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Technical Note

Practical Aspects of Correlation Analysis of Compressive Strength from Destructive and Non-Destructive Methods in Different Directions

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Abstract: The research presented here demonstrates the practical aspects of the numerical correlation of the results of the compressive strength test. The destructive test (DT) in a hydraulic press and the non-destructive test (NDT) using a Schmidt hammer in several process variations were evaluated. The aim was to evaluate the real differences between the tool supplier's curve and testing. Therefore, 150 concrete cube specimens with an edge length of 150 mm were produced using a mixture of three types of concrete classes: C30, C35, and C40. The test was carried out 7 and 28 days of age of the concrete. The Schmidt hammer test was carried out in horizontal (θ = 0) and vertical (θ = 90) directions and using a series of 10 measurements. Furthermore, the tests were performed in two sets: first, the sample was placed on the ground, and second, under a hydraulic jack with a load of 50% of the maximum bearing capacity of specific concrete. Then, regression analysis was performed on the data sets to establish linear mathematical relationships between compressive strength and number of bounces. The results showed that the correlation between the DT and NDT tests has a high value for each group, but the correlation equations are different and must be taken into account.

Keywords: compressive strength; concrete; destructive testing; non-destructive testing; regression; Schmidt hammer

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1. Introduction

Concrete is one of the important construction materials that is widely used in building structures due to its availability, low cost, and workability [1,2]. Because concrete under load pressure can fail, determining its compressive strength plays a vital role in judging its quality. Both destructive and non-destructive testing methods have been applied to estimate compression strength. A considerable amount of work has focused on the compressive strength of concrete. Regarding destructive testing (DT) methods, such as the use of a hydraulic jack, it should be mentioned that the results obtained from this method are accurate [3–7]. However, this method suffers from drawbacks such as high cost, energy consumption, labor, time, and lack of ability to measure in situ concrete. Therefore, non-destructive testing (NDT) methods are now popular in that they are carried out without destroying the concrete specimen, while in DT methods the specimen should be crushed to fail [8–10]. These NDT methods are suitable for in situ measurements on existing structures or for long-term measurements, where it is necessary to determine the changes in concrete strength over time.

NDT methods can directly evaluate the quality of a building even on-site by estimating the compressive strength of the concrete structure, and the most commonly used NDT method is the Schmidt hammer [8,11,12]. Several authors have used the Schmidt hammer to measure concrete strength [8,13–16]. A Schmidt hammer, also known as a Swiss hammer or a rebound hammer, is a portable device that measures the elastic properties or the strength of concrete. Moreover, NDT methods are highly beneficial for measuring different parameters of concrete, i.e., strength, durability, and homogeneity [9]. Previously, some studies have compared a destructive testing method (core testing) with an NDT method. NDT methods are used for the analysis of concretes of different basic materials and different applications [10,17].

According to their research, the NDT method has the following advantages in comparison to DT methods: (1) lower cost, (2) simplicity, (3) reduction in labor consumption, (4) greater speed, and (5) evaluation of concrete property without damaging it [18]. The amount of rebound depends on several concrete parameters, i.e., hardness, coefficient of elasticity, ore, water content morphology of the sample, surface roughness, type of aggregation, and concrete ingredient [19,20]. Moreover, small test areas, lack of equipment, and test direction should be considered as determining parameters in NDT methods [21]. Regardless of the advantages associated with NDT methods, this method is anisotropy in which different directions of measuring can affect their value. Moreover, because the results obtained from using a Schmidt hammer can be affected by several parameters such as the amount of porosity, moisture, hardness, roughness, etc., the results are more of an approximation than a precise value. Consequently, researchers have tried to overcome this limitation by finding a correlation between DT and NDT values to increase the accuracy of measuring compressive strength.

In recent years, other authors have also searched for the correct correlation relations between NDT methods and DT methods, because these correlations were not determined on non-standard concretes [22,23]. There are also studies using machine learning methods to predict the dynamic compressive response of composite materials [24].

In the presented research, both DT (hydraulic press machine) and NDT (rebound hammer) methods were proposed to evaluate the compressive strength of C30, C35, and C40 to define a method more reliable and practical. It should be noted that in order to minimize errors in investigations, water content, processing, and atmosphere temperature were kept constant. Then, attempts were made to compare the results obtained from the cube samples by regression to find an accurate relationship between the DT and the NDT data in which the correlation coefficient is greater than 0.85. The results of a large number of tests were used to evaluate the practical use of the Schmidt hammer in many aspects. The statistical and numerical evaluation of accurate measured data in large quantities is of great importance for both academia and practice, where the Schmidt hammer is used and has significant value. This is not the only reason why the results presented and evaluated are placed in the context of current trends and habits.

2. Materials and Methods

2.1. Mixtures and Samples

Three types of concrete with different required strengths had to be prepared for the experiments. The concrete composition is based on ordinary Portland cement of the Tehran brand (OPC), potable water (as per ASTM D1067 [25]), fine aggregate (sand), and coarse aggregate (gravel) from a local source (Qom, Iran). The design of the mixtures was carried out in accordance with ACI-211 [26], and the composition is shown in Table 1.

Table 1. Mixture design.

Concrete	Sand (kg)	Gravel (kg)	Cement (kg)	Water (lit)	Slump	Water/Cement
C30	950	852	400	228	7.5–10	0.57
C35	950	852	450	234	7.5–10	0.52
C40	950	852	500	240	7.5–10	0.48

These three types of concrete were selected because they are the most commonly used in the construction industry. The reason for the three types was to account for differences in the case of strength. All concretes had the same fine aggregate and coarse aggregate, but different cement and water contents. This resulted in different w/c ratios and thus different resulting strengths.

The manufacture of the concrete was carried out in accordance with BS 1881: Part 108:1983 [27]. In the production of concrete, the dry ingredients were mixed with each other at ambient temperature, then half of the water was added, and all the ingredients were mixed for 2 min to form a homogeneous mixture. The rest of the water was then added and the materials were mixed for 2 min. The samples were then cast into cube molds, compacted, and left at room temperature for 24 h; they were transferred to a tank of water and cured for 7 and 28 days. A total of 150 cubic specimens (50 samples for each class) cubic specimens (150 mm × 150 mm × 150 mm) were produced in 3 different classes. Therefore, each test set is based on 25 identical test samples. Thus, as shown below, it was tested in two different directions, and a large statistical evaluation was obtained due to the number of 25 samples per condition.

2.2. Experimental Program

Three tests were prepared in the experimental program—non-destructive vertical hammer test, non-destructive horizontal hammer test on a loaded specimen, and destructive pressure test in a hydraulic press machine. A 50% value of the maximum predicted force was used for each type of concrete—for concrete C30, it was 15 MPa, for concrete C35 it was 17.5 MPa, and for concrete C40 it was 20 MPa. All tests were performed sequentially on the same specimens to maintain a complete correlation of results. Figure 1 shows the steps to use a Schmidt hammer. The first picture is the calibration sample, the second picture is the test measurement in a vertical way, and the third picture is the test measurement in a horizontal way.


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

Figure 1. Steps to use a Schmidt hammer: (**a**) placing the calibration element, (**b**) testing vertically, (**c**) testing horizontally.

Before starting the test, the hammer should be calibrated; the average of ten reading numbers should be considered as calibration before each test. Furthermore, the test surface should be smooth, even in the laboratory or on site. The specimen should also be held by a rigid keeper to avoid shaking. It should be noted that the direction of the hammer can affect the hardness values. According to ASTM C805-02 [28], the hammer should first be kept vertical and then the specimen placed on a hydraulic jack to take the number of opposite faces of the cube specimen. An average of 10 reading numbers for each surface was considered as a hammer rebound number. If the measured value deviated from the average by 20%, it was not included in the final investigation. Furthermore, if these neglected reading numbers were more than 2 on each surface, then the test was not reliable and was cancelled. Finally, the specimen was destructively tested to determine the compressive strength of the hydraulic press machine. The compressive strength of concrete is a test carried out on a cube, a cylinder, or a suitable piece of broken beam, sometimes on core holes. A minimum of three bodies are always tested. Before the actual test, the geometry of the test body is verified. Specimens that fail non-standardly are excluded from the test. A record of each test and its results shall be kept.

2.3. Statistics

The main aim was to find a relationship between the DT and NDT results. These two groups were first correlated for all concretes using Pearson's correlation coefficient (PCC) [29]. The Pearson correlation coefficient is a descriptive statistic that sums up the characteristics of a data set. Specifically, it describes the strength and direction of the linear relationship between two quantitative variables. For example, a PCC greater than 0.5 means strong strength. The same set was then analyzed using linear regression [30] and the determinant R^2 [31,32]. R^2 is a statistic used in the context of statistical models whose main purpose is to predict future outcomes.

This analysis provides a measure of how well observed outcomes are replicated by the model, based on the proportion of total variation of outcomes explained by the model. Linear regression analysis is used to predict the value of a variable based on the value of another variable. The variable you want to predict is called the dependent variable. The variable you use to predict the value of another variable is called the independent variable. This form of analysis estimates the coefficients of a linear equation involving one or more independent variables that best predict the value of the dependent variable. A linear regression corresponds to a line or area that minimizes the differences between the predicted and actual values of the output.

The evaluation of correlation and linear regression indicates whether two parameters have a very high, high, moderate, low, or no dependence. These numerically obtained linear correlation curves were faced with the normative curve of the Schmidt hammer used. The curves obtained were also described using the equation and the statistical parameters described above.

3. Results and Discussion

DT and NDT investigations were carried out on three different grades of concretes, namely, C30, C35, and C40, to estimate compressive strength with a good approximation. Tables 2 and 3 present the average of 25 compressive strength measures in MPa and 25 rebound numbers in vertical and horizontal hammer positions for concrete cured for 7 and 28 days, respectively. According to the results, the compressive strength increased with increasing concrete grade; with respect to samples cured for 7 days, the compressive strength increased from 31.7 MPa (C30) to 38.9 MPa (C40). Furthermore, for samples cured for 28 days, the compressive strength increased from 42.9 MPa (C30) to 51.1 MPa (C40). Therefore, by comparing the results, it is obvious that increasing the number of days that concrete samples were cured in water led to an increase in compressive strength. Moreover, it can be understood from Tables 2 and 3 that if the hammer position changes from a horizontal direction to a vertical direction, the rebound number decreases.

These observations do not deviate from the expectations and information available in the literature [8,11,18]. Evaluation of the standard deviation shows that in all cases the numbers are less than 10% of the mean, which corresponds to the restriction that no result had to be excluded from the statistical set.

Table 2. Average compressive strengths in MPa and rebound number for different concrete cured for 7 days.

Age	Class	Test	Mean	STD
7 days	C30	Compressive Strength	31.7 MPa	3.19
		Rebound number (horizontal)	28.5	2.81
		Rebound number (vertical)	23.1	1.22
	C35	Compressive Strength	37.5 MPa	2.74
		Rebound number (horizontal)	30.1	2.48
		Rebound number (vertical)	24.5	2.25
	C40	Compressive Strength	38.9 MPa	4.22
		Rebound number (horizontal)	33.2	2.14
		Rebound number (vertical)	26	1.75

Table 3. Average compressive strength in MPa and rebound number for different concrete cured for 28 days.

Age	Class	Test	Mean	STD
28 days	C30	Compressive Strength	42.9 MPa	4.82
		Rebound number (horizontal)	34.1	2.19
		Rebound number (vertical)	25.9	1.73
	C35	Compressive Strength	47.1 MPa	4.36
		Rebound number (horizontal)	35.5	1.19
		Rebound number (vertical)	28.6	2.36
	C40	Compressive Strength	51.1 MPa	3.68
		Rebound number (horizontal)	36.1	1.55
		Rebound number (vertical)	30.7	3.15

A comparison between the standard deviation of the hydraulic press measurement and the standard deviation of the rebound test shows that in this application the rebound results have less variance. This was observed for all three types of concrete.

To find the correlation between Schmidt rebound number and compressive strength, the crushing concrete strength in MPa versus rebound numbers is plotted for 7-day-old concrete and in horizontal hammer position for concrete C30 (see Figure 2), C35 (see Figure 3), and C40 (Figure 4). Similarly, data from vertical measurements at 7 days after concreting were analyzed. The results are presented together with the regression curve in Figures 5–7. Furthermore, data at 28 days for all concretes in the horizontal direction (see Figures 8–10) and the vertical direction of the hammer measurement (see Figures 11–13) are presented.

First, an evaluation of the results measured 7 days after the concrete. The correlation between the horizontal rebound hammer measurement and the hydraulic compressive strength of concrete C30 shown in Figure 2 shows a PCC of 95%, demonstrating high agreement. Even the graphical evaluation of the linear correlation has a determination value of over 0.9. On the other hand, in Figure 3, where the same pair is correlated but for C35 concrete, a slightly higher PCC is seen, but the linear regression has a better fit in this case. The equation for the curve has a different basis but a very similar slope. Figure 4 then shows the concrete C40, for which the correlation regression curve has a negative intercept value on the y-axis, and so it can be seen that the curve is significantly different. Unlike the first two concretes (C30 and C35), the C40 concrete has a normative instrument curve with almost the same slope as the resulting correlation curve from the numerical evaluation.

Figure 5 shows the correlation of the vertical rebound test experiment and the compressive strength of the press for C30 concrete. The correlation of the results is at a very high level and the curve determination is also very high. The slope of the curve does not correspond to the normative curve. Figure 6 then shows the same tests, but for C35 concrete. Again, we see high correlation coefficient numbers and high agreement. Figure 7 shows the same for C40 concrete. Again, for this concrete, the slope of the regression curve is very similar to the normative curve.

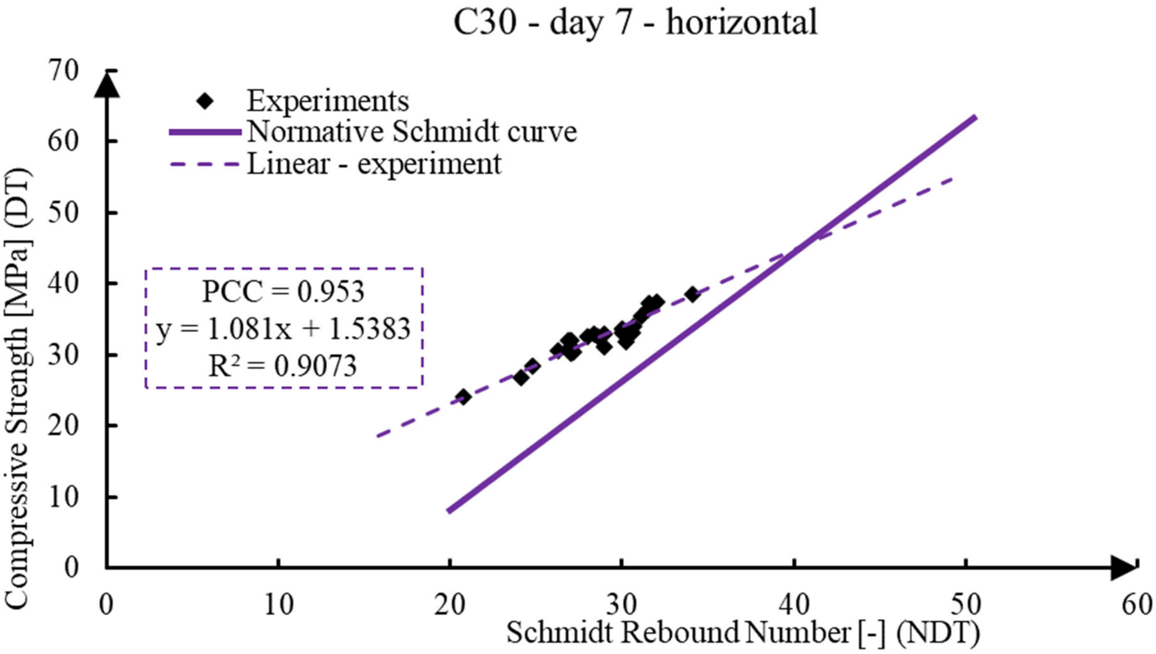

Figure 2. Correlation of the rebound index of the horizontal test and compressive strength at 7 days for concrete C30.

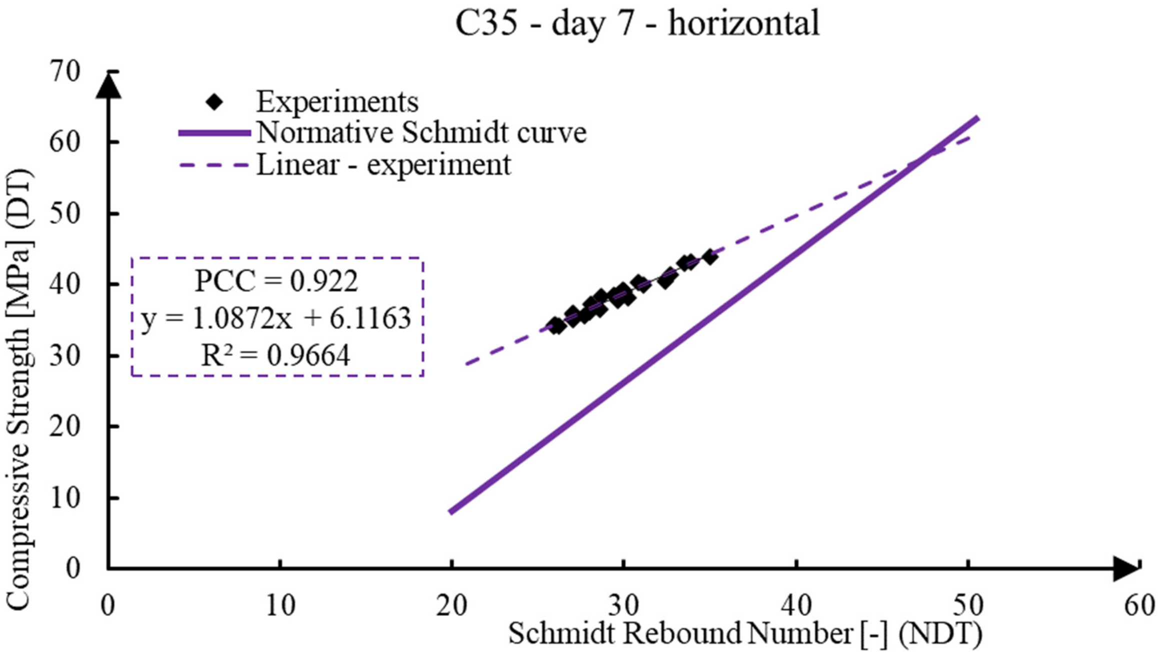

Figure 3. Correlation of the rebound index from the horizontal test and compressive strength at 7 days for concrete C35.

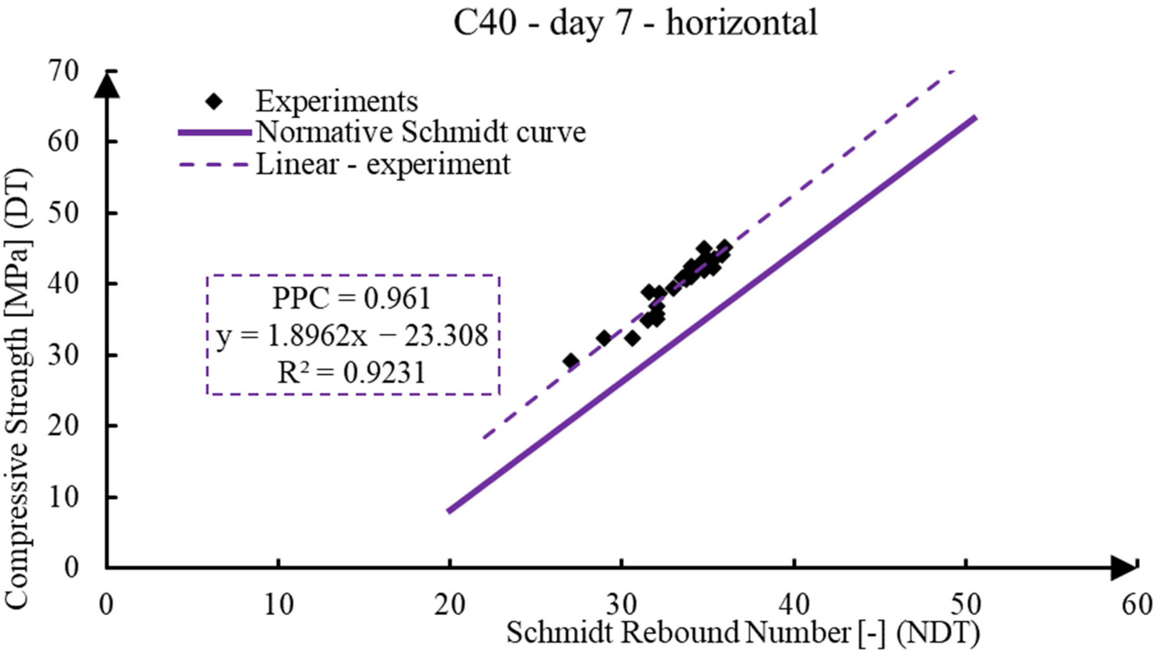

Figure 4. Correlation of the rebound index of the horizontal test and compressive strength at 7 days for concrete C40.

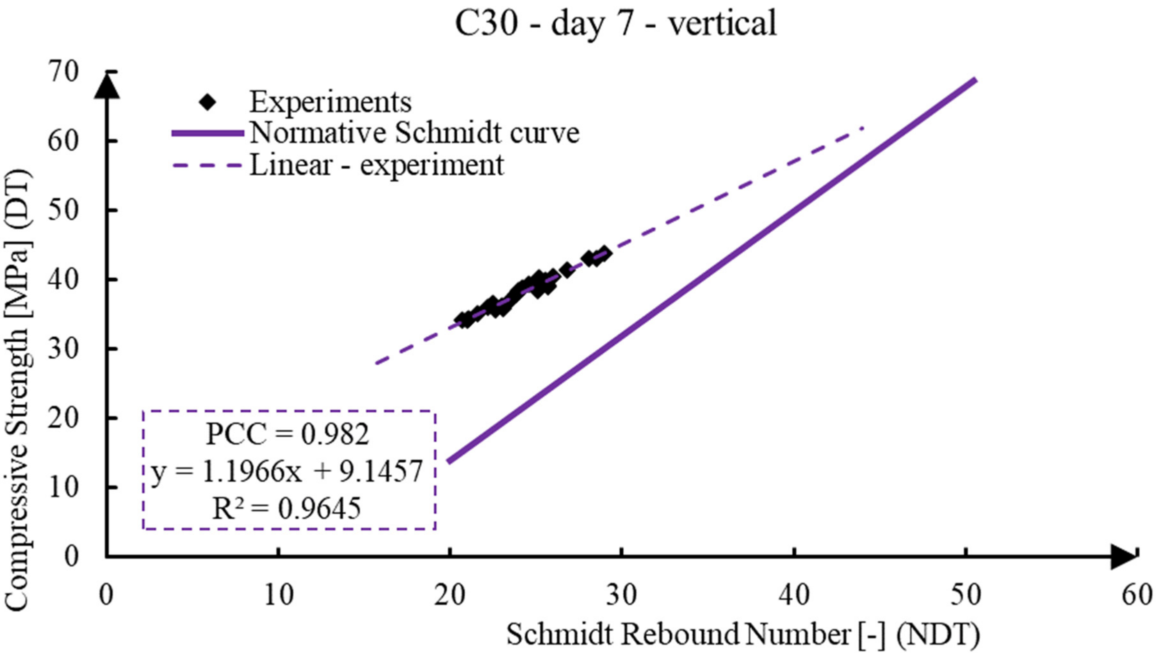

Figure 5. Correlation of the rebound index of the vertical test and compressive strength at 7 days for concrete C30.

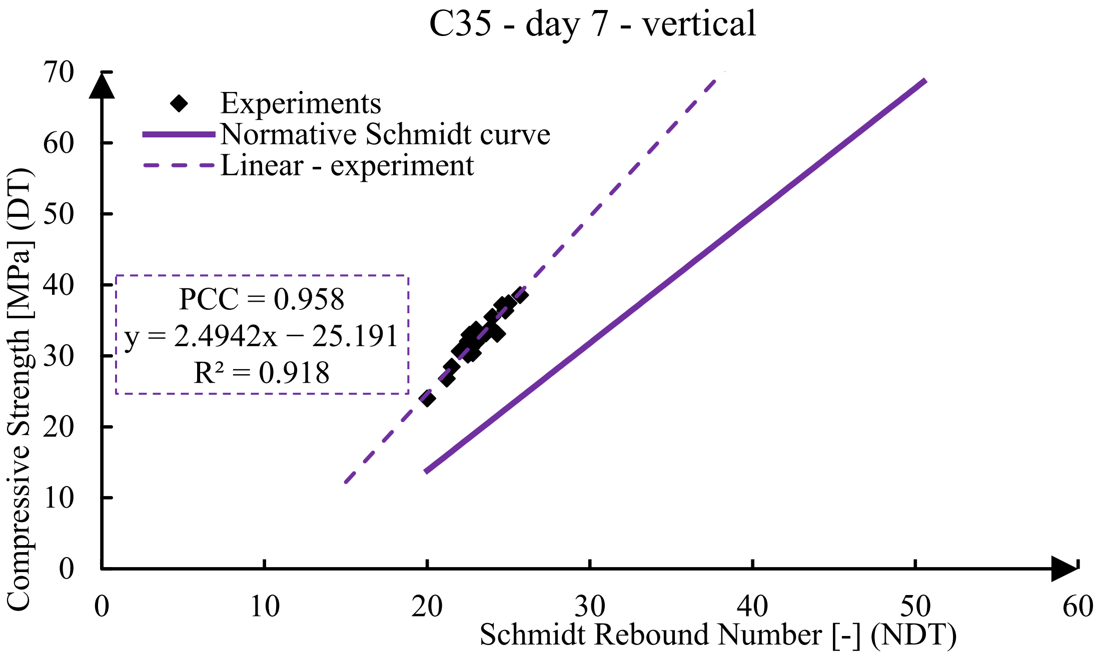

Figure 6. Correlation of the rebound index of the vertical test and compressive strength at 7 days for concrete C35.

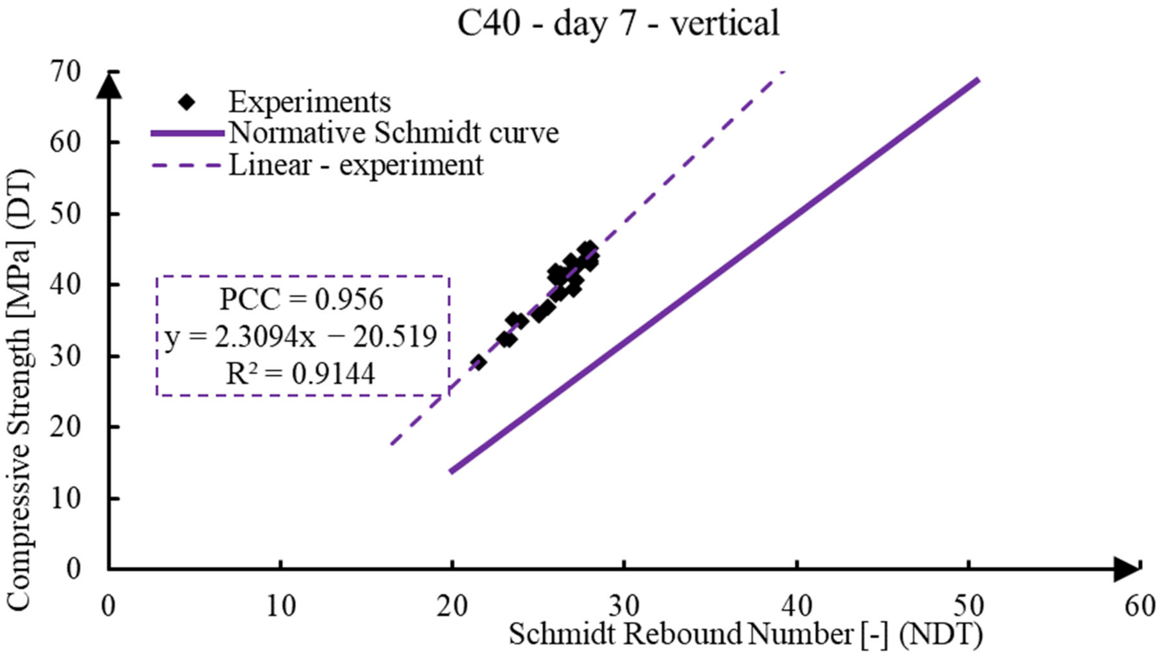

Figure 7. Correlation of the rebound index of the vertical test and compressive strength at 7 days for concrete C40.

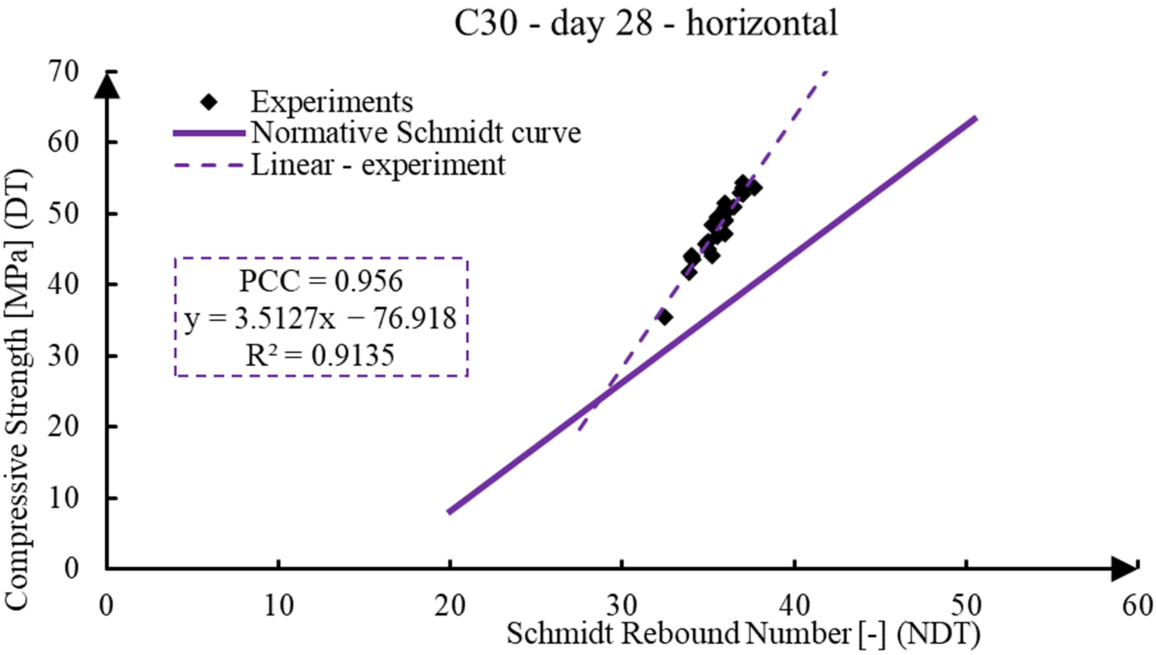

Figure 8. Correlation of the rebound index from the horizontal test and compressive strength at 28 days for concrete C30.

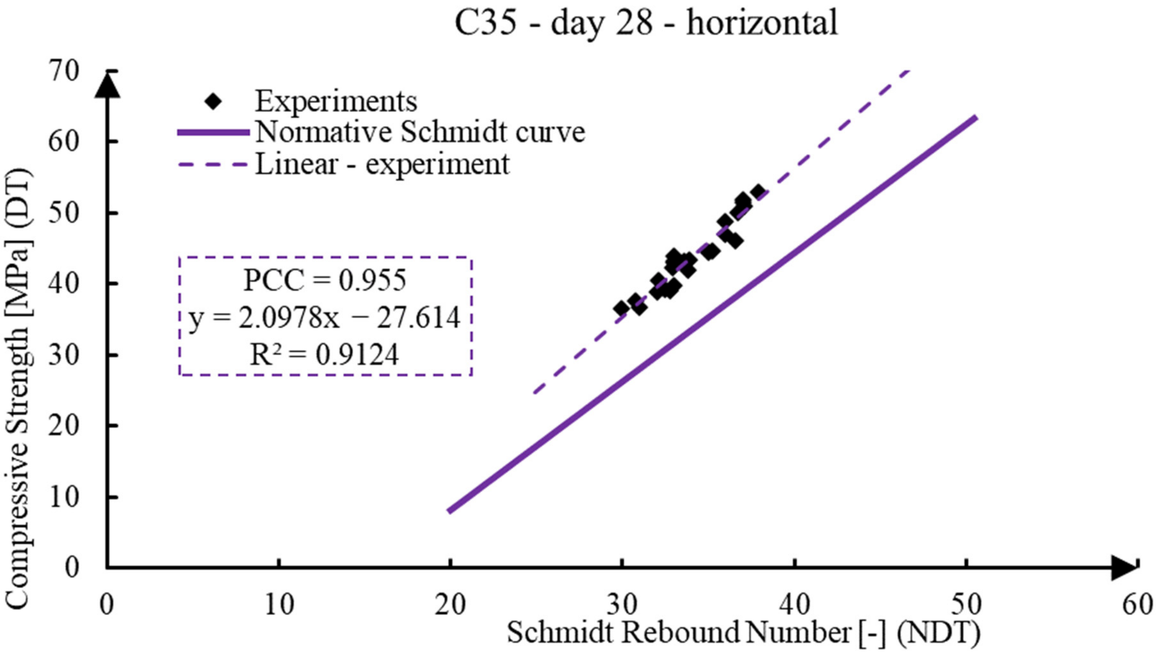

Figure 9. Correlation of the rebound index of the horizontal test and compressive strength at 28 days for concrete C35.

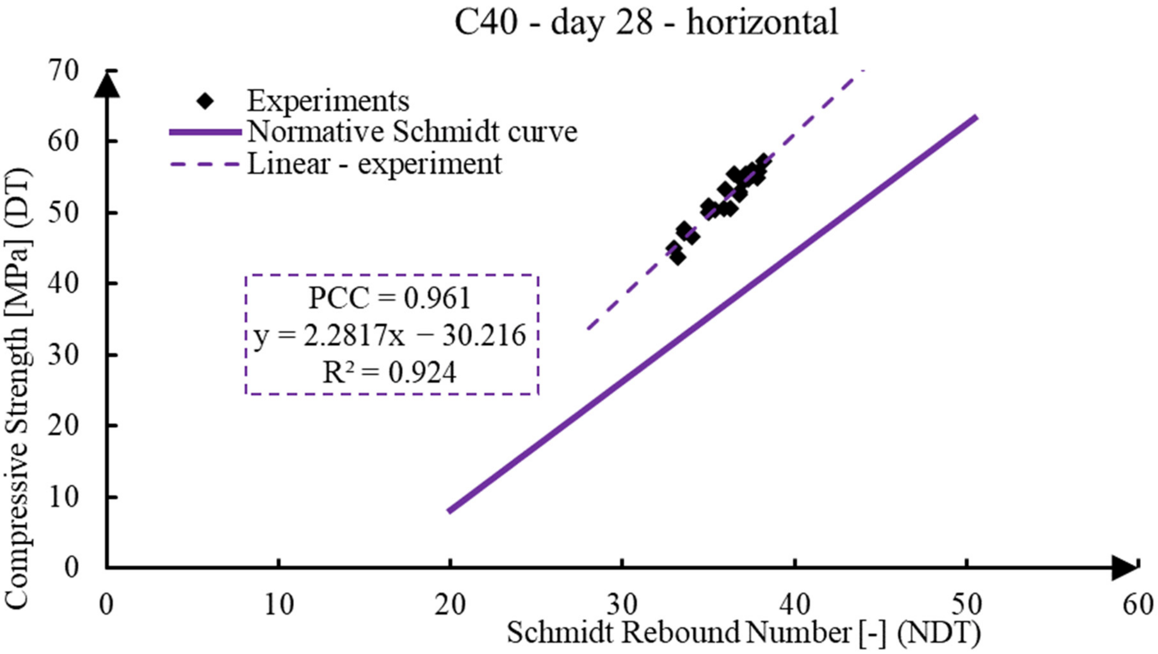

Figure 10. Correlation of the rebound index from the horizontal test and compressive strength at 28 days for concrete C40.

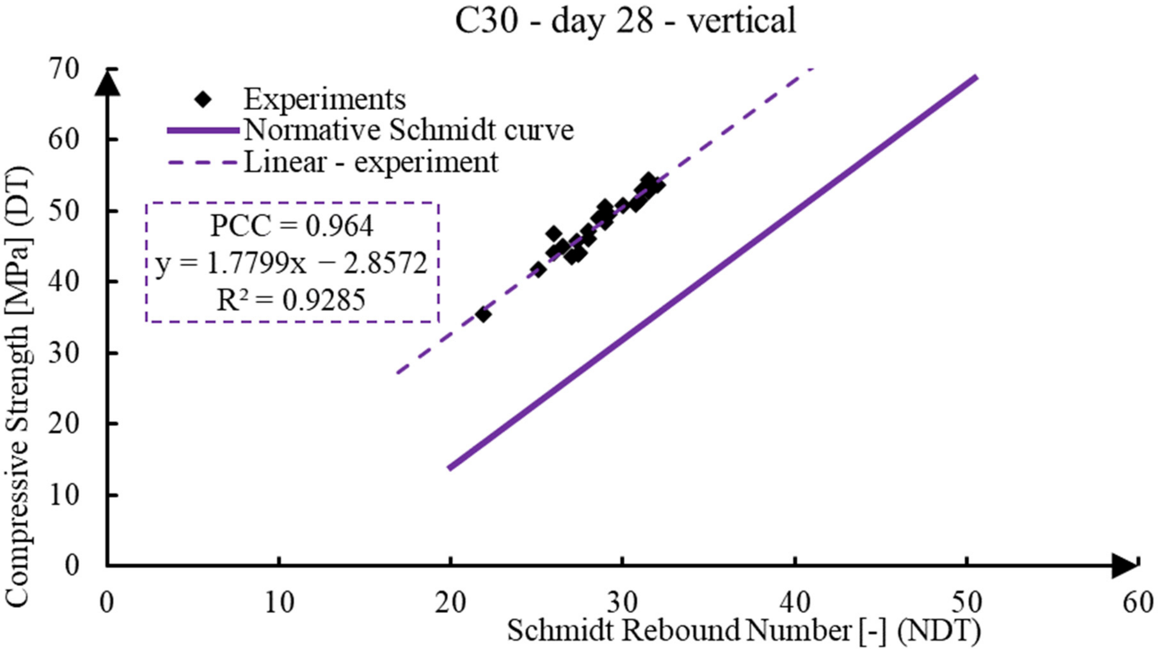

Figure 11. Correlation of the rebound index of the vertical test and compressive strength at 28 days for concrete C30.

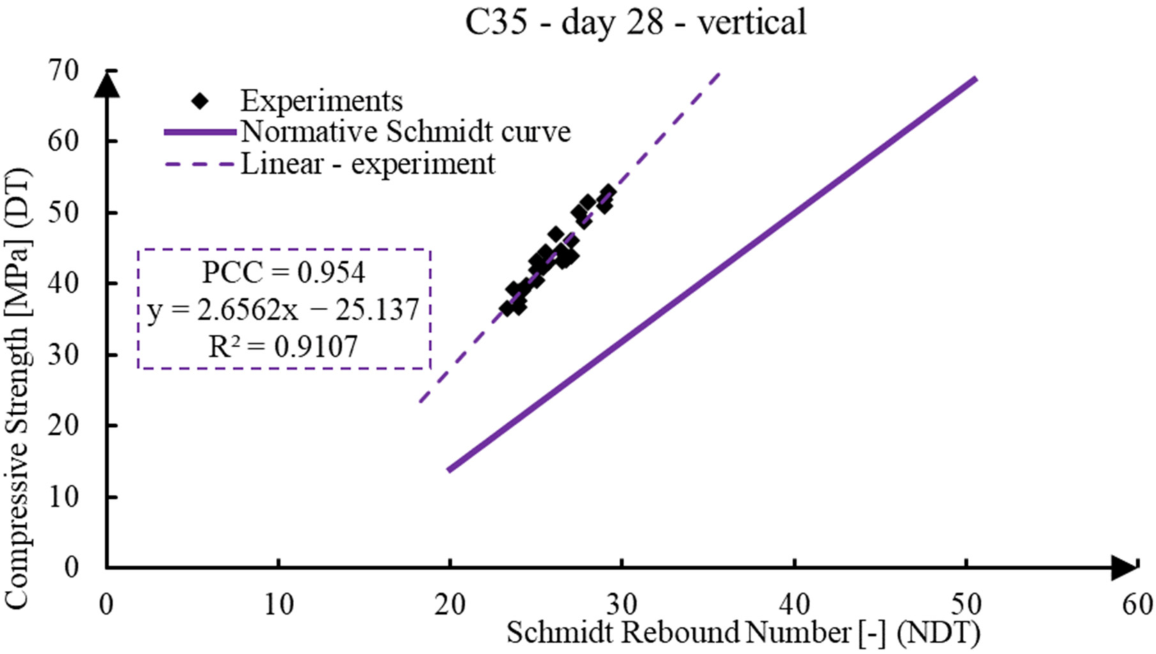

Figure 12. Correlation of the rebound index of the vertical test and compressive strength at 28 days for concrete C35.

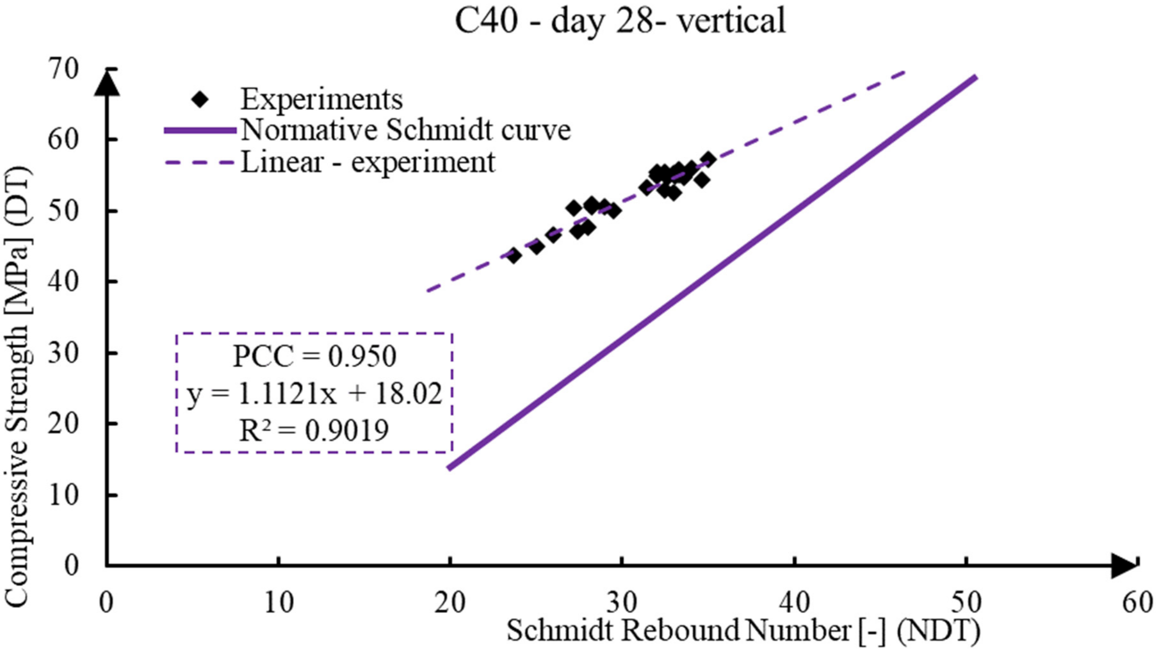

Figure 13. Correlation of the rebound index of the vertical test and compressive strength at 28 days for concrete C40.

The next six graphs show the measurements after 28 days of concreting. Figure 8, which corresponds to the results for concrete C30 for the horizontal reflection measurements, shows a significant difference between the slope of the regression curve and the normative curve. However, individual measurements significantly complement this regression. Figure 9, which shows the concrete C35 values, shows great agreement in terms of the correlation, regression, and slope of the curves. Finally, the C40 concrete and its correlation and slope curve are in agreement.

The last set of three graphs shows the results of the vertical rebound tests and the hydraulic press strength after 28 days of concreting. Figure 11 is for concrete C30. Here, there is the best fit of all the data, and the best fit of the slope of the correlation curve and the normative curve. The C35 concrete in Figure 12 has a high correlation, but the curve has a slope different from the norm. This is also true for the concrete C40 in Figure 13.

In all cases (see Table 4), the ratio between the strength obtained from the destructive test and the non-destructive test shall be higher than the calibration curve supplied by the manufacturer. However, it is not a rule that the linear regression chosen for the unit concrete, the direction of loading, and the age of the concrete is of the same slope as the calibration curve. The C40 concrete results at 7 and 28 days for the horizontal measurement have the same slope. Then, there is the C30 concrete at 28 days for the vertical measurement. All other measurements show a different slope, both smaller and larger.

Table 4. Results of correlation of all data sets.

Age	Class	Type of Schmidt Test	PCC	Linear Equation	R^2
7 days	C30	horizontal	0.953	$y = 1.081x + 1.5383$	0.9073
		vertical	0.982	$y = 1.1966x + 9.1457$	0.9645
	C35	horizontal	0.922	$y = 1.0872x + 6.1163$	0.9664
		vertical	0.958	$y = 2.4942x - 25.191$	0.918
	C40	horizontal	0.961	$y = 1.8962x - 23.308$	0.9231
		vertical	0.956	$y = 2.3094x - 20.519$	0.9144
28 days	C30	horizontal	0.956	$y = 3.5127x - 76.918$	0.9135
		vertical	0.964	$y = 1.7799x - 2.8572$	0.9285
	C35	horizontal	0.955	$y = 2.0978x - 27.614$	0.9124
		vertical	0.954	$y = 2.6562x - 25.137$	0.9107
	C40	horizontal	0.961	$y = 2.2817x - 30.216$	0.924
		vertical	0.950	$y = 1.1121x + 18.02$	0.9019

In terms of the evaluation of these linear regressions, it should be noted that the results cannot be directly applied to concrete types other than those presented here. The results are also limited to the specified concrete classes, i.e., C30, C35, and C40. They cannot be applied to high-performance concrete. Therefore, it is highly desirable to prepare research that would address this topic on non-standard concretes and use the knowledge gained here.

4. Conclusions

To predict the compressive strength of concrete, destructive and non-destructive testing methods were performed on laboratory-produced concrete to determine the relationship between Schmidt hammer values (rebound index) and the compressive strength of concrete. The horizontal and vertical directions of the Schmidt hammer were applied to concrete aged 7 and 28 days. Calibration curves were drawn and compared for concretes aged 7 and 28 days. Taking into account all the data, it is clear that all the R-squared values obtained are greater than 0.8, indicating that there is a close relationship between the compressive strength of the DT tests and the Schmidt hammer values. This implies that the Schmidt hammer can be used as a reliable tool to calculate the compressive strength close to its actual strength. Taking all results into account, it was found that the correlations of the equations for concretes aged 28 days are better than those for concretes aged 7 days. Furthermore, it can be seen that the correlation coefficient is higher when the hammer is in a vertical position compared to a horizontal position. It has been found that, in all cases, the Schmidt chart issued by the manufacturer is lower than the experimental data. Therefore, this means that Schmidt hammers are designed and manufactured with a safety margin to minimize risk, which is a conservative estimate of the compressive strength value of concrete.

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