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Destructive and Non-destructive Testing of Concrete Structures

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ABSTRACT

The estimation of mechanical properties of concrete can be carried out by several methods; destructive and non-destructive. In this context, the crushing of the samples is the usual destructive test to determine the concrete strength. The rebound hammer test and the ultrasonic device are used in the field of non-destructive tests to determine respectively the compression strength and the ultrasonic pulse velocity (UPV) in the concrete. In this work, eight concrete compositions were used to prepare cylindrical specimens (16 cm x 32 cm) by varying the water/ cement ratio and the cement dosage. An experimental study was conducted to determine the compressive strength of concrete by destructive (compression) and non-destructive (rebound hammer) tests at different ages (7, 14 and 28 days). In addition, the influence of several factors on the modulus of elasticity determined by pulse velocity test was investigated. These factors mainly included the age of concrete and the water/ cement ratio. The results showed that the difference between the resistance values obtained by destructive and non-destructive methods decreases with increasing age of concrete. The dynamic modulus of elasticity increases with the curing time of the concrete until the age of three months. In addition, a simplified expression has been proposed to estimate the rebound number from the value of the dynamic modulus of elasticity determined by pulse velocity test.

KEYWORDS: Rebound hammer test, Compression test, Pulse velocity test, Destructive test, Non-destructive test, Dynamic modulus of elasticity.

INTRODUCTION

It is often necessary to test concrete structures after the concrete has hardened to determine whether the structure is suitable for its designed use. Ideally, such testing should be done without damaging the concrete. The tests available for testing concrete range from completely non-destructive tests, where there is no damage to the concrete, through those where the concrete surface is slightly damaged, to partially destructive tests, such as core tests and pull-out and pull-off tests, where the surface has to be repaired after the test. The range of properties that can be assessed using non-destructive tests and partially destructive tests is quite large and includes such fundamental parameters as density, elastic modulus and strength as well as surface hardness, surface absorption, reinforcement location, size and distance from the surface.

The crushing of the specimens is the usual destructive test to assess the strength of concrete. Non-destructive methods like rebound hammer test and ultrasonic test do not damage buildings and allow to have an inventory of structures and conditions. Non-

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destructive tests are widely applied to study mechanical properties and integrity of concrete structures (Ravindrarajah, 1997; Nazarian et al., 1997; Proverbio and Venturi, 2005; IAEC, 2005). They are simple to use and often economically advantageous. They are suitable for taking measurements on site and taking continuous measurements. These non-destructive methods are usually associated with each other to improve diagnosis and reduce the number of tests (Breysse, 2012).

Ultrasound measurements provide a simple non-destructive and inexpensive method to evaluate the elastic modulus of concrete. The formulae proposed by different standards to estimate the dynamic modulus of elasticity from the resistance are very approximate (Baalbak et al., 1992). The dynamic modulus of elasticity is strongly influenced by the aggregates, it cannot be determined accurately based on the strength, which depends mainly on the cement paste and the particle size (Giaccio et al., 1992). For temperatures between - 10° C and + 30° C, there is an increase in the dynamic modulus of elasticity of the concrete with temperature (Gardner, 1990; Marzouk and Hussein, 1990).

This paper presents measurements of compressive strength and dynamic modulus of elasticity determined from destructive and non-destructive tests. The results obtained from non-destructive tests were compared with destructive test results. The influences of the age of the concrete, its strength and water/cement ratio on the resistance determined by rebound hammer test and compression test were studied. A simplified expression has been proposed to estimate the rebound number from the value of dynamic modulus of elasticity determined by pulse velocity test.

EXPERIMENTAL STUDY

Material Characteristics

The cement used was CEM I 42.5 in conformity with Tunisian Standard NT 47.01 produced by the Cement Company of GABES. It has an absolute density of 3.10 g/cm^3 and a Blaine specific surface of 380 m²/kg. The chemical composition of cement is given in Table 1.

The physical characteristics of the aggregates used in the preparation of concrete specimens (16 x 32) are shown in Table 2.

Table 1. Chemical composition of cement

S_iO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	CaO (%)	MgO (%)	SO_3 (%)	Cao (%)
28.48	4.19	3.77	56.26	0.89	1.54	0.57

Table 2. Physical characteristics of the aggregates

	Los Angeles (%)	Fineness modulus	Absorption (%)	Specific gravity (g/cm^3)	Bulk density (g/cm^3)
Sand 0/5	-	2.51	3.20	2.65	1.45
Gravel 4/15	34	-	2.50	2.60	1.47

Mixtures

In our study, the mixtures are formulated initially by the method of Dreux-Gorisse (Dreux, 1981; Gorisse, 1978). This method is a technique which defines, in a simple and fast way, a composition with little meadows adopted with the studied concrete. The composition of all prepared mixtures is given in Table 3.

Test specimens were kept in their molds. After 24 h, they were removed from the molds and subjected to water curing at 20°C. At the correspondent age, the specimens were taken out and kept in laboratory conditions until testing time.

Table 3. Composition of the concrete specimens

Designation of concrete / Mixtures [kg/m^3]	C1	C2	C3	C4	C5	C6	C7	C8
Cement	450	450	450	450	350	350	350	350
Sand 0/5	500	670	750	1000	620	540	570	610
Gravel 4/15	1150	990	920	650	1170	1040	1100	1240
Water	225	225	225	225	190	196	210	220
W/C	0.50	0.50	0.50	0.50	0.54	0.56	0.60	0.63

TEST PROCEDURES

Schmidt Rebound Hammer Test

The Schmidt rebound hammer is principally a surface hardness tester. It works on the principle that the rebound of an elastic mass depends on the hardness of the surface against which the mass impinges. There is little apparent theoretical relationship between the strength of concrete and the rebound number RN of the hammer. However, within limits, empirical correlations have been established between strength properties and the rebound number. The Schmidt rebound hammer is shown in Figure 1. The hammer weighs about 1.8 kg and is suitable for use both in a laboratory and in the field. The hammer can be used in the horizontal, vertically overhead or vertically downward positions as well as at any intermediate angle, provided that the hammer is perpendicular to the surface under test. The position of the mass relative to the vertical, however, affects the rebound number due to the action of gravity on the mass in the hammer. Thus, the RN of a floor would be expected to be smaller than that of a soffit, and inclined and vertical surfaces would yield intermediate results. Although a high RN represents concrete with a higher compressive strength than concrete with a low RN, the test is only useful if a correlation can be developed between the RN and concrete made with the same coarse aggregate as that being tested.

This test was performed on the specimens according to standards (EN 12504-2 2001, EN 12309-3 2003). Schmidt rebound hammer test gave values of RN. The compressive strength of the concrete was derived using the chart provided with the device (Aydin and Saribiyik, 2010). A light load was applied on the test pieces to prevent their movement during the test. No action has been located within 40 mm of the flat faces of the specimen. The hammer has to be used against a smooth surface, preferably a formed one. Open textured concrete cannot therefore be tested. If the surface is rough, e.g. a trowelled surface, it should be rubbed smooth with a carborundum stone. RN was equal to the median of 27 measures spread over the three generators of the specimen tested (Figure 1).

Pulse Velocity Test

The 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 the initiation of a pulse generated at the transmitting transducer and its arrival at the receiving transducer .The pulse velocity test was determined using cylindrical specimens in accordance with the requirements of EN 12504-4.

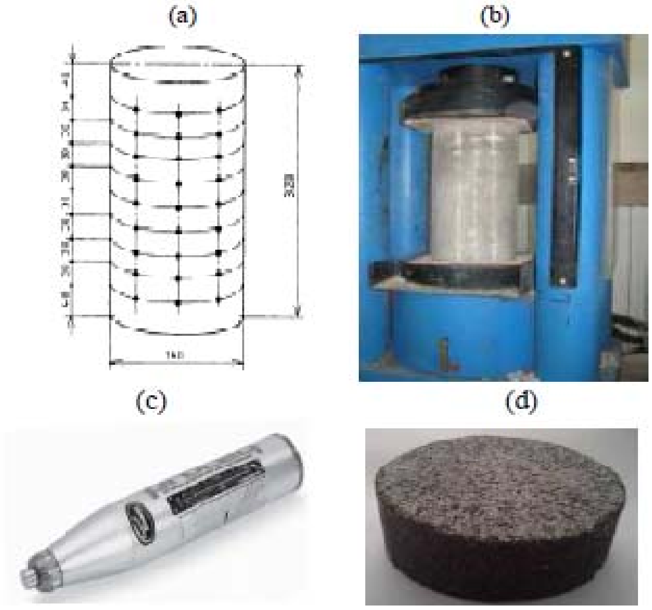


Figure (1): Schmidt rebound hammer test. (a) Preparation of the measuring points, (b) Measurement of rebound number, (c) Schmidt rebound hammer, (d) carborundum stone

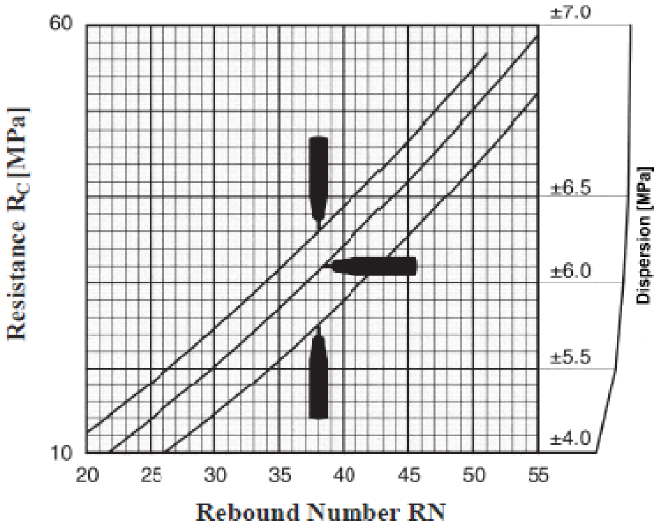


Figure (2): Chart for determining the resistance as a function of the rebound number

The device used was an electronic tester with microprocessor in a portable case (Figure 3). It is capable of measuring transit time over path lengths ranging from about 100 mm to the maximum thickness to be inspected to an accuracy of ±1%. The transducers used were in the range of 50 to 60 kHz.

Calibration using a calibration bar (known in time course) was carried out before the measurements and after an hour of use as recommended by the manufacturer.

Figure (3): Ultrasonic pulse velocity tester with microprocessor

A pulse of longitudinal vibrations is produced by an electro-acoustical transducer, which is held in contact with one surface of the concrete under test. When the pulse generated is transmitted into the concrete from the transducer using a liquid coupling material such as grease or cellulose paste, it undergoes multiple reflections at the boundaries of the different material phases within the concrete. A complex system of stress waves develops, which includes both longitudinal and shear waves and propagates through the concrete. The first waves to reach the receiving transducer are the longitudinal waves, which are converted into an electrical signal by a second transducer. Electronic timing circuits enable the transit time T of the pulse to be measured. Longitudinal ultrasonic pulse velocity is given by:

$$UPV = \frac{L}{t}(m/s) \tag{1}$$

Pulse velocity measurements made on concrete structures may be used by placing the two transducers on either (Figure 4):

- Opposite faces (direct transmission);
- Adjacent faces (semi-direct transmission); or
- The same face (indirect or surface transmission).

Since the maximum pulse velocity is transmitted at right angles to the face of the transmitter, the direct method is the most reliable one from the point of view of transit time measurement. Also, the path is clearly defined and can be measured accurately, and this approach should be used wherever possible for assessing concrete quality.

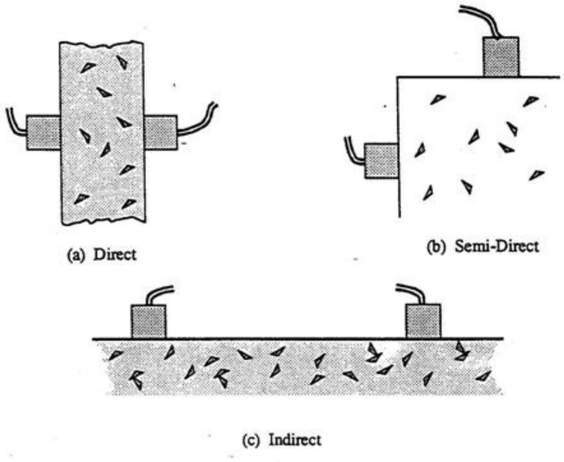


Figure (4): Type of measurement (a) Direct, (b) Semi-direct, (c) Indirect

Dynamic Modulus of Elasticity

The relationship between the dynamic modulus of elasticity and the velocity of an ultrasonic pulse travelling in an isotropic elastic medium of infinite dimensions is given below:

$$E_d = UPV^2.\rho.\frac{(1+\mu)(1-2\mu)}{1-\mu} \tag{2}$$

where

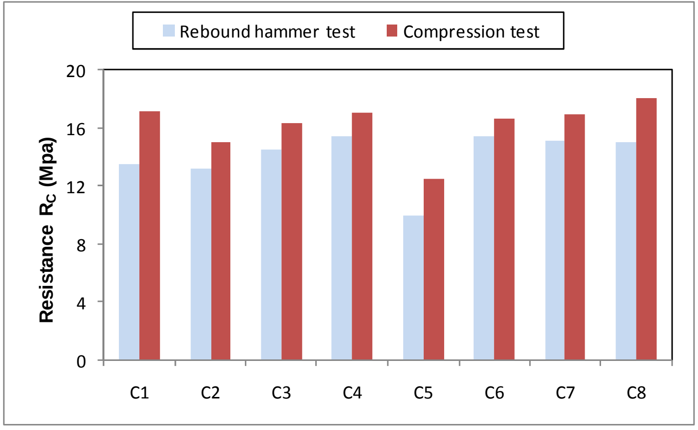
- E_d: the dynamic elastic modulus (MPa)
- μ : the dynamic Poisson's ratio
- ρ : the density (kg/m^3)
- UPV: the ultrasonic pulse velocity (m/s).

Compression Test

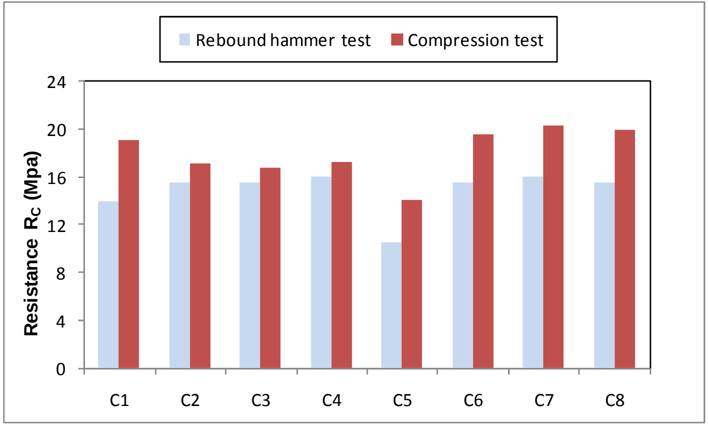
The compressive strength of cylinder concrete specimens was determined by destructive testing with a compression test machine. Progressive loading with a rate of 0.5 MPa/s was applied to the crushing of the specimen. The resistance value was read directly from the computer screen (Figure 5).

Figure (5): Compression test

(a)



(b)



(c)

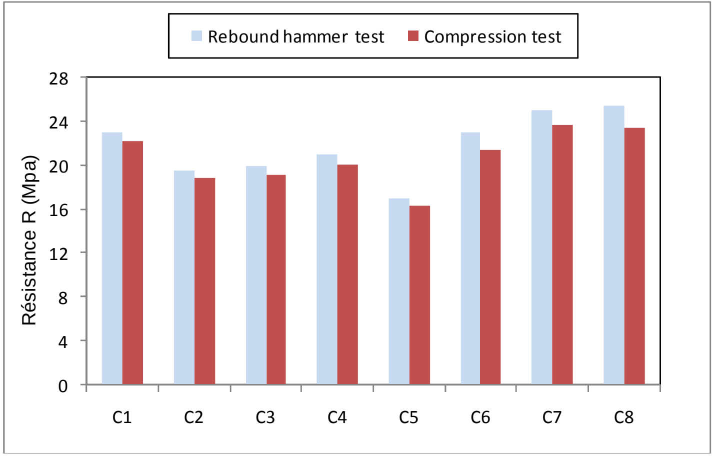


Figure (6): Effect of destructive and non-destructive tests on the resistance of concrete at the ages of: (a) 7 days, (b) 14 days, (c) 28 days

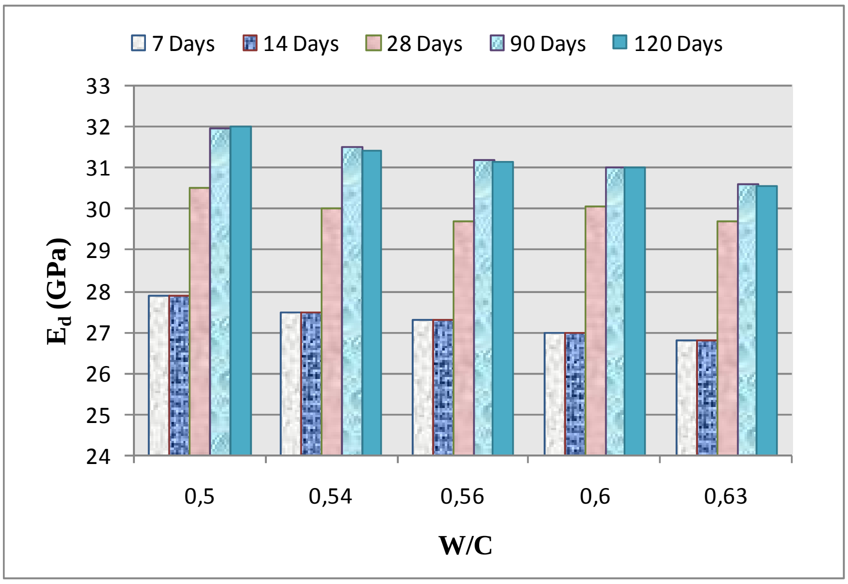


Figure (7): Evolution of the modulus of elasticity as a function of the age of the concrete for different W/C ratios

EXPERIMENTAL RESULTS AND DISCUSSION

Effect of Age of Concrete

Figure 6 shows the compressive strength determined by destructive test (compression test) and non-destructive test (rebound hammer test) at different ages of the concrete. At the ages of 7 and 14 days, the resistances obtained by the compression test were higher than those obtained by the rebound hammer test. The respective average differences between the two methods at the ages of 7 days and 14 days were 14% and 17%, respectively. At the age of 28 days, there has been a reversal of the situation; resistances obtained by the compression test were lower than those obtained by the rebound hammer test with an average difference of 5%. This result could be explained by the maturing of the concrete. The rebound hammer test may be used for evaluating the compressive strength and homogeneity of the concrete *in situ* without a core. This conclusion is valid for older concretes than for younger concretes.

Effect of Age of Concrete and W/C Ratio on the Modulus of Elasticity

The dynamic modulus of elasticity was calculated using equation (2). The UPV of specimens B1, B5, B6, B7 and B8 was measured at 7 days, 14 days, 28 days, 3 months and 4 months. Figure 7 illustrates the evolution of the modulus of elasticity as a function of the age of the concrete for the W/C ratios of respectively 0.5, 0.54, 0.56, 0.6 and 0.63. The modulus of elasticity was increased with the time of hardening of the concrete. This increase was very significant for the first 7 days where the modulus of elasticity could reach 80% of its value and continued to increase between the ages of 28 days and 3 months.

Figure 7 also shows the influence of the W/ C ratio values on the modulus of elasticity. For example, the modulus of elasticity measured at 7 days was decreased from 27.88 GPa to 26.40 GPa for W/C ratios of 0.5 and 0.63, respectively. Indeed, the W/C ratio had a great influence on the porosity of the hydrated cement paste and therefore on the mechanical properties of concrete.

RN Compared to Modulus of Elasticity

RN was compared to the modulus of elasticity of concrete measured at ages of 7, 14 and 28 days. The UPV in concrete has often been used in practice to estimate the strength of concrete in compression (Alexandre et al., 2013; Phoon et al., 1999). Unfortunately, this resistance has no direct correlation with the physical UPV, which essentially depends on the aggregates, while the compressive strength mainly depends on the cement paste, the grain size and the W/C ratio. For the modulus of elasticity, it is directly related to the UPV and can be determined with precision.

Figure 8 illustrates the values of rebound number determined at ages 7, 14 and 28 days. It was found that, despite the dispersion, the RN provided an indication on the modulus of elasticity which can be estimated at the age of 28 days by the exponential equation (3) with a correlation coefficient close to 1:

$$E_d = 16{,}406\, e^{0{,}0196\, RN} \quad \text{avec} \quad R^2 = 0{,}9806 \qquad (3)$$

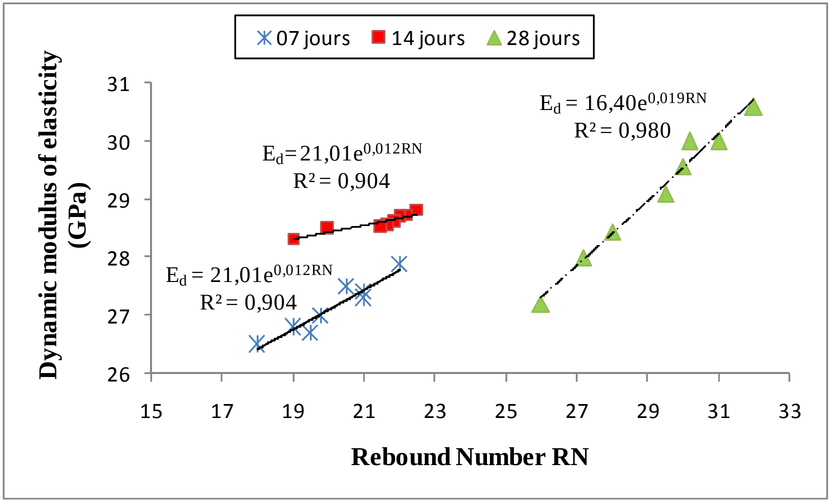


Figure (8): RN compared to the dynamic modulus of elasticity at the ages of 7, 14 and 28 days

CONCLUSIONS

The various techniques for measuring the compressive strength and modulus of elasticity were presented from destructive and non-destructive tests on concrete specimens with different compositions. The following conclusions can be drawn from this study:

- The difference between the values of resistance obtained by destructive and non-destructive tests decreased considerably at the age of 28 days. The rebound hammer test can be used to evaluate the compressive strength of old concrete and not young concrete.
- The UPV decreases with the increase of W/C ratio, which promotes a very important capillary porosity. Instead, UPV increases with the age of the concrete.
- The dynamic modulus of elasticity determined by ultrasonic measurement increases over time of hardening of the concrete up to the age of three months. Moreover, the dynamic modulus of elasticity decreases as the W/C ratio increases.
- Equation (2) has been proposed to estimate the relationship between RN and dynamic modulus of elasticity for the concrete for 28 days of age and for a W/C ratio between 0.5 and 0.63.

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