10DBMC International Conférence On Durability of Building Materials and Components
LYON [France] 17-20 April 2005

Reliability of nondestructive tests for on site concrete strength assessment

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TT8-227

ABSTRACT

Concrete is an inhomogeneous materials and even if a uniform distribution of its component is assumed it is very difficult to develop a model to correctly evaluate its on site mechanical behavior. Also compressive tests of concrete cores gives results affected by uncertainty and strongly dependent on reference standard used.

Several nondestructive testing methods have been developed in the past for on site concrete strength assessment. Among them rebound hammer and ultrasonic pulse velocity (UPV) tests are the most commonly used in practice though their reliability and usefulness is quite controversial. A good calibration of the methods it is only possible if a good knowledge of the concrete properties is already achieved, i.e. it is necessary to use some destructive tests to obtain such information. When assessing wide inhomogeneous structure such limit could be crucial from an economical and practical point of view.

An improvement of the reliability of nondestructive tests could be obtained by their combination as well as in the SONEB method. Basing on a wide number of experimental determinations under laboratory condition different regression models have been here proposed. A poor correlation between UPV and concrete strength was evidenced. Better results was obtained for rebound hammer test. It was evidenced that a preliminary knowledge of concrete characteristics it is of great importance to optimize regression model. A coefficient of determination higher than 0.9 was obtained by using a combined method.

KEYWORDS

Concrete strength, nondestructive tests, ultrasound, rebound hammer, cores

1 INTRODUCTION

The increasing age of reinforced concrete structures over all the world has led to a growing demand for reliable tools for concrete degradation assessment. The wide extension of some of these structures requires such assessment tools to be economical and easy to use. Concrete is an inhomogeneous materials and even if an uniform distribution of its component is assumed it is very difficult to develop reliable predictive models to correctly evaluate its on site mechanical behavior. Several efforts in such sense have been however done by researchers and some models are available on literature [Bazant & Becq-Giraundon, 2002; Bazant *et al.* 2002; Ince *et al.* 2003; Yang & Huang 1996]. Several nondestructive testing methods have been developed in the past for on site concrete strength assessment, a comprehensive literature survey can be found in ACI Committee 228 [1988], Malhotra & Carino [1991], Bungey & Soutos [2001], Tay & Tam [1996]. Among them the rebound hammer and the ultrasonic pulse velocity (UPV) tests are the most commonly used in practice. Even if these methods are standardized their reliability, also taking into account all limits and suggestions given in the standards, is quite low. A good calibration of the testing methods it is only possible if a good knowledge of the concrete properties is already available, i.e. it is necessary to use some additional destructive tests to obtain such information. When assessing wide inhomogeneous structure such limit could be crucial from an economical and practical point of view.
Results from compression tests of concrete cores could be used as a reference for the above mentioned nondestructive tests. However it is well known that compression tests themselves are affected by a number of factors which result in some uncertainty in the concrete strength determination. Besides, measured concrete compression strength is strongly dependent on testing standards adopted and in some case far from the intrinsic strength of concrete, if an intrinsic strength of concrete could be defined [Neville, 1996].
Aim of the present work was to evaluate the reliability of rebound hammer test and UPV test on concrete of different composition and strength class. Basing on a wide number of experimental determinations different regression models of general purpose are proposed by the authors. Coefficient of correlations were however observed to be influenced by concrete samples used (cubes and core with different height to diameter ratio) as well as on concrete information already available.

2 CONCRETE TESTING

2.1 Compressive strength

Compressive strength test is described in several standards. European standards EN 12390-1/3 allows the use of cubic, cylindrical and prismatic specimens, ASTM C39 and C192 standards allows the use of cylindrical specimens. A great importance is given to geometrical size and length to diameter ratio, especially when non standard specimens, as well as concrete cores, are used. The influence of length to diameter ratio is well documented and related to the friction between concrete surface and press steel plate as a consequence of the difference Poisson's ratio of the two materials. The effect of end restrain is conventional assumed to be negligible for a specimen with a length to diameter ratio (l/d) of 2. For other cases correction factor are recommended. Correction factors however slightly differ from standard to standard. ASTM C42-90 commends correction factor not linearly ranging from 0.87 to 1 for a l/d ratio from 1 to 2 respectively, whilst BS 1881 basing on Concrete Society suggestion [1987], recommends correction factor starting from 0,8. A comprehensive analysis of mathematical models to represent the l/d strength correction factor is given by Barlett et MacGregor [1994]. The dimension of the specimen may also influence the measured strength and variability. The problem is of particular importance for high strength concrete [Patnaik & Patanaikuni, 2002; Tokyay & Ozdemir, 1997] due to the need to reduce the size of test cylinders in order to account the performance of existing testing facilities. A survey of the most common correction factors used is given in the Concrete Society Technical Report 11/87 [Concrete Society, 1987].

2.1.1 Estimation of cube strength

The estimation from a concrete core of standard cube strength, i.e. the strength of a cube made with fresh concrete, vibrated and cured under standard condition, must account two main factors:

1) the estimation of cylinder strength, i.e. the strength of a standard cylinder taking into account the effect of the length to diameter ratio, the effect of voids and improper compaction as well as the damages induced by drilling.
2) the conversion to an equivalent cube strength using an empiric correction factor.

The Concrete Society [1987] recommends the use of the previously mentioned *l/d* factors plus a further 6% reduction to take into account the effect of a lateral surface obtained by drilling compared to the smooth surface obtained from the mould. A strength reduction of 15% is also included to allow for a weaker top surface zone of a corresponding cast cylinder. The cylinder to cube conversion is obtained multiplying by a factor 1.25, a further 8% difference between vertical and horizontal drilling is also taken into account thus resulting in the following formulas

$f_{is,cube} = \frac{2.5 f_\lambda}{1.5 + 1/\lambda}$ (1) or $f_{is,cube} = \frac{2.3 f_\lambda}{1.5 + 1/\lambda}$ (2) respectively where $f_{is,cube}$ is the estimated in situ cube strength, f_λ is the compressive strength of the core with a $\lambda = l/d$ ratio. It is interesting to note that in this case for $\lambda = 1$ the estimated in situ cube strength $f_{is,cube}$ is equal to f_λ. Following the Concrete Society the 'potential' strength (f_{pot}) of a properly cured cube standard specimen is however 30% higher than the actual in situ cube strength, the recommended formulas will change therefore as follows:

$f_{pot,cube} = \frac{3.25 f_\lambda}{1.5 + 1/\lambda}$ (3) or $f_{pot,cube} = \frac{3.0 f_\lambda}{1.5 + 1/\lambda}$ (4) for horizontally or vertically drilled cores respectively.

In the European standard prEN 13791:2003 correction factor for standard (potential) strength to in situ (actual) strength is fixed to 0.85, testing cores with equal length and nominal diameter from 100 up to 150 mm are considered to give a strength values equivalent to the strength value of a 150 mm cube manufactured and cured under the same conditions. Testing cores with a nominal diameter at least 100 mm and not larger than 150 mm with a length to diameter equal to 2 are considered to give a strength value equivalent to the strength value of a 150x300 cylinder manufactured under the same conditions. A two step method for converting a concrete core compression test result to the in situ strength of the corresponding volume of concrete core and a survey of the different correction factors available on literature is reported by Barlett & MacGregor [1997].

2.2 Rebound hammer

The test is described in ASTM C805 and EN 12504-2:2001 and is classified as a hardness test. The simplicity and speed of the test contrast with several drawbacks which can lead to misleading or useless results. The results of rebound hammer are significantly influenced by several factors [Malothra & Carino, 1991; Bungey & Millard, 1996] such as: smoothness of test surface; size, shape, and rigidity of the specimens; age of the specimen; surface and internal moisture conditions of the concrete; type of coarse aggregate; type of cement; type of mould; carbonation of concrete surface. The influences of the above mentioned factors are so great that it is very unlikely that a general calibration curve relating rebound hammer to strength, as provided by the equipment manufacturers, will be of any practical values.

A calibration curve for each concrete under testing have to be performed, taking into account the specimen condition, as well as a frequent check on a standard steel mass to verify spring performance or friction problem between the impacting mass and the plunger. EN 12504-2 standard recommends that calibration have to be performed on samples properly clamped between the plate of a testing equipment under a compressive load of about 15% of concrete strength and in any case higher than 7 N/mm^2. According to prEN 13791:2003 standard rebound hammer test with calibration by means of cores test may be used for assessment of in situ strength. In situ strength can be estimated using a basic relationship and a determined factor for shifting the basic relationship curve to take into account of the specific concrete and production procedure. Calibration for a specific area of the concrete structure under evaluation have to be performed on a region large enough for at least 9 test location for rebound test and for taking out cores to be tested for in situ compressive strength (f_{is}).

2.3 Ultrasound pulse velocity

The velocity of sound in a solid material is a square root function of its dynamic modulus of elasticity and its density. Compressive P wave propagation is characterized by the following expression:

$$V_p = \sqrt{\frac{E_d}{\rho} \frac{1-\nu_d}{(1+\nu_d)(1-2\nu_d)}} \qquad (5)$$

where E_d is the dynamic modulus of elasticity, ρ is the mass density, ν_d is the dynamic Poisson's ratio. Knowing the modulus of elasticity of the concrete, other mechanical properties can be estimated from empirical correlation with it, that is the basic idea of the ultrasound pulse velocity (UPV) test. The methods is based on the determination of the time required for a pulse of vibration at an ultrasonic velocity and generated by a transducer on the concrete surface to travel through the concrete. Since wavelength (λ), which is related to sound velocity by the relationship $\lambda = V_p / \phi$ has a great influence on wave scattering and attenuation in a very heterogeneous medium such as concrete, a great importance have to be done to the choice of ultrasound frequency (ϕ) used. Transducers with natural frequency between 20 kHz and 150 kHz are the most suitable for use with concrete. The test is described in ASTM C597, BS 1881-203:1986 and EN 12504-4:2004, a critical comparison of several standards from different countries is given in a review paper by Komlos *et al.* [1996] who showed that, despite the common basis of the measurement of ultrasonic longitudinal wave velocity, there are differences among the procedures as recommended by different nations, furthermore the inherent uncertainty in the various assessments is so high that, according to him, the assessments are not suitable for many practical purposes. The UPV in concrete is in fact influenced by many variables [Lin *et al.*, 2003, Malothra & Carino, 1991] including mixture proportion, aggregate type and size, age of concrete, moisture content, etc.., furthermore some factors significantly affecting UPV might have little influence on concrete strength as well as, for a constant w/c ratio, the aggregate content. The most simple and generally accepted relationship between concrete strength and ultrasound velocity has the following form [Bungey & Millard, 1996]:

$$f_c = Ae^{BV} \quad (6)$$

where A and B are constants, f_c is the concrete cube strength and V the ultrasound velocity. A proper calibration of the basic curve on the concrete under evaluation have to be done in order to use UPV method for concrete strength assessment. According to prEN 13791:2003 UPV method with calibration by means of cores test may be used for assessment of in situ strength. In situ strength can be estimated using a basic relationship and a determined factor for shifting the basic relationship curve to take into account of the specific concrete and production procedure. Calibration for a specific area of the concrete structure under evaluation have to be performed on a region large enough for at least 9 test location and for taking out cores to be tested for in situ compressive strength (f_{is}).

2.4 Combined method

The reduction of the influence of several factors affecting rebound hammer test and UPV method could be partially achieved by using both methods together. A classical example of this application is the SONREB method, developed mostly by the effort of RILEM Technical Committees 7 NDT and 43 CND [RILEM, 1994] and widely adopted in Romania [Facaoaru, 1970]. The relationship between UPV, rebound hammer and concrete compressive strength are there given in the form of a nomogram. The improvement of the accuracy of the strength prediction according to Facaoaru [1970] is achieved by the use of correction factors taking into account the influence of cement type, cement content, petrologic aggregate type, fine aggregate fraction, aggregate maximum size. The accuracy of the

estimated strength is considered however to range between 10 and 14 % for a concrete of known strength and between 15 and 20 % when only composition is known.
Several liner and nonlinear multiple correlation equations have been developed and available in literature [Tanigawa *et al.*, 1984; Malothra & Carino, 1991; Qasrawi, 2000; Arioglu *et al.*, 2001]. When non linearity of rebound number R and pulse velocity V is taken into account in the form of a power product (i.e. $f_c = AR^B V^c$ (7) , where A, B and C are constants) the best prediction could be obtained [Arioglu *et al.*, 2001].

3 EXPERIMENTAL

3.1 Materials

Intentionally different concrete samples (cylindrical cores and standard cubes) with different compressive strengths were used for this experimentation. Cores were drilled from the wall of a road tunnel: 39 cores with a nominal diameter of 150 mm (21 cores with a length to diameter ratio of 2 and 18 cores with a length to diameter ratio of 1), 11 micro cores with a length to diameter ratio of 2. Concrete mixture was unknown, aggregate was obtained from scistous rocks, that are generally very laminated and under concrete compression test failed usually along flaking planes. Design concrete strength class was C25, and maximum aggregate size was 20 mm.
Standard cubes were control samples from a precasting factory. Cubes (150 mm side) were cured in water a tested at the age of 28 days. Portland cement type I 52.5 R (in accordance to EN 197/1) and basaltic aggregate with a maximum size of 19 mm was used for concrete mixture. Different cement content allowed to obtain concretes of different strength class, more specifically 17 cube of C55 strength class, 17 cubes of C45 strength class and 5 cubes of C 30 strength class were used for this experimentation. All samples type are summarized in Table 1.
Cores were reduced to standard sizes (l/d=1 or 2) by diamond saw, to reduce the influence of capping all cores load bearing surfaces were diamond ground up to obtain a surface planarity error lower than 20 µm (EN 12390-1: 2002 requires a planarity error lower than 60 µm) . In order to reduce the influence of unknown water content in the concrete, cores were water saturated by dipping into a controlled temperature bath (20 ± 5° C) until constant weight according to EN 12390-7. All samples, cubes included, were tested in saturated surface-dry condition. Concrete mass density was determined according to EN 12390-7.

Sample type	*Sample name*	*Number of specimens*	*Specimen dimension (mm)*	*Cement type*	*Aggregate type*	*Strength class (cubic)*
Cylinder 1:1	C1:1	18	150x150	Unknown	Scistous rock	C25
Cylinder 2:1	C2:1	21	150x300	Unknown	Scistous rock	C25
Cylinder 2:1	MC	11	50x100	Unknown	Scistous rock	C25
Cube	Ku55	17	150x150	Portland I 52.5 R	Basaltic rock	C55
Cube	Ku45	17	150x150	Portland I 52.5 R	Basaltic rock	C45
Cube	Ku30	5	150x150	Portland I 52.5 R	Basaltic rock	C30

Table 1. Summary of the sample used for the experimentation

3.2 Methods

Compression tests have been carried out by means of a 3000kN hydraulic press, precision class 1, with a load rate of 0.5 N·s/mm^2 according to EN 12390-3. In order to evaluate the influence of steel loading plate on concrete lateral expansion restrain, 6 specimens Ku55 and 6 specimens Ku45 have been tested by inserting between plates and concrete surfaces a 4 mm tetrafluoroethylene foil.
Ultrasonic Pulse Velocity test has been carried out on concrete specimens soon after their extraction from a thermostatic bath in a saturated surface-dry condition, using a vertical direct transmission

configuration with 52 kHz transducers. In order to improve transducer to concrete surface contact vaseline grease was used. Tests have been performed according to BS 1881-203:1986.
In order to reduce and to control surface water content specimens, before being tested at the rebound hammer test, have been stored in a thermostatic room at 20 ± 5° C and 90% R.U. Tests have been performed by means of both an analogical and a digital N type rebound hammer. According to EN 12504-2 standard a regular check on a standardized steel anvil have been performed, during testing concrete samples were properly clamped between the plates of a testing equipment under a compressive load of about 15% of their compressive strength. Determinations have been carried out on 12 point, 6 for each of two opposite faces. The mean values of the determination was the rebound number reported in the results.

4 RESULTS AND DISCUSSION

Potential compressive strength of concrete can be directly obtained by testing cubic standard specimens, by using cylindrical cores different correction factors as previously described have to be used. Correction factors related to length to diameter ratio (2 in our cases) and correction factors related to different curing condition of concrete. Mean compressive strength and standard deviation for C1:1 and C2:1 samples were $f_{\lambda 1:1}$= 20.14 MPa, $\sigma_{\lambda 1:1}$=5.81 MPa and $f_{\lambda 2:1}$= 17.42 MPa, $\sigma_{\lambda 2:1}$= 4.35 MPa respectively. The ratio between $f_{\lambda 2:1}$ and $f_{\lambda 1:1}$ was considered as the geometrical correction factor indicated in different standards. In our case such factor was equal to 0.86, that is lower than that one indicated by ASTMC42-90. The actual cubic compressive strength was calculated by means of equation (1) for C1:1 and C2:1 samples, considering a coring direction perpendicular to concrete casting direction, obtaining the following mean values: $f_{is,cube,1:1}$ = 20.14 MPa and $f_{is,cube,2:1}$ = 21.77 MPa respectively. Also potential compressive strength values was calculated in a similar manner by means of equation (3): $f_{pot,cube,1:1}$ = 26.18 MPa and $f_{pot,cube,2:1}$ = 28,30 MPa. For cubic specimens compressive strength f_c was considered of course equivalent to actual strength and to potential strength. If it is taken into concern that restrain effect during compressive tests have a great influence on the result, it could be possible to consider, as mentioned above, that results obtained by testing a concrete cylinder with a length to diameter ratio equal to 2 should be considered as the "true" (under pure uniaxial compression condition) concrete strength. So it was calculated the "true" compressive strength for 1:1 length to diameter ratio cores by multiplying f_y for the above mentioned coefficient 0.86. According to this concept it was also assumed that cubic specimen tested with tetrafluoroethylene foils could give the "true" concrete strength for a cubic geometry (columnar cracks morphology on tested samples supported this assumption). The so defined ratio between true and potential strength was however evaluated to be sensitive to strength class: i.e. 0.65 for C55 concrete and 0.72 for C45 concrete. Non linear regression models based on power products were used to correlated strength concrete to UVP and rebound hammer number (RHN), in order to optimize correlation the variables mass density (MD) and class strength (CS) were also used. Regression models had the general form $y = a + bx_1^c \cdot x_2^d \cdot x_3^e \cdot x_4^f$ where y was the concrete strength (true or potential) and $x_1, x_2, x_3, x_4,$ the quantitative variables UPV, RHN, MD and CS, when present, and a, b, c, d, e, f the model parameters.
Results are summarized in Table 2. The correlation between true or potential compressive strength and UPV was quite poor, with a determination coefficient (R^2) below 0.5 in both cases, the sum of square residuals (SSR) was double for potential compressive strength than for true compressive strength. By taking into account the mass density no improvement of the regression model was observed (a reduction of the R^2 was instead observed). A good result was on the other side obtained by taking into account the concrete class strength (a parameter however frequently unknown) obtaining an R^2 values of 0.97. In this case a sensible increase of the sum of square residuals was observed when potential compressive strength was considered than the true one. An almost negligible improvement of the regression model was achieved including in both cases the mass density variable. Rebound hammer numbers showed a better correlation with concrete strength resulting in a determination coefficient as high as than 0.8. Once again mass density variables had no influence. A very good value for the determination coefficient was obtained taking into account the concrete strength class (R^2= 0.95, SSR=

1040.9). The best regression models were obtained by considering, like SONREB method, both UPV and RHN (R^2= 0.86, SSR= 2946.2) optimized with inclusion of concrete strength class variables (R^2= 0.97, SSR= 635.0). Once again correlation with potential concrete strength was characterized by a worse regression model (R^2= 0.81, SSR= 8424.3 and R^2= 0.94, SSR= 2518.6 for models not including and including class strength variables respectively).

Dependent variables (compressive strength)		Quantitative variables				Model parameters						R^2	Sum of square residuals
True	*Potential*	*UPV*	*RHN*	*MD*	*CL*	*a*	*b*	*c*	*d*	*e*	*f*		
X		X				-224.27	1.67	0.62				0.46	11626.8
	X	X				-703.31	62.05	0.30				0.47	24267.1
X		X		X		-75.82	0.00	1.81	-0.43			0.41	12748.9
	X	X		X		92.48	-770.07	-2.82	2.61			0.17	37947.0
X		X			X	-194.23	13.45	0.20	0.21			0.97	749.7
	X	X			X	-240.15	9.22	0.26	0.23			0.96	1768.8
X		X		X	X	-74.51	0.00	0.34	0.67	0.39		0.97	737.9
	X	X		X	X	-141.15	0.64	0.40	0.06	0.34		0.96	1687.0
X			X			-54.72	1.87					0.82	3809.5
	X		X			-77.12	2.70					0.80	8949.5
X			X	X		-23.96	61.14	1.68	-0.84			0.81	4080.7
X			X	X	X	-52.03	2.74	0.27	-0.06	0.49		0.95	1040.9
X		X	X			-76.30	0.17	0.46	0.70			0.86	2946.2
X		X	X	X		-103.41	0.61	0.42	0.54	-0.01		0.86	3022.6
X		X	X	X	X	-59.50	0.39	0.50	0.22	-0.24	0.41	0.97	635.3
X		X	X		X	-61.14	0.04	0.58	0.13	0.41		0.97	635.0
	X	X	X			933.84	-3197.52	-0.11	-0.11			0.81	8424.3
	X	X	X		X	-36.65	1.47	0.07	0.19	0.78		0.94	2518.6

Table 3. Results of nonlinear regression analysis

The use of NDT for on site evaluation of concrete strength have to be considered very carefully. Also the evaluation on laboratory condition on properly controlled specimens gave not very good results especially when UPV method was used. A good improvement of the correlation between NDT result and concrete strength can be obtained taking into consideration a preliminary knowledge of concrete properties, e.g. class strength or concrete mix design. Unfortunately during on site inspection a limited knowledge of the materials used for the structures is in most cases available. A calibration of the NDT method chosen with compressive tests on cores taken from the structure is therefore imperative. When that is economically possible a great care have to be taken in evaluating compressive concrete strength. Results obtained by NDT methods are strongly dependent on the physical properties and condition of the concrete whilst "potential" compressive strength as evaluated in accordance to standards is no more than a conventional notion adopted for purpose of evaluation and it is quite hard to define an intrinsic, "true", concrete strength that is on the other side more directly correlated with the physical properties of the concrete itself. Results obtained in this experimentation seem to confirm such consideration.

5 CONCLUSION

A laboratory testing program was undertaken to evaluate the reliability of UPV and rebound hammer tests for evaluation of compressive strength of concrete. A nonlinear regression model based on power products was used to correlate experimental results. A poor correlation between UPV and concrete strength was evidenced notwithstanding the well controlled laboratory conditions. Better results was obtained for rebound hammer test. It was evidenced that a preliminary knowledge of concrete characteristics it is of great importance to optimize regression model. The influence of the definition of concrete strength was also evaluated: the use of the "true" concrete strength, considered as the value determined under non restrained condition testing, resulted in a better regression model than when considering the potential compressive strength as defined in the standards.

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