coefficient was obtained by averaging the data from an entire mix series for each specific core diameter. This value is not deterministic but is useful in estimating the correlation between concrete cores and cylinder specimens made from high strength concrete. This factor can be further updated and modified when more test results are available.
4. Using a combination of both estimation equation and strength correction factor for high strength concrete may be a good strategy for the practical maintenance of NPP members made of the high strength concrete.

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