ASIAN JOURNAL OF CIVIL ENGINEERING (BHRC) VOL. 18, NO. 2(2017)
PAGES 191-205

ANALYSIS OF THE RELATIONSHIP BETWEEN NONDESTRUCTIVE AND DESTRUCTIVE TESTING OF LOW CONCRETE STRENGTH IN NEW STRUCTURES

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Received: 25 May 2016; **Accepted:** 25 August 2016

ABSTRACT

The quality of concrete of the most of Algerian construction sites is often low. In the case of low compressive strength results, non-destructive tests such as rebound hammer and ultrasonic pulse velocity are performed to check these results. Correlations curves from either equipment manufacturers or from the literature are used by quality control laboratories in order to estimate concrete strength. The estimation of strength based on these correlations is often subject to confusion and contradictory results when compared with the core test results. This clearly shows the need for appropriate correlations for concrete made with local materials and under local environmental conditions. The main objective of this paper is to propose appropriate simplified correlations for concretes made by local materials and for compressive strength levels reflecting the conditions and current practices on building sites in Algeria. This study presents some models established between destructive and individual or combined nondestructive tests (Rebound hammer and ultrasonic pulse velocity) in order to obtain a better estimation of concrete strength on site. The results show the reliability of the combined methods and the important difference in concrete strength estimation as compared to the models available in the literature.

Keywords: Construction sites; in situ concrete strength; nondestructive tests; Rebound hammer; ultrasonic pulse velocity; combined techniques.

1. INTRODUCTION

The in-situ concrete strength is mutually very dependent on a whole range of factors such as: mix proportions, ambient conditions at the time of casting, size and location of the structural

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component, degree and the extent of after-care (curing) and the exposure conditions. For this reason, design of a reinforced and pre-stressed concrete structure is based on the commonly accepted principle that concrete can be considered as a randomly variable material, the test results of which follow a normal distribution. Differences in the concrete strength value between the standard specimens and that of in-situ are practically inevitable. In design, these differences among other factors are taken into account by the introduction of the partial safety factor for concrete strength [1].

On the other hand, the production of concrete in many developing countries, in particular in housing projects, is done mainly on site and rarely by ready-mixed concrete. In Algeria, Concrete is frequently made by workmen without adequate qualification, leading often to a bad proportioning and an excess in water content, which explains partially the low performance of most reinforced concrete buildings after earthquakes. In this country, compressive strengths of about 15 to 25 MPa are often reported and hence lower than the 25 MPa which usually used in structural design in most medium size reinforced concrete projects. For this reason, several statistical studies [2-5] were carried out on concretes produced on sites located in various climatic zones in Algeria. The results of these studies showed that concrete produced on sites have generally lower strength than that designed or recommended by standards. Consequently, Nondestructive testing (NDT) methods has been successfully employed to address these issues.

According to Woodson [6], NDT can be used to determine various relative properties of concrete, such as strength, modulus of elasticity, homogeneity, and integrity of concrete. Many techniques can be used for in-situ tests. On the one hand, Qasrawi [7] reported that the use of one method alone would not be sufficient to study and evaluate the required property. On the other hand, the use of more than one method yields more reliable results [8]. Hence, using combined methods together will reduce the errors produced by using one method alone to evaluate concrete strength. . Indeed, among the various combinations proposed by several researchers and from the reported data, it seems that only the combined techniques based on the rebound hammer (ASTM C 805) [9] and ultrasonic pulse velocity (UPV) (ASTM C 597) [10] measurements have been adopted in some parts of the world for practical evaluation of the in-situ compressive strength of concrete [11].

However, despite the available of a large panel of potentially efficient nondestructive testing methods used in order to characterize the condition of material, the relationship between the NDT observables and the indicators of the material's condition is not obviously defined. This is due to the strong variability of material, the combined effects of the indicators and the difficulty of transposing laboratory results to the site [12]. It is not sufficient to simply average the values of the in-situ test results and then computes the equivalent compressive strength by means of the existing established relationship. It is indispensable to account for the uncertainties that exist [13].

The first objective of this paper is to propose simple correlations between the rebound hammer and ultrasonic pulse velocity tests for concretes containing local materials and for strengths reflecting the current practices on building sites in Algeria [14]. Furthermore, the effects of site, curing and age on the response of NDT measurements and concrete strengths were identified and quantified.

2. EXPERIMENTAL STUDY

2.1 Presentation of selected sites

In this study, the examined concrete was sampled from three building sites during construction located in the north of Algeria for a period of approximately eight months (from April to November). The first building site is a 300 student's school, established in the region of Ain-Defla (Fig. 1a). The second is a University pole with several faculties, located in El-Affroun town which belongs to the Blida department (Fig. 1b). The third is a mosque being able to accommodate 2000 faithful, situated in Chlef town (Fig. 1c). These three sites are found in various climatic zones and located at 170 km, 70 km and 230 km Western of Algiers, respectively. The three selected projects are composed of several blocks with various floors (from one to five stories). The main structures are a portico system braced by shear walls, made with reinforced concrete.

(a) Project n° 1 (b) Project n° 2 (c) Project n° 3

Figure 1. Overall view of the projects

2.2 Concrete mixture design

Table 1 depicts the concrete mixtures recommended for the selected projects. Standard cubic specimens of 10 cm were made on site in two layers compacted by 25 strokes for each one. All specimens were covered and stored on the building site. After 24 hours, the specimens were demoulded, of which the half was subjected to water curing (WC) in laboratory and the other one to site curing (SC) in the air on building site under climatic conditions (sunning, wind and bad weather), as nearly as possible, the same conditions as the concrete in the structure. On the eve of the test, the water cured specimens were dried in the laboratory environment during approximately 24 hours before the test.

2.3 Protocol tests

At 7 and 28 days of concrete age, NDT tests (Rebound and UPV) were carried out in parallel on the specimens (Figs. 2-a and 2-b) and the structural components (Figs. 2-c and 2-d). Moreover, compression tests were also carried out at the same time with NDT tests. All tests of compression and NDT measured on specimens or components were both tested perpendicularly to the direction of concrete casting.

Table 1: Concrete mixtures designed for the selected projects

Designation of the ingredients		Content (kg/m³)			
		Project N°1	Project N° 2		Project N° 3
Cement:	Chlef	350	370	-	-
CEMII/A 42.5	Sour El-Ghozlane	-	-	370	-
	Oued Rass	570	-	-	600
Sand	Boussada	-	240	419	-
	Tizi-Ouzou	-	366	-	-
	3/8	313	235	346	170
Gravel	8/15	461	422	427	410
	15/25	321	556	606	570
Mixing water		210	170	190	160
Superplastiser		-	4.81	4.44	2.50
Compressive strength at 28 days (MPa)		28.0	32.9	27.5	29.0

(a) (b) (c) (d)

Figure 2. NDT measurements on specimens and components

On each project, various types of components such as footing, beam foundations, columns, shear walls or beams distributed on various levels and various blocks were selected for the study. In addition, for each component type, the sounding is related to one or more groups of three components. There are about 51 components distributed on 17 groups were submitted for NDT testing with two to three measurements on each component (Table 2). However, each group of three components was cast from the same batch of concrete. Furthermore, from the same batch of each group of three components, there is only one sampling of fresh concrete was carried out. The total number of concrete sampling on the three selected projects was 17. For each sampling, twelve (12) specimens were made, of which six were subjected to WC and six to SC (Fig. 3). As shown in Table 2, the total number of the specimens made is 204 (=17x12) which is distributed on 68 groups of three specimens. Each group of three specimens or three components cast from the same batch of concrete, cured under the same conditions and tested at the same age, constitutes a « test region » or a « strength level ». The results of crushing or NDT_tests presented in this study correspond to the average values of each group of three specimens or three components.

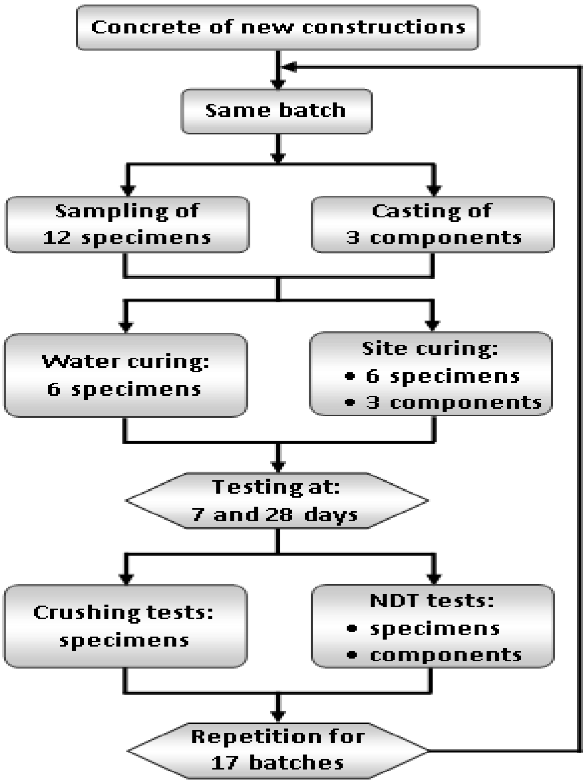


Figure 3. Flow chart of the experimental methodology

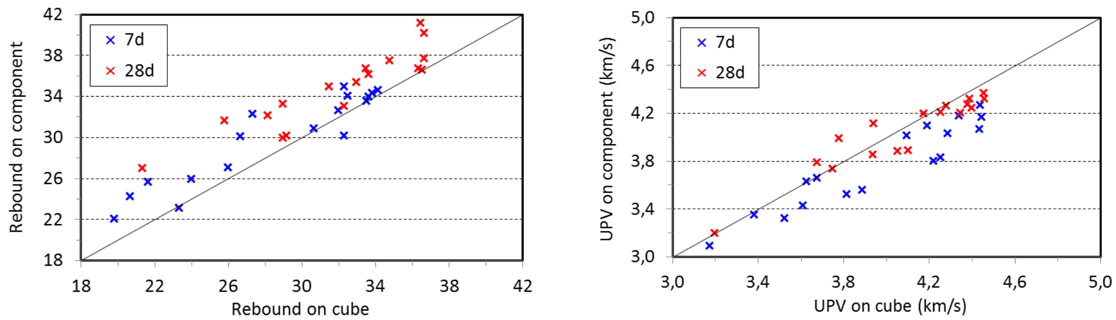
Table 2**:** Distribution of the number of components and specimens

Component type	Project N° 1					Project N° 2					Project N° 3				
	Nber of specimens				Nber of components	Nber of specimens				Nber of components	Nber of specimens				Nber of components
	Water Curing		Site curing			Water curing		Site curing			Water curing		Site curing		
	7d	28d	7d	28d		7d	28d	7d	28d		7d	28d	7d	28d	
Footing	06	06	06	06	06	-	-	-	-	-	-	-	-	-	-
Beam foundations	06	06	06	06	06	-	-	-	-	-	-	-	-	-	-
Columns	03	03	03	03	03	09	09	09	09	09	03	03	03	03	03
Shear walls	03	03	03	03	03	09	09	09	09	09	03	03	03	03	03
Beams	03	03	03	03	03	03	03	03	03	03	03	03	03	03	03
	21	21	21	21		21	21	21	21		09	09	09	09	
Total	42		42		**21**	42		42		**21**	18		18		**09**
	84					**84**					**36**				

3. RESULTS AND DISCUSSION

3.1 Difference between NDT measurements of components and laboratory tests

It is noted that the testing in-situ takes into account the effects of both the materials and execution (compaction, curing, etc.) [1]. Fig. 4 compares the NDT values obtained from testing the specimens and structural components. These specimens and components were cast from the same batches, subjected to the same conditions of curing and tested at the same age. For comparison, it should be noted that the rebounds measured directly on the components are higher than on the specimens (Fig. 4-a), but for the UPV, the contrary case is observed (Fig. 4-b). Malhotra and Carino [11] also found that UPV in columns cast from the same concrete were lower than in the site cured and laboratory cured specimens.



(a) Rebound (b) UPV

Figure 4. Comparison between NDT on specimens and components

The effect due to the difference between NDT measured on components and specimens is called here “site effect”. In order to quantify this difference, the average sensitivity of measurements was calculated. The sensitivity of NDT to the site effect “S_{site}” is defined as the rate of variation in NDT values which are measured on specimens “NDT_p” and components “NDT_c” (Eq. 1).

$$S_{site} = \frac{NDT_c - NDT_p}{NDT_p} \text{x}100 \quad (1)$$

The sensitivity to the site effect is slightly significant for the rebound than for the UPV. In addition, it is little higher at 28 days age (9%) than at 7 days (6%) for the rebound, but for the UPV, it is lower at 28 days (1%) compared to at 7 days (5%) (Fig. 5).

The difference in rebound number between components and specimens can be explained by the surface produced by the material of the cube molds can differ from the surface produced by the form material for the structure. This factor should also be considered in the correlation testing [15]. However, the difference in UPV is probably due to the degree of concrete compaction which is generally slighter on the components. At 7 days, both concrete specimens and components have a nearer water contents (they are casting from the same batch), whereas at 28 days the drying conditions influence much more the concrete specimens than that of components. Consequently, the evolution of UPV in specimens is less significant compared to that in components. For this reason, this difference is noted slighter at 28 days than at 7 days.

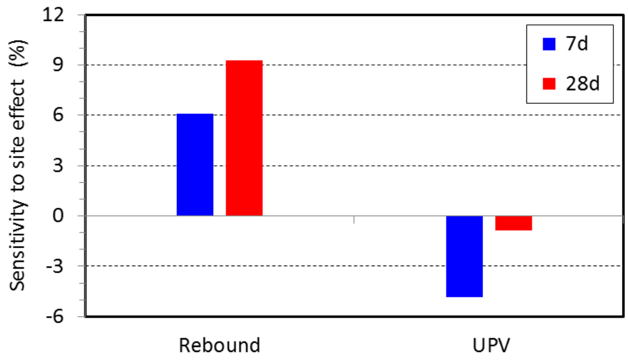
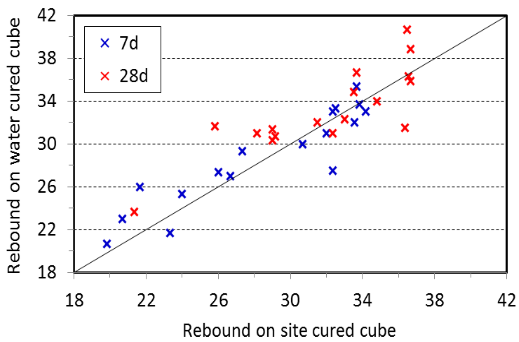


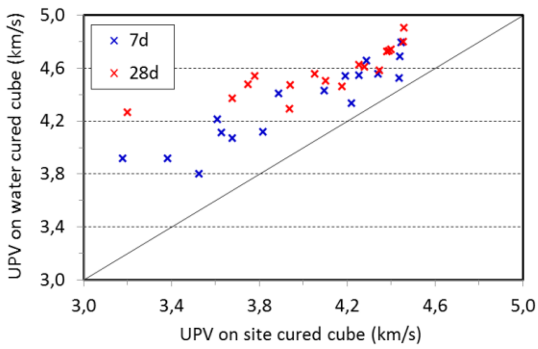
Figure 5. Sensitivity of the rebound and UPV to the site effect

3.2 Effect of curing on strength and NDT variation

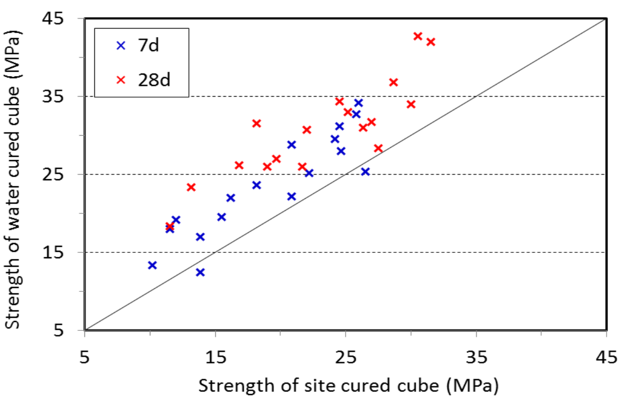
Fig. 6 compares the NDT and strengths measured on specimens that were subjected to different curing conditions: a part of specimens were subjected to WC whereas the others to SC. Each pair of these specimens was cast from the same batch and tested at the same age.



(a) Rebound



(b) UPV



(c) Strength

Figure 6. Effect of curing on the evolution of strength and NDT measurements

In our case, the rebounds are proximate between the site cured and water cured specimens (Fig. 6-a). However, [16, 17] reported that the moisture content of the concrete influences the rebound test results. In addition, it should be noted that the moisture content of the concrete influences the rebound number [11]. The decrease in the rebound number of about 20% was observed when the moisture content of concrete increases from air dry condition up to water saturated condition. The situation is similar for water saturated surface dry condition, too [17].

The UPV for water cured specimens was higher than for site cured specimens. (Fig. 6-b). The same conclusion was also found by Malhotra and Carino [11]. Indeed, this difference in UPV decreases when UPV increases (Fig. 6-b). According to the literature, moisture generally has less influence on UPV in high-strength concrete than on low-strength, because this due to the difference in the porosity [11].

As shown in Fig. 7, the sensitivity of strength and NDT measurements to the curing effect at 7 and 28 days. The sensitivity of NDT to the curing effect is defined as the rate of change in NDT values which are measured on both water cured “NDT_W“ and on site cured “NDT_S “ specimens (Eq. 2).

$$S_{cure} = \frac{NDT_w - NDT_s}{NDT_s} \text{x}100 \qquad (2)$$

In our case, the sensitivity of the rebound to the curing effect is almost insignificant. However, the sensitivity of strength is considerably important (Fig. 7). According to the literature [1, 11, 18 and 19], the strength of concrete tested in a wet state is approximately 10 to 15% lower than the same concrete tested at the dry state. On the other hand, the wet cured increase the concrete strength approximately of 45% at 28 days of age compared to the same concrete subject to dry cured [20]. Then, in the event of a concrete subjected to the wet cured with a test in a wet state, it can be deduced that strength increases approximately 30% compared to the dry cured with the test in a dry state.

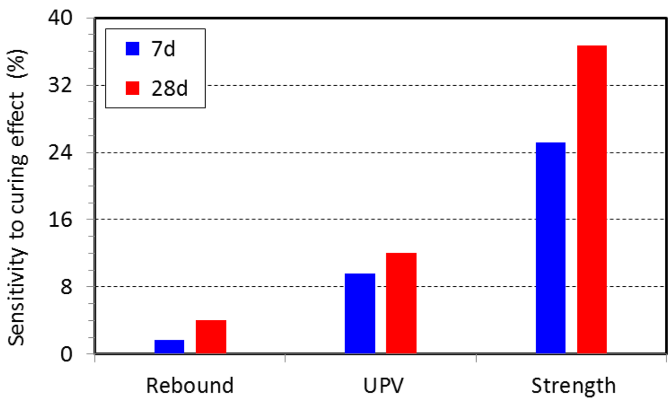
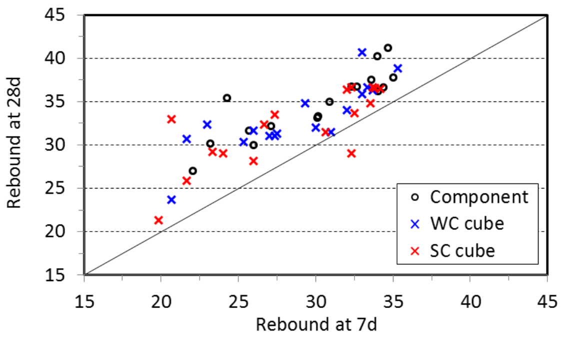


Figure 7. Sensitivity of the NDT and strength to the cure effect

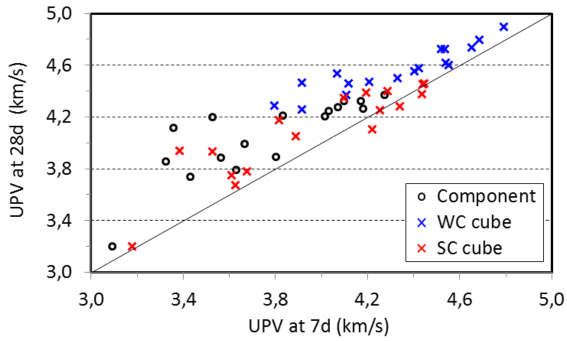
The sensitivity of UPV to the curing effect is almost noted to have the same tendency as that of strength but with a lower intensity (Fig. 7). In addition, the sensitivity of UPV to the curing effect is influenced by the strength evolution and the internal moisture rate in the water cured specimens. Moreover, this sensibility is noted slightly higher at 28 days than at 7 days. This is probably due to the moisture rate in the site cured specimens is even higher at 7 days than at 28 days.

3.3 Evolution of strength and NDT with age

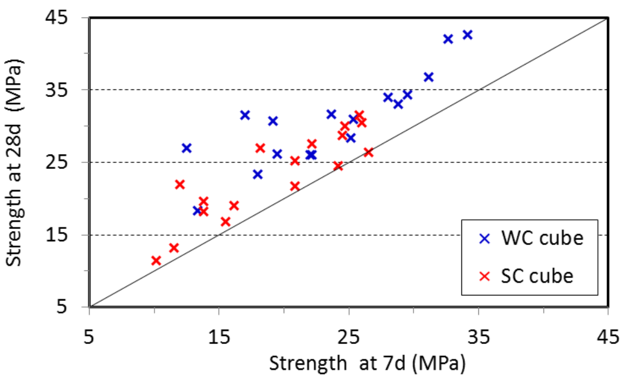
Fig. 8 compares the NDT and strengths measured at 7 and 28 days on components and water and site cured specimens, which were made by the same batches. It is observed that the NDT and strengths measured at 28 days are higher than at 7 days in the three studied cases (water and site cured specimens and components). In addition, this difference in UPV decreases when the UPV increases (Fig. 8-b), whereas this difference in strength increases when the strength increases (Fig. 8-c).



(a) Rebound



(b) UPV



(c) Strength

Figure 8. Effect of the age on the variation of strength and NDT

Fig. 9 shows the sensitivity of strengths and NDT to the age effect for the water and site cured specimens and for the components. It is known that the sensitivity of NDT to the age effect is defined as the rate of variation in NDT values which are measured at 7 days age " NDT_7 " and 28 days " NDT_{28} " on specimens or components (Eq. 3).

$$S_{age} = \frac{NDT_{28} - NDT_7}{NDT_7} \text{x100} \quad (3)$$

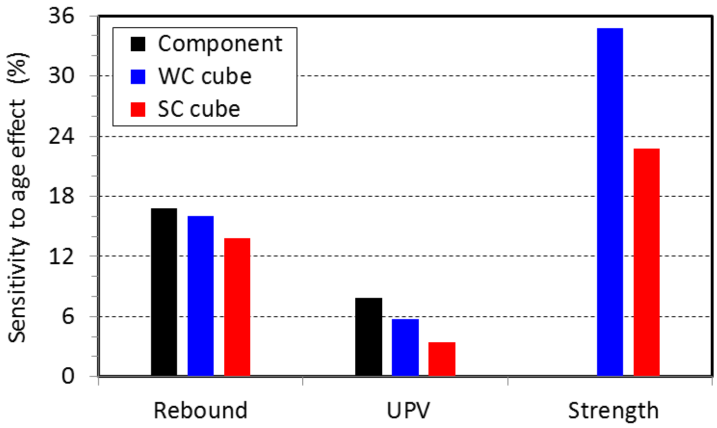


Figure 9. Sensitivity of the NDT and strength to the age effect

It is obvious, to observe that strength, the rebound and UPV are higher at 28 days than at 7 days, but the evolution between 7 and 28 days of age is noted higher for strength and less low for UPV on the three cases (Fig. 9). Soshiroda et al. [21] also noted the same behavior of the evolution of strength, rebound and UPV on wet cured specimens between the age of 7 and 28 days. The sensitivity of the rebound and of UPV to the age effect is observed little higher on the components than on the specimens.

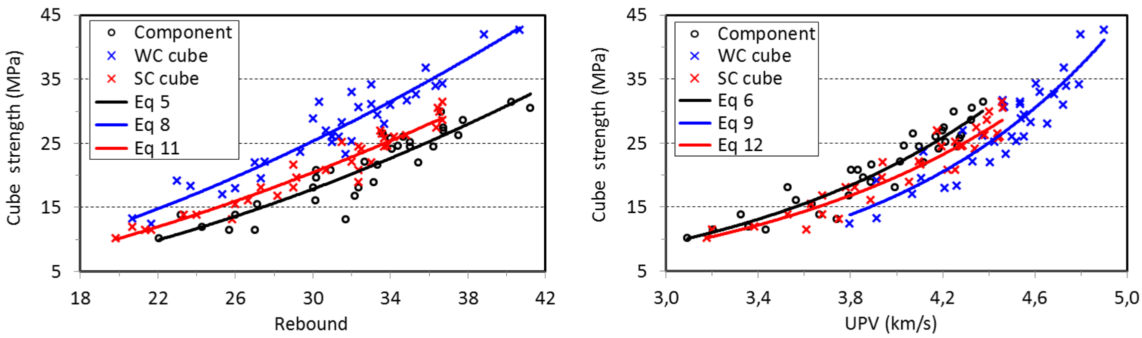
The age effect on the rebound is marked more on the water cured than of site cured specimens. This is can be attributed to the effect of strength evolution on the rebound, although the strength evolution from 7 to 28 days is higher for the water cured than the site cured specimens (Fig. 9).

Contrary to the strength and the rebound, it is clear that the UPV evolution is less sensitive to the age effect between 7 and 28 days. This sensitivity is observed slightly higher on the water cured than the site cured specimens (Fig. 9), although the water curing influences the UPV evolution considerably. This indicates that the water curing has not a better influence on UPV measurements beyond 7 days of age.

3.4 Analysis of relationship between strength and NDT measurements at various scales

This study makes it possible to establish the empirical relationships between the concrete strengths and NDT measurements and to analyze the quality of correlation while taking as statistical indicators: the coefficient of determination "r^2" and the Normalized Root Mean Square Error “NRMSE". It is noted that the coefficient r^2 alone is not a sufficient indication of the adequacy of the models. Moreover, even though the coefficient r^2 is large, this does not necessarily imply that the regression model will provide accurate predictions [7, 22]. Indicator RMSE is often regarded as the best means to test the performance of a model [23, 24]. Error NRMSE is often useful for reasons of comparison and represents the RMSE standardized with the average of measured strength “ $\overline{F}_m$“ (Eq. 4).

$$\text{NRMSE (\%)} = \frac{RMSE}{\overline{F}_m} \text{x100} \quad (4)$$



(a) Rebound (b) UPV

Figure 10. Relationship between strength and NDT tested on specimens and components

In order to identify the relationships between strengths and NDT measurements, the forms of the most models used in practice of engineering and in the scientific literature have been tested: the form power for the rebound, the exponential form for UPV and the form bi-power for the combined NDT. The relationship between NDT values (rebound "R" and ultrasonic pulse velocity "V") measured on the components and the water and site cured specimens and the corresponding strengths is shown in Fig. 10. Table 3 presents the mathematical forms of the relationships, the coefficients of determination r^2 and the error NRMSE for separated methods NDT (simple regression: one-variable) and combined NDT (multiple regression: two-variable) established on the three studied cases.

Table 3: Relationships between strength « F » and NDT on specimens and components

Studied cases	NDT Testing	Shape models	r^2	NRMSE (%)	Equation number
Component	Rebound "R"	$\mathbf{F} = 0.0278*\mathbf{R}^{1.9012}$	0.84	10.95	5
	UPV "V" (km/s)	$\mathbf{F} = 0.7274*\exp(0.8503*\mathbf{V})$	0.89	9.20	6
	Combined NDT	$\mathbf{F} = 0.0806*\mathbf{R}^{0.7496}*\mathbf{V}^{2.1547}$	0.91	8.41	7
Water cured cube	Rebound "R"	$\mathbf{F} = 0.0681*\mathbf{R}^{1.7403}$	0.90	8.48	8
	UPV "V" (km/s)	$\mathbf{F} = 0.3191*\exp(0.9914*\mathbf{V})$	0.85	10.52	9
	Combined NDT	$\mathbf{F} = 0.0435*\mathbf{R}^{1.1892}*\mathbf{V}^{1.5672}$	0.92	7.65	10
Site cured cube	Rebound "R"	$\mathbf{F} = 0.0572*\mathbf{R}^{1.7286}$	0.94	7.29	11
	UPV "V" (km/s)	$\mathbf{F} = 0.7925*\exp(0.8039*\mathbf{V})$	0.91	9.13	12
	Combined NDT	$\mathbf{F} = 0.0634*\mathbf{R}^{1.2392}*\mathbf{V}^{1.1202}$	0.95	6.41	13

For new construction, the preferred approach is to establish the strength relationship by a laboratory-testing program that is performed before using the in-situ test method in the field.

In fact, the testing program typically involves preparing test specimens using the same concrete mixture proportions and materials to be used in construction [15]. However, for the rebound, Fig. 10-a shows that the models developed on the specimens (Eqs. 8 and 11) over-estimate strength on the one hand in comparison to the components (Eq. 5), with approximately from 2 to 3 MPa for the site cured specimens and from 5 to 11 MPa for the water cured specimens. On the other hand, for UPV (Fig. 10-b), an underestimation of strength is observed for the models developed on the specimens (Eqs. 9 and 12) compared to that of the components (Eq. 6), with about from 0 to 4 MPa for site cured specimens and 5 MPa for the water cured specimens. Idrissou [25] also proposed two different correlations: the first is related the strengths with NDT measurements (Rebound and UPV) carried out on air cured specimens, but the second is based on cores strength correlated with NDT measurements carried out on columns. It has been concluded that the correlation developed from the tests on columns gives closer strength results to the reality compared to that developed on specimens. Fig. 11 shows a correlation established between the crushing strengths of the site cured specimens and both the rebound number and the UPV together measured on components (Eq. 7).

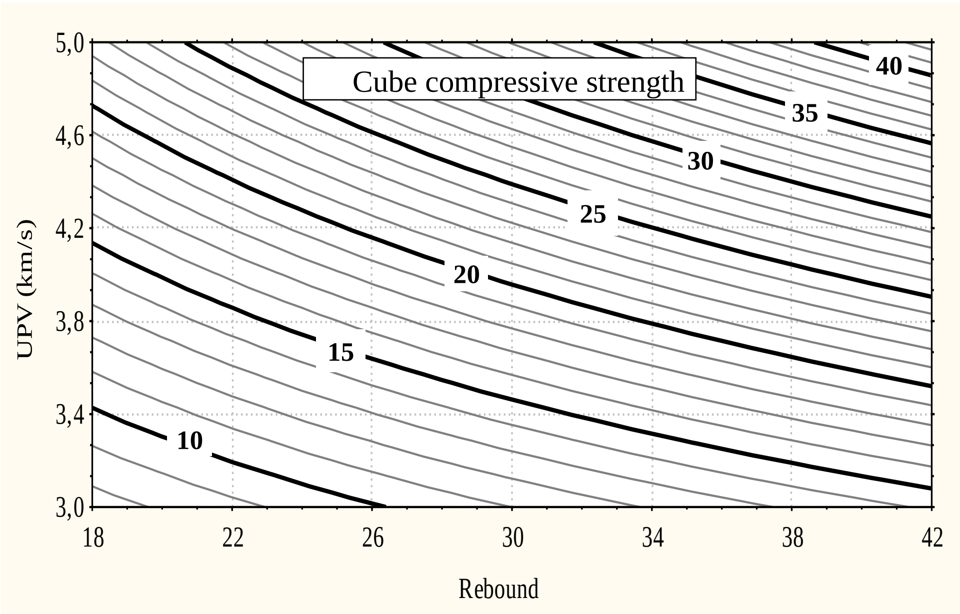


Figure 11. Combined correlation between crushing strengths and NDT measured on structural components

It is observed on the three studied cases that all the one-variable regressions (separated NDT) present relatively good correlations (with coefficients $r^2 \geq 0.84$ and NRMSE ≤ 10.95%). The correlation of using the combined method (Eqs. 7, 10 and 13) is more accurate and gives a higher coefficient r^2 ($r^2 \geq 0.91$) and a lower error NRMSE (NRMSE ≤ 8.41%) compared with both methods based on either rebound number alone or UPV alone (Table 3). Similar conclusions were reported by several researchers [21, 26].

A comparison between the combined model suggested by this study (Eq. 7) and other combined models established by several researchers is shown in Fig. 12. The measured strengths of our study are compared with those estimated by several literature combined models which were established by Soshiroda et al. [21] (Eq. 14), Hobbs and Kebir [26] (Eq. 15) and Sakhraoui and Mouffok [27] (Eq. 16), taking account of the specimens scale effect.

$$\mathbf{F} = 1.416*\mathbf{R}+8.63*\mathbf{V}-51.581 \tag{14}$$

$$\mathbf{F} = 1.307*\mathbf{R}-4.069\mathbf{V}^2+57.693*\mathbf{V}-173.033 \tag{15}$$

$$\mathbf{F} = 0.866*\mathbf{R}+17.13*\mathbf{V}-62.684 \tag{16}$$

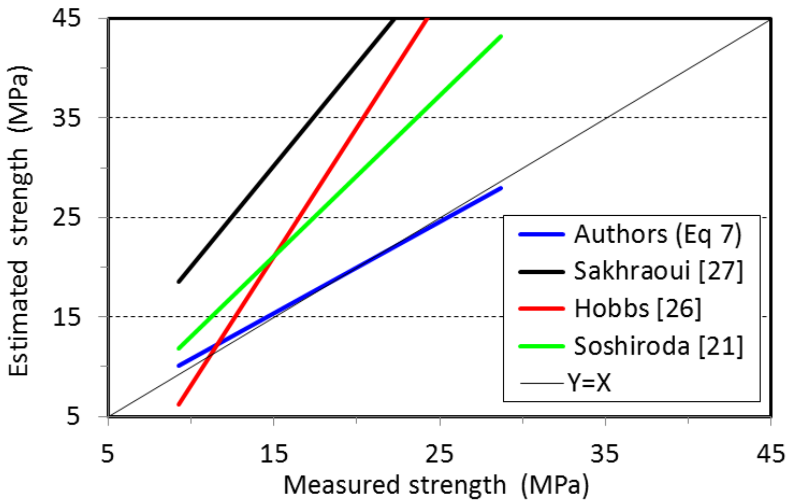


Figure 12. Comparison between measured strength and that estimated by literature combined models

It is noted that the literature models over-estimate the strength in comparison with that proposed in this study, whereas Hobbs and Kebir [26] were indicated that their proposed models for strength evaluation could be used safely for concrete strength estimation for the forensic engineering investigation in Algeria. This large gap confirms that the concrete produced on Algerian sites have generally lower strength, and clearly shows the need for appropriate correlations for concrete made with local materials and under local environmental conditions.

4. CONCLUSIONS

Analysis of the effect of site, curing and age on the response variability of NDT measurements and concrete strengths is the subject of methodological developments in progress. From this study, it can be concluded that:

- It should be noted that the rebounds measured directly on the components are higher than on specimens, whereas for UPV, the contrary case is observed;

- The rate of variation to the effect of curing is definitely higher for strength than for NDT, while it is almost unimportant for the rebound;
- The strength evolution is also more sensitive to the age effect (between 7 and 28 days) than for NDT. This evolution is slighter for UPV than for rebound. The variation in NDT to the age effect is slightly higher on the components than on the specimens. In the same way, it is also little higher on water curing than on site curing;
- The models established on structural components offer a better approach of the in-situ concrete strength estimation as compared to on testing specimens;
- The estimate of strength from the combined NDT gives a better accuracy compared to the single methods;

The estimate of concrete strength from the models proposed by the equipment manufacturers or those available in the literature shows a large gap to compare to the strength results which observed by cube crushing in this study.

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