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ORIGINAL ARTICLE

Reliability of using nondestructive tests to estimate compressive strength of building stones and bricks

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Abstract This study aims to investigate the relationships between Schmidt hardness rebound number (RN) and ultrasonic pulse velocity (UPV) versus compressive strength (fc) of stones and bricks. Four types of rocks (marble, pink lime stone, white lime stone and basalt) and two types of burned bricks and lime-sand bricks were studied. Linear and non-linear models were proposed. High correlations were found between RN and UPV versus compressive strength. Validation of proposed models was assessed using other specimens for each material. Linear models for each material showed good correlations than non-linear models. General model between RN and compressive strength of tested stones and bricks showed a high correlation with regression coefficient R^2 value of 0.94. Estimation of compressive strength for the studied stones and bricks using their rebound number and ultrasonic pulse velocity in a combined method was generally more reliable than using rebound number or ultrasonic pulse velocity only.
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1. Introduction

The objective of nondestructive in-place tests of concrete structures is to estimate properties of concrete in the structures. Very often the desired property is the compressive strength. To make strength estimation, it is necessary to have a known relation between the results of in-place test and the strength of concrete. This relation is usually estimated in the laboratory. The accuracy of the strength prediction depends directly on the degree of correlation between the strength of concrete and the quantity of measured in-place tests [1].

Rebound measurement and ultrasonic pulse velocity (UPV) are among the most widely used NDT methods regarding concrete strength assessment, and a recent European standard provides a formal solution on how concrete strength can be estimated from in situ testing [9]. The development and validation of a methodology that would lead with an acceptable level of confidence to a reliable strength assessment remains a key issue. A main point is that of ‘‘calibration’’, i.e. that of building and using a reliable relationship between NDT values and strength [10].

If the concrete specimens is small, any movement under the impact will lower the rebound readings, as stated by the ACI MONOGRAPH Series. In such cases the specimen has to be

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fixed or backed up by a heavy mass. It is best to grip the specimen in the testing machine. It has been shown by Mitchell and Hoagland that the restaining load at which the rebound number remains constant appears to be about 15% of the ultimate strength of the specimen [12]. In the present study 25% of the ultimate strength of the rocks specimens were considered.

A common statement is that while neither UPV nor rebound are, when used individually, appropriate to predict an accurate estimation for concrete strength, the use of combined methods produces more trustworthy results that are closer to the true values when compared to the use of the above methods individually. The combined approach leads to contrasted results as it have provided marginal improvements. A large number of relationships have been proposed in order to estimate the strength from a couple of (UPV, rebound) values. It appears that there is not a unique relationship and that calibration remains a key issue, as it is the case for individual methods [11].

Prior to the use of reinforced concrete structures, stones like lime stone was the main building material for major construction [2]. Most of historical and ancient buildings were made using stones and bricks. For example, for ancient buildings in Egypt, the main structure element in the structure system of these buildings depended mainly on some columns with base made with a certain type of rocks like marble, basalt, granite or lime stone. The governments do not allow to perform cores to estimate the compressive strength of these rock materials. This operation is necessary during the repairing or rehabitation processes of these buildings. So, nondestructive tests are the only allowable method to estimate the compressive strength of these materials.

Some new constructions, the estimation of compressive strength by nondestructive method can be used to reduce the number of specimens for compressive strength test. For example, for refractory bricks ASTM C 133 suggested 10 bricks for each 1000 bricks must be tested to ensure the compressive strength of this type of brick. In some constructions these number of bricks are not enough due to the importance or the dangerous of these structures. Chimneys of power stations are an example of these constructions in which the quality of the used bricks is very important to achieve the safety of these structures. So, in this case number of specimens of compressive strength tests must be increased or the same number of specimens according to ASTM C 133 can be used to get a relation between compressive strength and other nondestructive in-place test to estimate the compressive strength for additional number of bricks without performing compressive strength test and these specimens can be used again in the structure.

The most famous nondestructive in-place tests for concrete structures are ultrasonic pulse velocity and surface hardness methods [3–5]. The ultrasonic pulse velocity method consists of measuring the travel time of pulse of longitudinal ultrasonic waves passing through the material. The travel times between the initial onset and reception of the pulse are measured electronically. The path length between transducers divided by the time of travel gives the average velocity of wave propagation. A suitable apparatus and standard procedures are described in ASTM C 597. The ultrasonic pulse velocity test has been pointed out by several authors as useful and reliable nondestructive tool of assessing the mechanical properties of concrete of existing concrete structures [6].

Surface hardness method consists of impacting a concrete surface with a given energy of impact and then measure the size of indentation or rebound number. The standard procedures for this test have been established and are described in details in ASTM C 805. The Schmidt hammer was initially developed for concrete, but extensive application of it has been performed as a preliminary estimation of the stone strength [7].

This paper presents the reliability of using ultrasonic pulse velocity and surface hardness methods to estimate compressive strength of some building stones and bricks.

2. Research significance

As mentioned before, reliable relations between concrete compressive strength and nondestructive in-place tests like ultrasonic pulse velocity and surface hardness were established. These relations were widely used to estimate concrete compressive strength of the existing concrete structures. In some cases, compressive strength of some members of ancient buildings or some new structures made with other building materials (other than concrete) shall be determined. There is a little information about the relations between nondestructive in-place tests and compressive strength of these building materials. This research work aims to construct reliable relations between ultrasonic pulse velocity and surface hardness (rebound number) and cube compressive strength of some building materials. This research work covers some famous used materials like marble, white lime stone, basalt, pink lime stone, lime-sand bricks and burned bricks.

3. Experimental work

Stones and bricks samples were collected from various locations. Marble, pink lime stone, white lime stone and basalt were chosen as famous types of stones in Egypt. Burned bricks and lime-sand bricks were also studied as two examples of bricks in Egypt. The experimental work included six steps to establish either the relation between ultrasonic pulse velocity or rebound number versus cube compressive strength. These steps are:

- *Step 1*: Collection of varies types of each material from different sources with different ages.
- *Step 2*: Preparing of specimens by sawing to satisfy the dimension limits of compressive strength test according to ASTM C 170 which includes cubes with minimum dimensions not less than 50.8 mm. The cubes were air dried until time of testing.
- *Step 3*: Ultrasonic pulse velocity according to ASTM C 597 for each specimen was measured.
- *Step 4*: Specimens from each building materials were put in the center of compression testing machine and loaded to about 25.0% of their ultimate compressive strength (this load was controlled to be constant for a certain time) and then rebound number of these specimens were measured. Fifteen readings were taken to estimate the average rebound number.
- *Step 5*: After reading the rebound number, the applied load was increased until failure and then cube compressive strength of each specimen was calculated.
- *Step 6*: Construct the relation between compressive strength and rebound number or ultrasonic pulse velocity of tested materials.

Table 1 Ultrasonic pulse velocity, rebound number and compressive strength test results of marble.

Specimen Number	Pulse velocity (km/s)	Average rebound number (horizontal)	Compressive strength (MPa)
1	5.57	52.30	49.14
2	7.00	57.00	67.60
3	5.71	55.00	49.27
4	5.60	50.80	40.08
5	5.49	50.80	41.64
6	6.63	56.00	60.67
7	6.03	54.00	54.50
8	5.54	47.50	46.76
9	6.23	49.40	45.31
10	6.19	48.60	42.64
11	6.43	51.30	52.77
12	6.06	50.80	46.76
13	5.83	51.00	39.60
14	5.73	47.30	39.07
15	6.36	56.00	51.25
16	5.57	46.00	40.34
17	4.99	47.30	38.74

Table 2 Ultrasonic pulse velocity, rebound number and compressive strength test results of white lime stone.

Specimen number	Pulse velocity (km/s)	Average rebound number (horizontal)	Compressive strength (MPa)
1	2.70	15.00	4.39
2	2.57	12.00	5.90
3	2.75	12.70	5.90
4	2.19	13.00	2.81
5	2.67	12.00	5.28
6	2.74	13.00	6.32
7	2.81	12.00	5.28
8	2.78	15.00	6.89
9	3.18	16.50	6.24
10	2.59	13.50	4.91
11	3.16	16.80	8.06
12	3.37	19.70	10.04
13	2.63	10.30	2.89
14	2.63	10.00	3.22
15	2.70	10.00	3.84
16	3.61	19.00	13.53
17	2.56	11.00	3.29
18	3.25	18.00	8.07
19	2.60	11.80	4.91
20	3.62	20.00	13.74
21	2.69	19.40	8.89
22	3.33	13.00	5.90
23	3.66	17.70	9.33

The test results of ultrasonic pulse velocity, and test results of rebound number for each building materials are used in combined method to correlate a relation between these in-place nondestructive tests and their compressive strength. Regression models were used to construct these relations for each building materials.

Table 3 Ultrasonic pulse velocity, rebound number and compressive strength test results of pink limestone.

Specimen number	Pulse velocity (km/s)	Average rebound number (horizontal)	Compressive strength (MPa)
1	3.62	42.00	24.48
2	3.48	40.00	23.10
3	3.58	38.00	18.46
4	3.70	40.80	26.13
5	3.90	43.00	34.97
6	3.49	40.00	19.19

Table 4 Ultrasonic pulse velocity, rebound number and compressive strength test results of basalt.

Specimen number	Pulse velocity (km/s)	Average rebound number (horizontal)	Compressive strength (MPa)
1	5.74	58.00	80.26
2	5.65	52.00	69.55
3	5.81	60.00	120.50
4	5.46	46.00	61.56
5	5.48	53.00	60.81
6	5.85	63.00	143.27

Table 5 Ultrasonic pulse velocity, rebound number and compressive strength test results of lime sand bricks.

Specimen number	Pulse velocity (km/s)	Average rebound number (horizontal)	Compressive strength (MPa)
1	2.981	31.60	16.705
2	2.938	28.40	18.447
3	3.211	31.20	19.435
4	3.300	28.00	17.329
5	3.015	29.00	17.537
6	2.863	27.80	17.459
7	2.512	24.30	13.117
8	3.411	34.05	21.905
9	18.122	27.80	3.316
10	15.646	27.35	2.759
11	15.031	26.30	2.630
12	21.268	32.30	3.265

4. Test results

The experimental test results of ultrasonic pulse velocity, rebound number in horizontal direction and compressive strength of studied rocks (marble, white lime stone, pink lime stone and basalt) and bricks (lime sand bricks and burned bricks) are tabulated in Tables 1–6. These test results can be used to estimate the best relations between rebound number, ultrasonic pulse velocity and compressive strength using regression models as shown in the following section. V and RN respectively denotes the measured values of UPV and rebound (see Table 6).

Table 6 Ultrasonic pulse velocity, rebound number and compressive strength test results of burned bricks.

Specimen number	Pulse velocity (km/s)	Average rebound number	Compressive strength (MPa)
1	4.215	45.30	40.248
2	3.521	47.30	35.100
3	2.897	41.75	28.522
4	2.944	41.80	32.422
5	2.958	42.80	31.265
6	2.831	36.20	30.537
7	3.368	37.80	26.312
8	2.669	38.60	29.549
9	3.035	41.80	29.107
10	3.030	38.80	29.653
11	3.046	37.00	27.274
12	3.041	31.50	26.832
13	3.077	39.00	27.846
14	3.150	41.40	32.955
15	4.571	49.30	41.236

5. Statistical analysis

5.1. Relation between rebound number and compressive strength

The experimental data were statistically analyzed to determine the best-fit correlation between Schmidt hammer rebound and compressive strength. Fig. 1 shows relations between rebound number (RN) and compressive strength (fc) of marble, white lime stone, pink lime stone and basalt. From this figure, there is a noticeable relation between rebound number and compressive strength. For all types of studied stones, compressive strength increases as rebound number increases. Linear model and non-linear model were suggested for each type of stone. Linear model was chosen because it is a simple model and it was suggested by others [8]. Non-linear model was chosen with higher regression coefficient R^2 value and with a simple formula. Table 7 summarizes the suggested models for relations between rebound number and compressive strength of each type of stone. Values of R^2 for linear models range from 0.65 to 0.76 while for non-linear models, R^2 values range from 0.76 to 0.95. These models were estimated using datafit software. These proposed models can be used to estimate the approximate compressive strength for each type of stone using its measured rebound number.

The pervious trend is also observed for lime sand and burned bricks. Fig. 2 shows relations between rebound number and compressive strength for each type of brick and Table 8 summarizes the suggested models.

From the pervious figures and tables, there are reliable relations between rebound number and compressive strength for studied stones and bricks. Fig. 3 shows the general relation between rebound number and compressive strength for all studied stones and bricks. A non-linear model is suggested. High correlation values are found between Schmidt hammer rebound number and compressive strength for studied stones and bricks. This model has high regression coefficient R^2 values = 0.94 as shown in Fig. 3.

$$fc = 2.6763 * e^{0.0584\text{RN}} \quad (1)$$

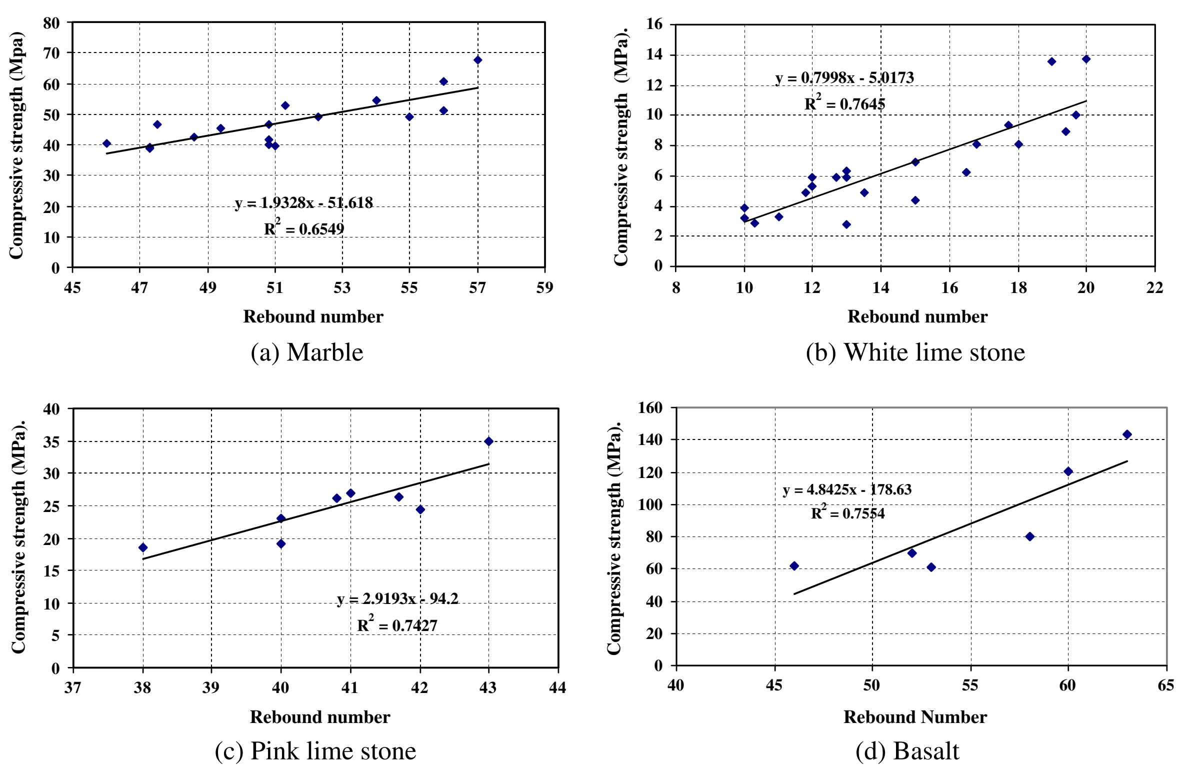
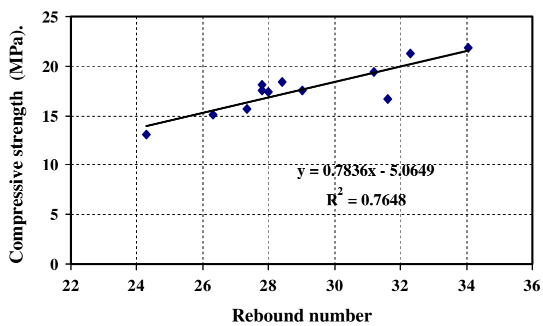


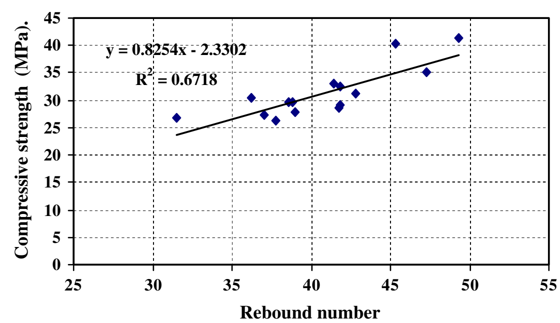
Figure 1 Relation between rebound number and compressive strength for stones.

Table 7 Suggested models for correlation between rebound number and compressive strength of studied stones.

Stone type	Model type	Formula	R^2
Marble	Linear	fc = 1.933RN – 51.62	0.65
	Non-linear	$fc = 15.83 + 0.0114RN^2 + 2.49 \times 10^{-24}e^{RN}$	0.76
White lime stone	Linear	fc = 0.8RN – 5.017	0.76
	Non-linear	$fc = 3.57 - (0.0078RN^{2.5}) + (0.0028RN^3)$	0.80
Pink lime stone	Linear	fc = 2.919RN – 94.2	0.74
	Non-linear	$fc = -0.03685 + 0.00034RN^3 + (1.528 \times 10^{-18}e^{RN})$	0.83
Basalt	Linear	fc = 4.843RN – 178.63	0.76
	Non-linear	$fc = 0.0135RN^3 - 1.73RN^2 + 72.62RN - 927.48$	0.95



(a) Lime-sand bricks



(b) Burned bricks

Figure 2 Relation between rebound number and compressive strength for lime-sand and burned bricks.

Table 8 Suggested models for correlations between rebound number and compressive strength of studied bricks.

Type	Model type	Formula	R^2
Lime sand bricks	Linear	fc = 0.784RN – 5.06	0.76
	Non-linear	$fc = 38.58 + 1.77 \times 10^{-15}e^{RN} - 605.2/RN$	0.78
Burned bricks	Linear	fc = 0.825RN – 2.33	0.76
	Non-linear	$fc = 410 - (38207.9/RN) + (1{,}276{,}275/NR^2) - (14{,}261{,}967/RN^3)$	0.77

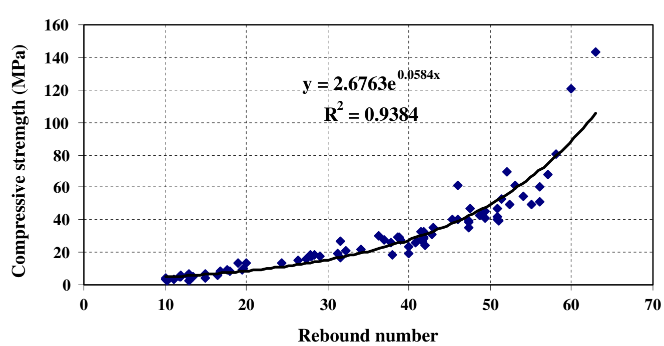


Figure 3 General relation between rebound number and compressive strength of studied stones and bricks.

5.2. Relation between ultrasonic pulse velocity V and compressive strength

Relations between ultrasonic pulse velocity (V) and compressive strength of studied stones and bricks are shown in Figs. 4 and 5. Tables 9 and 10 summarize the suggested models and the corresponding R^2 values. These models can be used to estimate compressive strength of each type using the measured ultrasonic pulse velocity.

General relation between ultrasonic pulse velocity and compressive strength of all tested stones and bricks are shown in Fig. 6. The proposed model for this relation is given in the following equation with $0.66R^2$ value.

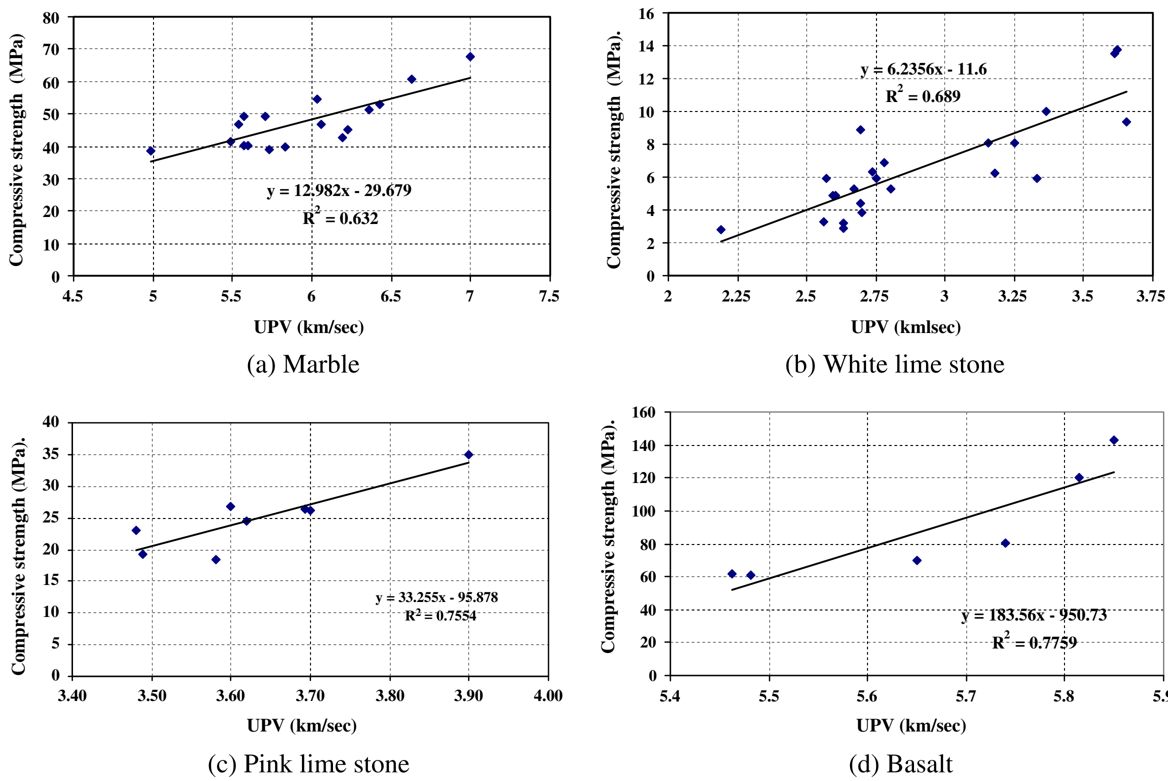


Figure 4 Relation between ultrasonic pulse velocity and compressive strength for stones.

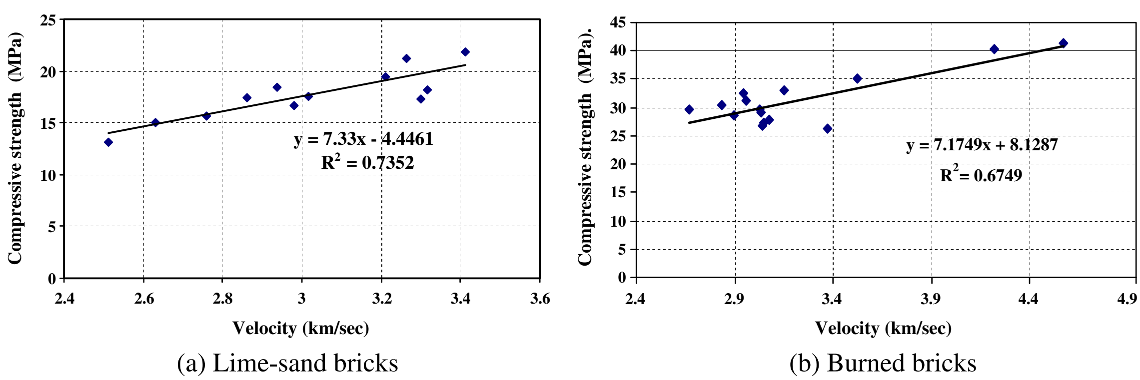


Figure 5 Relation between ultrasonic pulse velocity and compressive strength for bricks.

Table 9 Suggested models for correlation between ultrasonic pulse velocity V and compressive strength of studied stones.

Stone type	Model type	Formula	R^2
Marble	Linear	$fc = 12.98V - 29.68$	0.63
	Non-linear	$fc = 41.53 - 0.0575V^{2.5} + 0.0424 * e^V$	0.74
White lime stone	Linear	$fc = 6.2356V - 11.6$	0.69
	Non-linear	$fc = 0.456 * 2.442^V$	0.70
Pink lime stone	Linear	$fc = 33.255V - 95.878$	0.76
	Non-linear	$fc = 4.73/(1 - 0.22^V)$	0.78
Basalt	Linear	$fc = 183.56V - 950.73$	0.78
	Non-linear	$fc = 7.04 \times 10^{-5} * (11.69^V)$	0.86

Table 10 Suggested models for relation between ultrasonic pulse velocity and compressive strength of studied bricks.

Type	Model type	Formula	R^2
Lime sand bricks	Linear	$fc = 7.33V - 4.446$	0.74
	Non-linear	$fc = 4.447V^{1.248}$	0.73
Burned bricks	Linear	$fc = 7.17V + 8.129$	0.67
	Non-linear	$fc = 24.72 + (0.181V^3)$	0.71

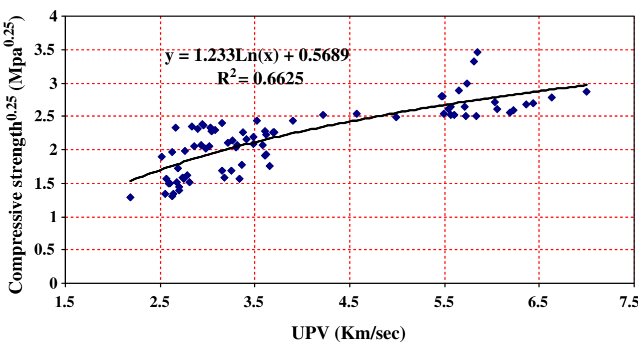


Figure 6 General relation between ultrasonic pulse velocity and compressive strength of studied rocks and bricks.

$$fc^{0.25} = 1.233 \ln V + 0.5689 \quad (2)$$

5.3. Relation between rebound number, ultrasonic pulse velocity V and compressive strength (combined method)

Relations between ultrasonic pulse velocity and rebound number versus compressive strength for stones and bricks are constructed. Figs. 7 and 8 show two examples of these relations for marbles and white lime stone specimens. Table 11 summarizes the proposed models and their R^2 values. These models can be used to estimate the approximate compressive strength using their ultrasonic pulse velocity and rebound number.

The general relation between ultrasonic pulse velocity and rebound number versus compressive strength for all stones and bricks, has $R^2 = 0.78$, is shown in Fig. 9 and the following equation.

$$fc = 0.0788 * (V^{0.424}) * (R^{1.462}) \quad (3)$$

6. Validation of proposed models

To check the validation of the previous models, other specimens from each type of stones and bricks delivered from different sources were used. These specimens were not used in estimation of proposed models given in Section 5. Table 12 gives the test results of Schmidt hammer rebound number, ultrasonic pulse velocity and compressive strength for validation test specimens. Table 13 gives the percentage of errors of validation for different proposed models between rebound number and compressive strength. From this table, generally linear model for each material yields lower error percentage value compared with non-linear models although non-linear models have higher R^2 values. Linear models either for stones and bricks are better than general models. The error percentages of linear models range from 1.02% to 20.2% for stones while these errors for bricks range from 0.94% to 39.15%.

Validation of relations between ultrasonic pulse velocity and compressive strength of stones and bricks are shown in Table 14. From this table, generally, also it is clear that using linear model for each material give a small error compared with non-linear model and general model. The resulting error percentages of linear models range from 0.35% to 35.3% for stones while these errors range from 5.83% to 39.71% for bricks. The use of general model for relation between ultrasonic pulse velocity and compressive strength is not preferred to estimate compressive strength using ultrasonic pulse velocity value. The error percentages range from 10.49% to 96.43%.

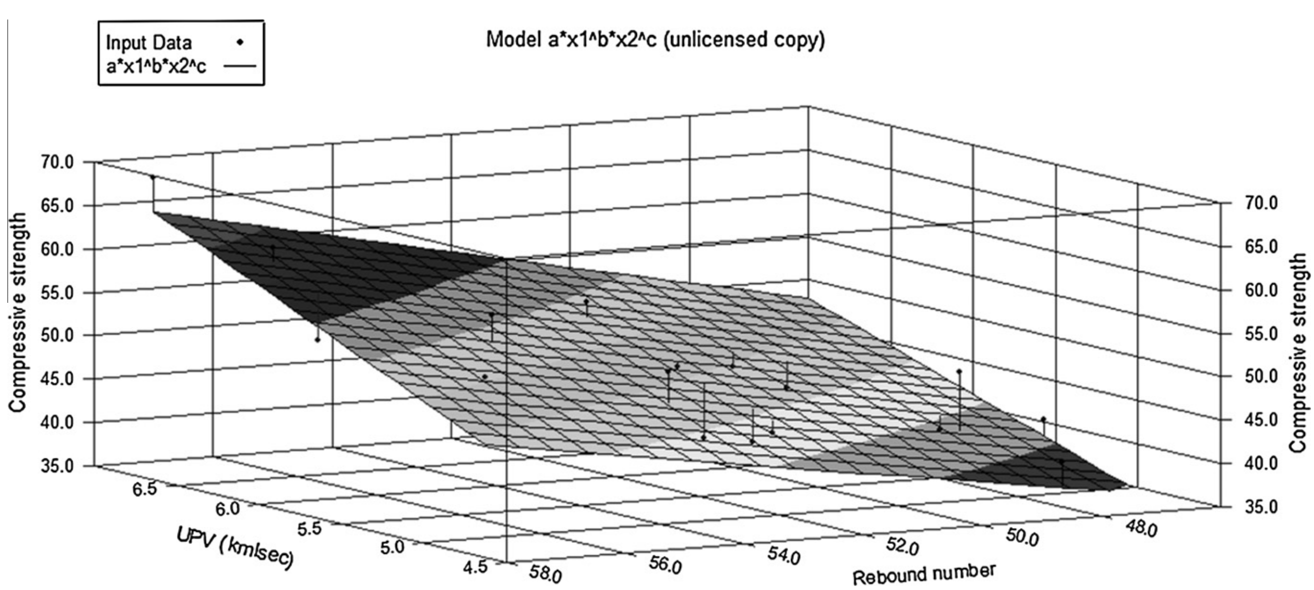


Figure 7 Relation between ultrasonic pulse velocity and rebound number versus compressive strength of marble.

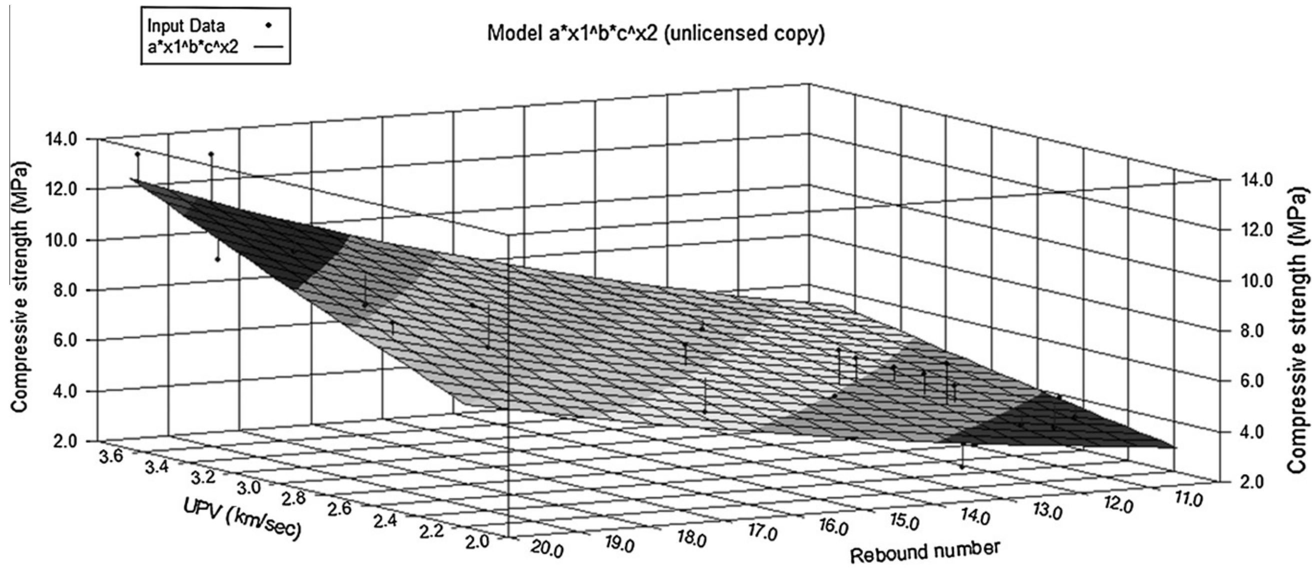


Figure 8 Relation between ultrasonic pulse velocity and rebound number versus compressive strength of white lime stone.

Table 11 Suggested models for relation between ultrasonic pulse velocity V and rebound number versus compressive strength of studied stones.

Type	Formula	R^2
Marble	$fc = 0.0447 * V^{0.98} * RN^{1.33}$	0.80
White lime stone	$fc = 0.498 * V^{1.2} * 1.088^{RN}$	0.87
Pink lime stone	$fc = 2.22 \times 10^{-5} * V^{2.692} * RN^{2.816}$	0.84
Basalt	$fc = 1.27 \times 10^{-7} * V^{8.122} * RN^{1.55}$	0.87
Lime sand bricks	$fc = 0.62 * V^{0.711} * RN^{0.761}$	0.87
Burned bricks	$fc = 2.02 * 1.137V * RN^{0.625}$	0.82

Validation of relation between rebound number and ultrasonic pulse velocity versus compressive strength is given in Table 15. From this table, it is clear that estimation of compressive strength using values of rebound number and ultrasonic pulse velocity is better than using ultrasonic pulse velocity only and is better some extent than using rebound number only. Also, it is clear that estimation of compressive strength of stones and bricks using the general model between rebound number and ultrasonic pulse velocity versus compressive strength is better than general models by rebound number or ultrasonic pulse velocity only.

7. Conclusions

This study included three phases; first phase, Schmidt hammer rebound number, ultrasonic pulse velocity and compressive strength were performed on four types of stones and two types of bricks. Second phase, the regression analysis of the obtained test results were correlated using linear and non-linear models

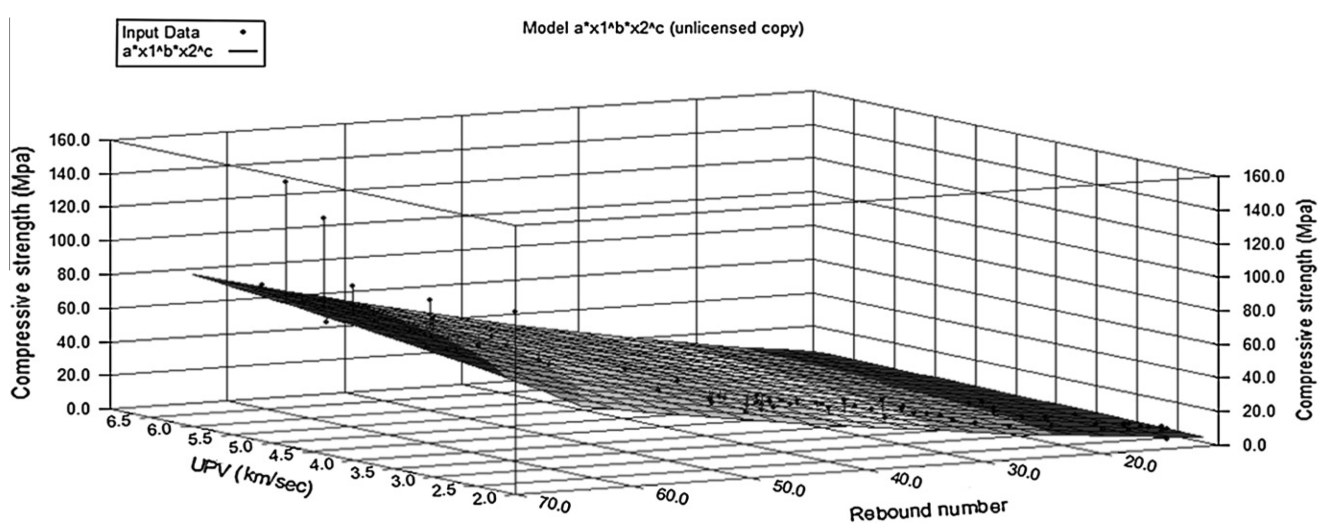


Figure 9 General relation between ultrasonic pulse velocity and rebound number versus compressive strength of all studied stones and bricks.

Table 12 Ultrasonic pulse velocity, rebound number and compressive strength test results of test specimens used for testing the validation of proposed models.

Type	Specimen Number	Pulse velocity (km/s)	Average rebound number	Compressive strength (MPa)
Marble	1	5.138	45.2	37.141
	2	5.766	49.2	41.964
	3	6.713	57.2	58.344
White lime stone	1	3.323	16.0	9.503
	2	2.234	10.5	3.601
	3	2.949	13.2	6.669
Pink lime stone	1	3.680	41.7	26.127
	2	3.800	42.7	32.328
Basalt	1	5.631	52.0	91.650
	2	5.714	59.0	125.190
Lime sand bricks	1	3.198	31.50	17.953
	2	3.110	29.00	17.030
Burned bricks	1	3.155	45.00	34.047
	2	2.127	31.80	21.515
	3	2.147	30.40	16.835

Table 13 Validation of proposed models of relations between rebound number and compressive strength.

Type	Specimen number	Average rebound number	fc Actual (MPa)	Linear models		Non-linear models		General models	
				fc Predicted (MPa)	Error (%)	fc Predicted (MPa)	Error (%)	fc Predicted (MPa)	Error (%)
Marble	1	45.2	37.141	33.75	−9.13	39.12	5.33	37.49	0.94
	2	49.2	41.964	43.48	3.61	43.43	3.49	47.36	12.86
	3	57.2	58.344	58.94	1.02	53.13	−8.94	75.56	29.51
White lime stone	1	16.0	9.503	7.78	−18.13	13.04	37.22	6.81	−28.34
	2	10.5	3.601	3.38	−6.14	5.55	54.12	4.94	37.18
	3	13.2	6.669	5.54	−16.93	8.65	29.70	5.49	−17.68
Pink lime stone	1	41.7	26.127	27.52	5.33	26.59	1.77	30.56	16.97
	2	42.7	32.328	30.44	−5.84	31.79	−1.66	32.40	0.22
Basalt	1	52.0	91.650	73.20	−20.13	69.04	−24.67	55.77	−39.15
	2	59.0	125.190	107.11	−14.44	107.59	−14.06	83.93	−32.96
Lime sand bricks	1	31.50	17.953	19.64	9.40	19.45	8.34	16.84	−6.20
	2	29.00	17.030	17.68	3.82	17.72	4.05	14.56	−14.50
Burned bricks	1	45.00	34.047	34.80	2.21	34.68	1.86	37.06	8.85
	2	31.80	21.515	23.91	11.13	27.08	25.87	17.14	−20.33
	3	30.40	16.835	22.75	35.14	26.53	57.59	15.80	−6.15

for each material and general models for all test specimens either stones or bricks. Third phase, other test specimens were used to assess the validation of each model. From the analysis and validation of proposed models, generally, for each material, using linear models were better than non-linear models although R^2 values of non-linear model were higher than those of linear models. This conclusion either for the relations between rebound number versus compressive strength and for relations between ultrasonic pulse velocity versus compressive strength. The use of general model which correlate rebound number with compressive strength gave better results than the general model between ultrasonic pulse velocity and compressive strength. Estimation of compressive strength for studied stone and bricks using their rebound number and

Table 14 Validation of proposed models of relations between ultrasonic velocity and compressive strength.

Type	Specimen number	Pulse velocity (km/s)	fc Actual (MPa)	Linear models		Non-linear models		General models	
				fc Predicted (MPa)	Error (%)	fc Predicted (MPa)	Error (%)	fc Predicted (MPa)	Error (%)
Marble	1	5.138	37.141	37.01	−0.35	45.31	21.99	44.78	20.57
	2	5.766	41.964	45.16	7.62	50.48	20.29	55.47	32.18
	3	6.713	58.344	57.45	−1.53	76.04	30.33	72.36	24.02
White lime stone	1	3.323	9.503	9.12	−4.03	8.86	−6.77	17.64	85.63
	2	2.234	3.601	2.33	−35.30	3.35	−6.97	5.92	64.40
	3	2.949	6.669	6.79	1.81	6.34	−4.93	13.10	96.43
Pink lime stone	1	3.680	26.127	26.5	1.43	24.84	−4.93	22.39	−14.30
	2	3.800	32.328	30.49	−5.69	28.84	−10.79	24.07	−25.54
Basalt	1	5.631	91.650	81.90	−10.64	76.22	−16.84	53.13	−42.03
	2	5.714	125.190	98.13	−21.62	93.48	−25.33	54.60	−56.39
Lime sand bricks	1	3.198	17.953	19.00	5.83	18.97	5.66	16.07	−10.49
	2	3.110	17.030	18.35	7.75	18.32	7.57	15.00	−11.92
Burned bricks	1	3.155	34.047	30.75	−9.68	30.40	−10.71	15.54	−54.36
	2	2.127	21.515	23.38	8.67	26.46	22.98	5.06	−76.48
	3	2.147	16.835	23.52	39.71	26.51	57.47	5.21	−69.05

Table 15 Validation of proposed models of relations between ultrasonic velocity and rebound number versus compressive strength.

Type	Specimen number	Pulse velocity (km/s)	Rebound number	fc Actual (MPa)	Models		General models	
					fc Predicted (MPa)	Error (%)	fc Predicted (MPa)	Error (%)
Marble	1	5.138	45.2	37.141	35.34	−4.85	41.47	11.66
	2	5.766	49.2	41.964	44.29	5.54	49.29	17.46
	3	6.713	57.2	58.344	62.81	7.65	65.53	12.32
White lime stone	1	3.323	16.0	9.503	8.11	−14.66	7.55	−20.55
	2	2.234	10.5	3.601	3.17	−11.97	3.45	−4.19
	3	2.949	13.2	6.669	5.55	−16.78	5.42	−18.73
Pink lime stone	1	3.680	41.7	26.127	27.03	3.46	32.00	22.48
	2	3.800	42.7	32.328	31.51	−2.53	33.58	3.87
Basalt	1	5.631	52.0	91.650	72.42	−20.98	52.91	−42.27
	2	5.714	59.0	125.190	99.20	−20.76	64.04	−48.85
Lime sand bricks	1	3.198	31.50	17.953	19.57	9.01	20.00	11.40
	2	3.110	29.00	17.030	18.01	5.75	17.52	2.88
Burned bricks	1	3.155	45.00	34.047	32.70	−3.96	37.50	10.14
	2	2.127	31.80	21.515	23.07	7.23	17.06	−20.71
	3	2.147	30.40	16.835	22.48	33.53	16.04	−4.72

ultrasonic pulse velocity in combined method was generally more reliable than using rebound number or ultrasonic pulse velocity only.

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