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Conversion Factors between Non-Destructive Tests of Cubic and Cylindrical Concrete Specimens

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ABSTRACT: Assessment of existing structures is an essential topic for engineers working in the field of construction in most industrial countries. Evaluation of compressive strength is one of the most critical factors for concrete structures. Non-Destructive Testing (NDT) techniques are the most extensively used techniques for the prediction of compressive strength in the existing concrete structures. Among NDTs, ultrasonic pulse velocity and rebound hammer are more common to predict the compressive strength of the concrete. This study also investigates surface electrical resistivity as an NDT. In many studies, concrete specimens are constructed in cubic or cylindrical shapes, but the role of conversion factor has been overlooked that may change the NDT results from cubic to cylindrical specimens and vice versa. Hence, in the present paper, an experimental study was conducted on concrete specimens based on NDTs. In this experimental process, cubic and real cylindrical specimens were assessed in the same mix designs at the ages of 7, 28, and 90 days. Herein, some accurate equations were also proposed to convert NDTs and compressive strength of cubic concrete specimens to cylindrical specimens based on experimental data and response surface methodology. Results showed that the proposed equations perform sufficient accuracy for the conversion intended.

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1- Introduction

Assessment of strength in existing buildings is an essential topic in structural disciplines. Such investigation is required when: (a) some damages are developed through time, (b) new requirements must be considered (due to changes in design codes, etc.), and (c) the material condition must be checked. In this way, NDT techniques may suitably be efficient, since they give information about material properties while imposing moderate costs with a short-time evaluation process. Hence, NDTs have been used for the evaluation of structural features in new concrete structures for several years, but the quality of estimation for decisions made regarding maintenance of the structure is considered a critical point [1, 2].

However, NDT techniques are influenced by physical properties. Hence, they are merely used for indirect prediction of the mechanical performance of the materials [3]. The assessment quality may be understandably influenced by some uncertainties risen by the testing method, environmental situation, human factors, and data interpretation [4, 5]. In this regard, the main issue is to accurately correlate physical NDT measurements with mechanical properties such as the compressive strength of concrete specimens [6].

Two common NDTs are utilized to evaluate the strength of the concrete, namely rebound measurement and Ultrasonic Pulse Velocity (UPV) [7]. Moreover, the development of an efficient methodology to assess the strength of the concrete is regarded as a critical issue.

Yet, for a more accurate prediction, combined NDT methods have been used to predict more accurately [8]. The SonReb combination (a combination of Ultrasonic Pulse Velocity (UPV) measurements and Rebound Number (RN) measurements) is a popular combination among a large number of alternatives. This combination was standardized in China in 2005 [9]. Besides, it is possible to perform it on any concrete structure, while measurements do not need professional expertise.

Either UPV or rebound can individually predict the concrete strength satisfactorily, but their combination leads to a reliable estimation with more accuracy [10]. Many relationships have been proposed for estimating the strength of the concrete by considering UPV and rebound values together [11]. In the literature, cubic or cylindrical concrete specimens are conducted separately to estimate the compressive strength of the concrete [5, 7-10]. Although, in many design codes, conversion factors have been proposed to change the compressive strength of cubic concrete specimens to cylindrical ones and vice versa, such factors are overlooked for NDT tests. For instance, the Design and Construction of Concrete Structures (Concrete design code of Iran) introduced three factors, including r_1, r_2, and r_3, to convert cubic concrete specimens to corresponding cylindrical ones. The following tables may perform such factors [12]:

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Table 1. Values of r1

$a \times 2a$	100×200	150×300	200×400	250×500	300×600
r_1	1.02	1.00	0.97	0.95	0.91

Table 2. Values of r2

b (cubic)	100	150	200	250	300
r_1	1.05	1.00	1.00	0.95	0.90

Table 3. Values of r3

f_c (Cubic) (MPa)	≤25	30	35	40	45	50	55
r_3	1.25	1.20	1.17	1.14	1.13	1.11	1.10
f_c (Cylindrical) (MPa)	Based on r_3	25	30	35	40	45	50

Where a is the diameter of the cylinder (mm), r_1 is a conversion factor between nonstandard and standard cylinder specimens (150×300 mm), b is the cube dimension (mm), r_2 is a conversion factor between nonstandard and standard cube specimens (200 mm), r_3 is a conversion factor between standard cube specimens and corresponding standard cylindrical specimens. There are no specific conversion factors for NDTs.

Hence, the current study is conducted aimed at proposing new conversion factors to change NDT results from cubic concrete specimens to similar cylindrical specimens and vice versa. To this aim, three different NDTs, known as UPV, RN, and Surface Electrical Resistivity are applied on cubic and corresponding cylindrical concrete specimens through the experimental process. Then, response surface methodology is performed to introduce new factors.

2- Ultrasonic Pulse Velocity (UPV)

UPV is a standard NDT method measuring the velocity of compressive stress waves. The velocity of such waves traveling through a solid material varies due to the density and the elastic properties of the material [13]. The pulse velocity technique is an efficient method to evaluate the quality of the concrete because; it just depends on elastic properties of the material and not on geometry, etc. Fig.1 shows a diagram of pulse velocity testing.

This equipment consists essentially of an electrical pulse generator, a pair of transducers, an amplifier, and an electronic timing device for measuring the time interval between initiation of a pulse generated at transmitting transducer and its arrival at receiving transducer. Two forms of electronic timing and display apparatus are available, one of which uses a cathode ray tube on which received pulse is displayed about a suitable time scale, the others use an interval timer with a direct reading digital display. Therefore, direct transmission arrangement should be used since the transfer of energy between transducers is at its maximum level, and the accuracy of velocity determination is governed principally by the efficiency of measuring the path length. Applied couplant should be spread as thinly as possible to avoid any end effects resulting from different velocities in couplant and concrete [15].

3- Rebound Number (RN)

This test is known as a rebound hammer, impact hammer, or Schmidt hammer, which is a well-known convenient and cheap NDT method. The principle of the rebound test states that an elastic mass depends on the hardness of the surface against which the mass impinges [16] and the energy absorbed by the concrete is related to its strength [17]. The rebound hammer test is given in ASTM C805 [16] and BS 1881: Part 202 [18]. This test had been investigated in many studies. Amasaki [19] investigated the effect of carbonation on the rebound number. Grieb [20] estimated strength using the effect of type of aggregates on rebound numbers. Willetts [21] showed that the moisture content of concrete influences on results of the rebound number test. Neville [22] presented the cognitive benefits of the rebound hammer test in concrete and indicated that the test all alone is not a strong type and its use is not accepted as a replacement for compression test. In this method, the main components include the outer body, plunger, hammer mass, and mainspring. Other features include a latching mechanism locking the hammer mass to the plunger rod and a sliding rider measuring the rebound of the hammer mass. Distance of the rebound is measured on an arbitrary scale marked from 10 to 100 and is recorded

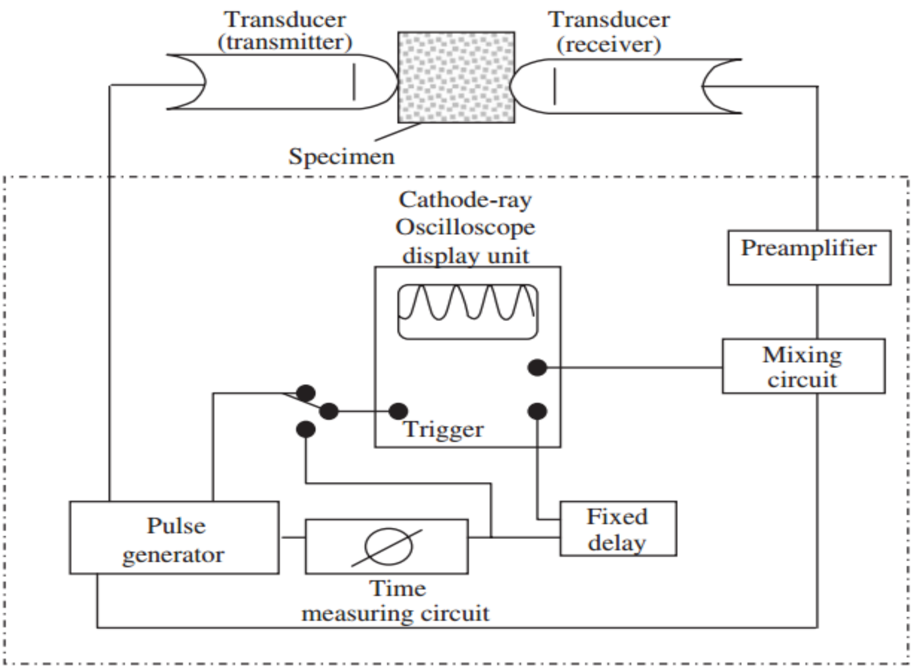


Fig. 1. Schematic diagram of pulse velocity testing circuit (adapted from ASTM C586) [14]

as a "rebound number" corresponding to the position of the rider on the scale. In this way, the hammer is pushed hard against the concrete, and the body is allowed to move away from the concrete until the latch connects the hammer mass to the plunger. Then, the plunger is held perpendicular to the concrete surface, and the body is pushed towards the concrete. This movement extends the spring, holding the mass to the body. When the maximum extension of the spring is obtained, the latch releases, and the mass is pulled towards the surface by the spring. The mass hits the shoulder of the plunger rod and gets rebound because the rod is pushed hard against the concrete. During rebound, the slide indicator travels with the hammer mass and stops at a maximum distance where the mass reaches after rebounding. A button on the side of the body is pushed to lock the plunger into the retracted position, and the rebound number is read from a scale on the body [15].

4- Surface Electrical Resistivity (SR)

In this method, the voltage between the electrodes is applied to the concrete, and then, the current is measured, or vice versa. The voltage-to-current ratio leads to electrical resistance (ohm), and electrical resistance (ohm-meter) is calculated by applying a geometric or constant cell parameter (m) [23]. Resistance measurements are performed by different kinds of approaches [23-28]. In this study, the Wenner four-electrode method was used to measure the surface electrical strength of the concrete based on previous research [23]. The spacing of the four probes determines regions of the concrete under investigation. It is generally accepted that, for practical purposes, the depth of the concrete zone influencing the measurement will be equal to the electrode spacing. If the spacing is too small, the presence, or absence of individual aggregate particles, usually having a very high resistivity, will lead highly scattered in the measurement. Using a larger spacing may cause inaccuracies resulting from the current field being constricted by the edges of the structure under study. Additionally, excessive error may cause theinfluence of embedded steel when larger spacing is employed. A spacing of 50 mm is commonly adopted that gives a very small degree of scattering and allows measuring the concrete sections at a thickness of higher than 200 mm with acceptable accuracy [15].

5- Polynomial Response Surface Methodology (PRSM)

PRSM is among the most efficient developments in surrogate modeling. The PRSM was firstly applied by Box and Wilson [29]. This approach is based on a mathematical process to estimate the output response by using a function including input parameters. The response is expressed as follows:

$$y = X\beta + \varepsilon_y \tag{1}$$

In the above formulation, X includes input data, β is the unknown coefficient, and å$_y$ is the error for this estimation. Eq. (1) can be mathematically expressed for a quadratic form as below:

$$y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \sum_{i=1}^{k} \beta_{ij} x_i x_j \tag{2}$$

The unknown polynomial coefficients are determined by minimizing the error using the least-squares estimation method as follows:

$$e(\beta)=\sum_{i=1}^{n}\left(y_i-\beta_0\sum_{i=1}^{k}\beta_{ij}x_ix_j-\sum_{i=1}^{k}\sum_{j=1}^{k}\beta_{ij}x_ix_j\right)^2=(y-x\beta)^T(y-x\beta) \qquad (3)$$

And the least-squares calculate β as:

$$\beta=\left[X^TX\right]^{-1}\left\{X^Ty\right\} \qquad (4)$$

Developments in PRSM have been an exciting subject for researchers, and many studies have been conducted on this issue [30-37]. Besides, recently, RSM has been introduced for estimating the compressive strength of the concrete columns confined with FRP sheets [36]. The application of RSM in a study [36] showed its accuracy for the estimation required.

6- Experimental Set-up

6.1. Materials

In this study, cubic and cylindrical concrete specimens were constructed using Portland cement type II, and Table 4 shows its chemical and physical specifications. Coarse aggregates were used in the crushed form with two sizes of 4.75- 12.5 (fine gravel) and 9.5-25 mm (coarse gravel), and used sand was functioned in the natural form (Table 5 presents results of the sieve analysis).

Table 6 shows the physical characteristics of the used aggregates. In terms of aggregation, applied totals are in good agreement with the standard curves of ASTM C 33 [38].

6.2. The Mix Design

In this study, 20 mix designs were performed based on ACI 318 details of which are given in Table 7.

6.3. Specimens and Experimental Process

Nine cubic (150×150×150 mm) and 9 cylindrical (100×200 mm) specimens were tested at the age of 7, 28, and 90 days for each mix design. After constructing the mixtures, they were immediately placed in a mold and were compressed by a rod following EN12390-2 Standard [39], and then, the

Table 4. Chemical compositions and physical specifications of the cement

Type	Chemical compounds (Weight percent)									Physical characteristics	
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O	SO_3	LOI	Specific weight kg/m^3	Specific surface area m^2/kg
Cement	21.42	5.01	3.88	63.18	1.55	0.65	0.45	2.31	1.85	3120	293

Table 5. Results of sieve analysis on the aggregates

Sieve size	Sieve size (mm)	% Passing		
		Coarse aggregates		Sand
		Coarse gravel	Fine gravel	
1"	25	100	100	-
$^3/_4$"	19	87	100	-
$^1/_2$"	12.5	21	98	-
$^3/_8$"	9.5	4.6	81	100
$^1/_4$"	6.35	2.5	47	-
#4	4.75	0.8	7.8	97
#8	2.36	-	2.8	70
#16	1.18	-	-	48
#30	0.6	-	-	27
#50	0.3	-	-	18
#100	0.15	-	-	8.7
#200	0.075	-	-	2.4

specimens were pulled out from the molds after 24 hours and were placed in lime-saturated water reservoirs for the needed time. After curing, the specimens were discharged from the water and were prepared for testing. For that purpose, each specimen, after draining, would be retained in the laboratory for some time to reach a dry surface with a saturated state. The time required varies due to humidity and environmental temperature.

According to the purposes of this research, four different tests were conducted on the specimens. These experiments were surface electric resistivity measurement, the velocity of ultrasound transmissions measurement, return number measurement, and compressive strength measurement. Fig. 2 shows how NDTs were conducted in the laboratory.

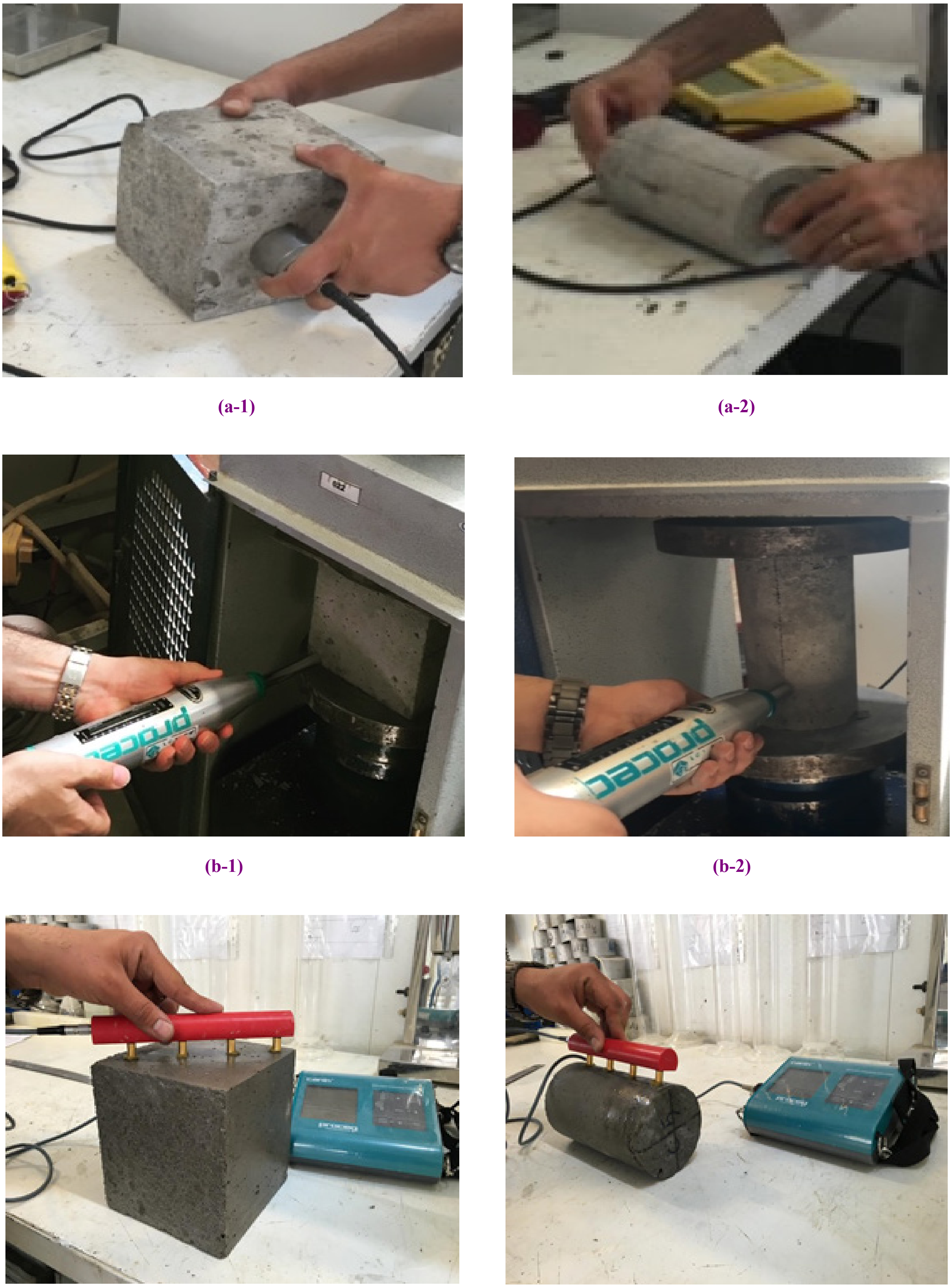
Surface electrical resistance was measured following the FM5-578 standard [40] using a quart-electrode device with a distance of 50 mm between the electrodes. For this purpose, the surface electrical resistance of the specimens was measured in four lateral faces of the specimen in twice the time. In this case, the electrodes were placed in diameters of

Table 6. Physical specifications of the aggregates

Aggregate	Specific weight kg/m^3	Water absorption %	Passing #200 %
Coarse gravel	2710	1.83	2.4
Fine gravel	2720	1.9	1.5
Sand	2680	2.6	1.4

Table 7. Details of concrete mix designs

Mix design No.	W/C	Cement (kg/m^3)	Coarse gravel (SSD) (kg/m^3)	Fine gravel (SSD) (kg/m^3)	Sand (SSD) (kg/m^3)
1	0.79	273	-	936	863
2	0.79	244	497	478	936
3	0.74	291	-	927	980
4	0.74	261	493	473	928
5	0.69	313	-	915	968
6	0.69	280	487	469	919
7	0.65	332	-	920	957
8	0.65	297	529	509	925
9	0.61	354	-	909	949
10	0.61	316	524	504	921
11	0.58	372	-	905	945
12	0.58	332	530	490	908
13	0.54	400	-	890	888
14	0.54	357	528	488	860
15	0.5	432	-	935	872
16	0.5	386	550	469	855
17	0.45	480	-	908	825
18	0.45	429	533	412	800
19	0.42	514	-	884	753
20	0.42	460	558	419	768



(a-1) (a-2)

(b-1) (b-2)

(c-1) (c-2)

Fig. 2. NDTs conducted on the concrete specimens: (a-1) UPV for cubic specimens, (a-2) UPV for cylindrical specimens, (b-1) RN for cubic specimens, (b-2) RN for cylindrical specimens, (c-1) SR for cubic specimens, (c-2) SR for cylindrical specimens

each face, and the average of 8 measurements was recorded as surface electrical resistance of the specimens.

After conducting a surface electrical resistance test, the velocity of ultrasound waves was also performed according to B.S 1881-PART 203 [41]. The surface of the generators was impregnated with a special gel or refractory grease, and 5 readings were done for each lateral side. The position of the generator was in a way that the entire sample surface and, therefore, the sample volume were tested. Time and the velocity of ultrasound transmission were measured in each record. The average results were recorded as transfer time and speed of the waves.

Afterward, the specimens were tested with the Schmidt hammer based on B.S 1881-PART 202 [18]. The specimens were located on the machine's jaws, and then five records were registered for each lateral side. The average of 20 records was registered as a hardness number of the specimens.

Finally, the specimens were tested based on EN12390-3: 2001 to measure compressive strength, and their values were recorded.

7- Results and Discussion

A total of 360 specimens were produced at different ages (7, 28, and 90 days) in the experimental program. These specimens designed in 20 different mix designs (3 cubic and 3 cylindrical specimens at different ages) were assessed in each mix design. Applied NDTs were Ultrasonic Pulse Velocity (UPV), Rebound Number (RN), and Surface Electrical Resistance (SR). Besides, the compressive strength of the concrete specimens was measured. In each mix design, 9 cubic and 9 cylindrical specimens were tested (3 specimens for the age of 7 days, 3 ones for 28 days, and 3 ones for 90 days).

As mentioned before, the concrete design code of Iran was considered for experimental data of this study to convert the compressive strength of cubic specimens to corresponding cylindrical specimens. Fig. 3 shows the correlation between these specimens (cubic and cylindrical) using conversion factors, as presented in Tables 1 to 3. This figure was plotted according to the following steps:

1. Firstly, averages of 3 specimens for each mix design and age were calculated (hence, the number of specimens reduced from 360 to 120, considering all the data).
2. Then, the cylindrical specimens (100×200) conducted in the experimental process, were converted to the standard cylindrical specimens (150×300) based on Table 1.
3. As the third step, the compressive strength of the cubic specimens was converted to corresponding standard cylindrical specimens based on Table 3.
4. Finally, governed values from steps 2 and 3 were compared by plotting Fig. 3 for all ages.

As shown in Fig.3, the determination coefficient of different ages is in good agreement with experimental results. Additionally, R^2=0.9022 is for the collective model.

Besides showing that, it is necessary to introduce some conversion factors between cylindrical and cubic concrete specimens for conducted NDTs; the following procedure was applied:

Considering the following ratio for each NDT and compressive strength of the specimens:

$$\alpha_{Test} = \frac{X_{Cylinder}}{X_{Cube}} \tag{5}$$

Where in

X is an experimental value for UPV, RN, SR, or f_c. After conducting Eq. (5) for each mix design, the following

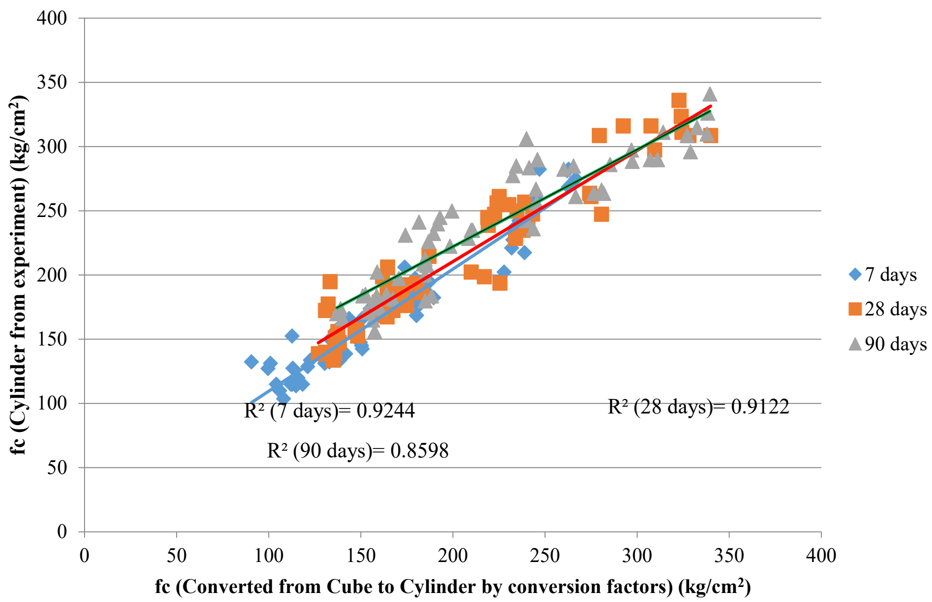


Fig . 3. Accuracy of conversion factors presented by the concrete design code of Iran

statistical parameters were calculated: Mean (μ_α), Standard deviation (σ_α), and Coefficient of Variation (CV_α). Table 8 presents the results obtained

As shown in Table 8, the mean of Eq. (5) for UPV is approximately 1 for all ages. Hence, Eq. (5) should be re-written as follows:

$$\alpha_{UPV} = \sum_{i=1}^{20}\left(\frac{UPV_{Cylinder}}{UPV_{Cube}}\right)_i \approx 1 \rightarrow$$
$$\left(UPV_{Cylinder}\right)_i \approx \left(UPV_{Cube}\right)_i, \quad \left(i = 1,\ldots,20\right) \tag{6}$$

Hence, it is obvious that the shape of concrete specimens does not affect the results of UPV. Therefore, there is no need to introduce a conversion factor for this NDT. Moreover, the mean value of Eq. (5) for other tests (RN, SR, and f_c) is not equal to one, hence it is necessary to introduce conversion factors in that regard (obviously, there are some conversion factors for compressive strength in design codes as mentioned in the Introduction Section). The effect of the shape of the specimen has been investigated in previous studies, and it has been shown that the results of RN and SR are different for different forms [18, 42]. Moreover, as indicated in Table 8, the α_{SR} is equal to 1.30. It means that, by decreasing the volume of the concrete specimen, SR will be increased.

Hence, as there are no specific conversion factors for RN and SR in the literature, it would be worthy of introducing conversion equations to convert the values of cubic specimens to corresponding cylindrical specimens. To do this, RSM was

Table 8. Results obtained from statistical analysis of the correlation between cylindrical and cubic concrete specimens

Age (days)		7	28	90	Collective
UPV	μ_α	1.00095	0.98589	0.96394	0.98539
	σ_α	0.0244	0.02122	0.01511	0.02432
	CV_α (%)	2.43753	2.15228	1.55839	2.46771
RN	μ_α	0.90565	0.89433	0.87538	0.89179
	σ_α	0.08212	0.06778	0.05735	0.07093
	CV_α (%)	9.06798	7.57837	6.55141	7.95415
SR	μ_α	1.31117	1.27306	1.36186	1.31536
	σ_α	0.11625	0.13394	0.13241	0.13286
	CV_α (%)	8.86609	10.5211	9.72298	10.1007
f_c	μ_α	0.86436	0.89131	0.92111	0.89226
	σ_α	0.06917	0.06982	0.06682	0.07242
	CV_α (%)	8.00265	7.83306	7.25455	8.11699

Table 9. Coefficients of conversion equations for converting the results of cubic specimens to corresponding cylindrical specimens using the first-order estimation

$y_{cylindrical} = a + bx_{cubic}$		x_{cubic}					
$y_{cylindrical}$	Age (days)	RN		SR		f_c	
		a	*b*	*a*	*b*	*a*	*b*
RN	7	1.84	0.82	-	-	-	-
	28	4	0.71	-	-	-	-
	90	3.64	0.73	-	-	-	-
	Collective	3.55	0.73	-	-	-	-
SR	7	-	-	1.48	1.03	-	-
	28	-	-	-1.57	1.45	-	-
	90	-	-	11.3	0.52	-	-
	Collective	-	-	-0.03	1.32	-	-
f_c	7	-	-	-	-	-2.81	0.87
	28	-	-	-	-	4.49	0.86
	90	-	-	-	-	52.24	0.72
	Collective	-	-	-	-	7.04	0.86

applied as an accurate method. These equations are related to the conversion of NDTs and compressive strength. Table 9 presents governed first-order equations obtained by RSM. Additionally, Table 10 shows the second-order functions provided by RSM.

For better comprehension, the accuracy of two models (first- and second-order estimations) was compared, and Table 11 presents their results.

As it can be concluded from Tables 9 to 11, the accuracy of first and second-order estimations are approximately the same, while the form of the first-order function is easiest and simple (except for some ages but the accuracy is the same for all data as the combination of all data can be more interested). Hence, the first-order function is selected for more investigation.

Also, other statistical parameters were used for investigating the accuracy of fitted models (first-order) to make a better comparison. For this purpose, the following parameters were defined [36]:

The total error is obtained as follows e_{tot}

$$e_{tot} = 100 * \frac{\sum_1^N |Expe_i - Theo_i|}{\sum_1^N |Expe_i|} \tag{7}$$

Where, $Expe_i$ and $Theo_i$ are experimental compressive strength and compressive strength results of RSM models, respectively, and N is a total of the samples.

Other statistical parameters were also given by Eq. (8) to Eq. (10) that are defined as Mean Square Error (MSE) measuring the average squared difference between estimated values and actual value, Average Absolute Error (AAE) that is the average over the test sample of absolute differences between prediction and actual observation where all individual differences have equal weight, and Standard Deviation (SD) that is a measure for the amount of variation in a set of values

$$AAE = \frac{\sum_1^N \left| \frac{Theo_i - Expe_i}{Expe_i} \right|}{N} \tag{8}$$

Table 10. Coefficients of conversion equations for converting the results of cubic specimens to corresponding cylindrical specimens using second-order estimation

$y = a + bx^2 + cx$		a	b	c
RN	7 days	5.515	0.009	0.452
	28 days	-1.0796	-0.010	1.169
	90 days	-3.450	-0.010	1.278
	Collective	-0.251	-0.007	1.057
SR	7 days	2.327	0.029	0.716
	28 days	7.613	0.094	-0.438
	90 days	-20.469	-0.152	4.956
	Collective	-2.708	-0.032	1.950
f_c	7 days	79.040	0.002	0.052
	28 days	-18.456	-0.0003	1.046
	90 days	-22.824	-0.001	1.294
	Collective	-32.152	-0.0006	1.190

Table 11. Coefficients of determination (R2) for first- and seconder-order estimations

Age		7	28	90	Collective
RN	1st order	0.655	0.646	0.589	0.783
	2nd order	0.660	0.773	0.816	0.786
SR	1st order	0.611	0.377	0.032	0.894
	2nd order	0.611	0.722	0.309	0.901
f_c	1st order	0.929	0.910	0.888	0.914
	2nd order	0.941	0.934	0.874	0.917

$$MSE = \frac{\sum_1^N (\frac{Theo_i - Expe_i}{Expe_i})^2}{N} \quad (9)$$

$$SD = \sqrt{\frac{\sum_1^N (\frac{Theo_i}{Expe_i} - \frac{Theo_{avg}}{Expe_{avg}})^2}{N-1}} \quad (10)$$

.Tables 12 to 15 present statistical parameters used to evaluate the accuracy of RSM models.

As shown in Table 12, the conversion model of UPV has an R^2=0.821 accuracy and the least accurate is related to the SR with R^2=0.611, this concluding remark is also approved by e_{tot}. Table 13 exhibits the aforementioned statistical parameters at the age of 28 days. As shown in Table 13, it was also confirmed that f_c and UPV are the best-fitted models.

Table 14 gives also the statistical parameters for the specimens with the age of 90 days. Except for SR, this table shows the efficiency of conversion models since the electrical resistance of the concrete is highly dependent on the pores in the cement hydrated paste and the porosity of the concrete. It is thus apparent by aging, hydration reactions will be completed,

Table 12. Statistical parameters for fitted models at the age of 7 days

Equations	e_{tot}	MSE	AAE	SD	R^2
RN	7.671	0.881	5.087	1.029	0.655
SR	8.094	0.608	4.838	1.023	0.611
f_c	6.090	0.324	3.594	1.015	0.929

Table 13. Statistical parameters for fit models at the age of 28 days

Theoretical models	e_{tot}	MSE	AAE	SD	R^2
RN	9.231	0.792	5.380	1.028	0.646
SR	40.928	9.786	23.510	1.052	0.377
f_c	20.051	2.680	12.055	1.011	0.910

Table 14. Statistical parameters for fitted models at the age of 90 days

Theoretical models	e_{tot}	MSE	AAE	SD	R^2
RN	15.155	1.691	8.540	1.032	0.589
SR	61.976	22.973	36.926	1.034	0.032
f_c	29.264	5.742	18.048	1.002	0.888

Table 15. Statistical parameters for fitted models for all the specimens

Theoretical models	e_{tot}	MSE	AAE	SD	R^2
RN	6.753	1.830	12.799	1.017	0.783
SR	9.737	2.583	17.268	1.025	0.894
f_c	6.775	1.293	12.522	1.014	0.914

Table 16. Results of comparison between proposed conversion factor and the factors presented in the Concrete design code of Iran

f_c	Design code (Iran)	RSM (1st orer)	$error\ \% = \left\lvert \frac{R^2_{Design\ code} - R^2_{RSM}}{R^2_{Design\ code}} \right\rvert \times 100$
7 days	0.9244	0.9290	0.50
28 days	0.9122	0.9100	0.24
90 days	0.8598	0.8880	3.28
collective	0.9022	0.9140	1.31

and hence effective porosity and porosity of hydrated paste will be lower [43]. As a result, the connection between the electrical and compressive strength of the concrete will be significantly reduced at a higher age, as well illustrated in this study. Besides, Table 15 reports the accuracy of the models among all the specimens. As evident, the standard deviation is roughly constant for all models. Even for UPV and f_c the standard deviation exhibits the lowest value that shows they are efficient. However, other statistical parameters prove the high accuracy of conversion models except for SR.

Furthermore, the comparison between the Iranian Code of Practice for Concrete design with the proposed first-order function is given in Table 16. As it can be seen, the comparable resemblance of the results for RSM is well demonstrated between the proposed conversion factor and those of the Concrete design code of Iran.

Yet further ascertain on the achievements, Figs. 4 to 6 are presented to compare various models to elaborate on the best model appropriate for all ages instead of a specific model for each model. As indicated in Fig. 4, compressive strength models of different ages are in good agreement with each other, and the collective model (total data)embraces all models at different ages, agreeably. Hence, the collective model can be used for all the specimens of different ages. Fig.5 shows the conversion models of RN. According to Fig.5, the collective model is well fitted with other models; hence, like previous parameters, the collective model is a proper conversion equation for all ages. Additionally, Fig. 6 presents the conversion models of SR. According to Fig.6, there is a good agreement between the collective model and

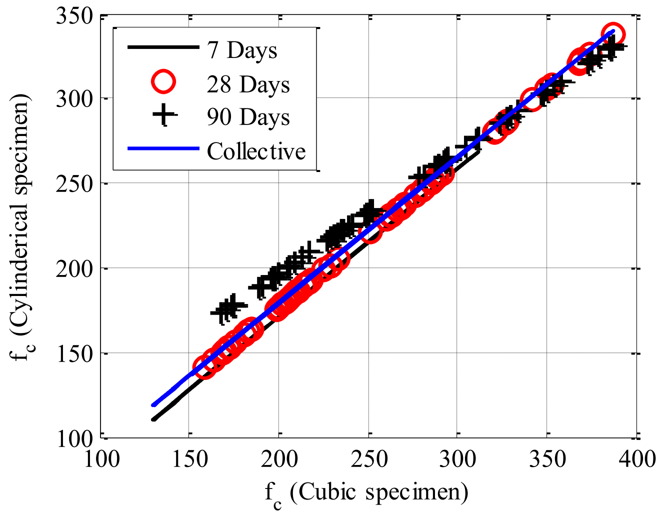


Fig . 4. Fitted conversion models of compressive strength in different ages

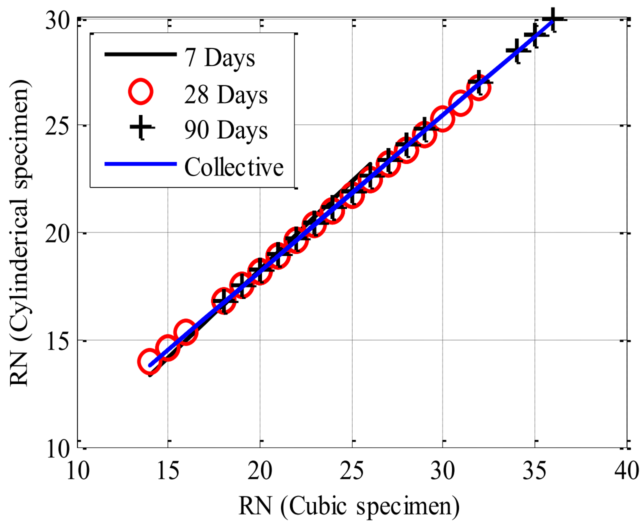


Fig. 5. Fitted conversion models of RN in different ages

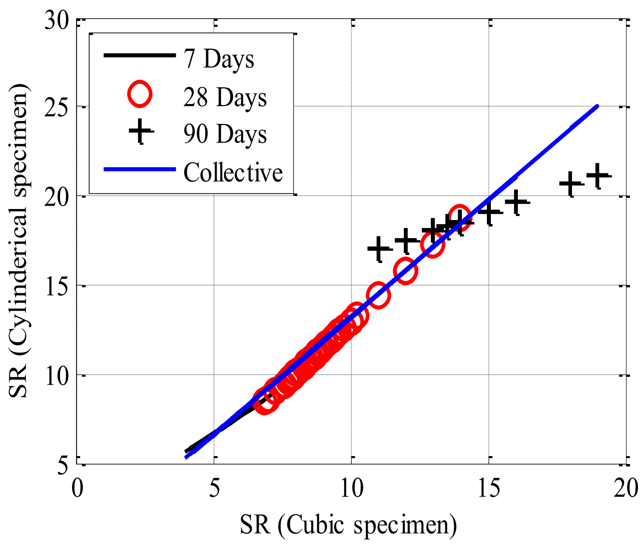


Fig. 6. Fitted conversion models of SR in different ages

those related to ages of 7 and 28 days, however the age of 90 days is not well fitted with the collective model. As stated earlier, SR could not be appropriately performed at the period of 90 days due to the completion of chemical action in the specimens.

8- Conclusion

Collectively, a total of 180 cubic concrete specimens and 180 conforming cylindrical specimens were constructed using 20 mixed designs at different periods (7, 28, and 90 days). All specimens were measured through three different NDTs, namely referred to as ultrasonic pulse velocity, rebound number, and surface electrical resistivity and also for the compressive strength. Conversion equations between cubic and cylindrical specimens were then governed at different ages for converting the values of cubic to the corresponding cylindrical specimens, using response surface methodology. The precisions of proposed models were studied using standard statistical parameters and by comparing the estimation accuracy through the Concrete design code of Iran for compressive strength. Experimental data showed that there is no need to introduce a conversion factor for UPV because; the shape of the specimen does not influence this test. Results also showed that governed equations for compressive strength have a high accuracy similar to the conversion factors proposed in design code at different ages. Hence, such models can be used reliably to convert the values of cubic specimens to cylindrical ones for any specific age studied here. Moreover, it was shown that, by decreasing the volume of the concrete specimen, values for SR will be increased but based on statistical analysis; SR does not provide a reasonable estimation especially for the age of 90 days, which is mainly related to the completion of chemical action and filling of the pores in the specimens. Furthermore, using illustrative figures, it was found that the collective model can be well used as a suitable substitution for different ages. Thus, only one equation may be sufficient for each NDT and for the compressive strength instead of using different models for different ages.

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