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Ultrasonic Pulse Velocity Test of Concrete Properties as Specified in Various Standards

K. Komloš,[a] S. Popovics,[b] T. Nürnbergerová,[a] B. Babál[a] & J. S. Popovics[c]

[a]Institute of Construction and Architecture, Slovak Academy of Sciences, Bratislava, Slovak Republic
[b]Department of Civil and Architectural Engineering, Drexel University, Philadelphia, PA, USA
[c]Center QEPF, Northwestern University, Evanston, IL, USA

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Abstract

This is a review paper comparing critically eight standards. Methods for the determination of longitudinal pulse velocity and assessment of concrete properties by ultrasonic pulse velocity, as recommended by standards of the UK, USA, Germany, Russia, Slovakia, Hungary, and RILEM, are evaluated. It is shown that, despite the common basis of the measurement of ultrasonic longitudinal wave velocity, there are differences among the procedures as recommended by different nations. For instance, the most frequent use of pulse velocity, the assessment of concrete strength, is discussed only briefly in ASTM and in DIN; the other standards, especially the Russian and the Slovak standards, provide much more detail and description. The assessments of other concrete properties are also compared: dynamic elastic constants, defects inside concrete, concrete uniformity, and changes in concrete properties with time. The inherent uncertainty in the various assessments is so high that the assessments are not suitable for many practical purposes. The common weakness of the analyzed standards is that they do not warn the user strongly enough about the uncertainties. For instance, the assessment procedures could be rated according to their reliability. © 1996 Elsevier Science Limited.

INTRODUCTION

The method based on longitudinal wave pulse velocity determination is popular for nondestructive testing of concrete because of its simplicity and cost effectiveness. Most nations have standardized procedures for the performance of this test. A partial listing of standardized methods is given in Table 1. The test is often used for the task of nondestructive estimation of the strength of concrete, but other NDE tasks are also performed. However, the reliability of these test results may be doubtful. Since these methods are described or mentioned in many standards, they are reviewed and critically compared in this paper.

The following eight standards are analyzed in this paper:

BS 1881: Part 203: 1986 'Testing Concrete-Recommendations for measurement of velocity of ultrasonic pulses in concrete'.

ASTM C 597-83 (91) 'Standard Test Method for Pulse Velocity Through Concrete'.

RILEM/NDT 1 1972 'Testing of Concrete by the Ultrasonic Pulse Method'.

DIN/ISO 8047 (Entwurf) 'Hardened Concrete-Determination of Ultrasonic Pulse Velocity' (in German).

'Testing of Concrete-Recommendations and Commentary' by N. Burke in Deutscher Ausschuss fur Stahlbeton (DAfStb), Heft 422, 1991, as a supplement to DIN/ISO 1048 (in German).

GOST 17624-87 'Concrete-Ultrasonic method for strength determination' (in Russian).

STN 73 1371 'Method for ultrasonic pulse testing of concrete' (in Slovak) (Identical with Czech CSN 73 1371).

MI 07-3318-94 'Testing of concrete pavements and concrete structures by rebound hammer and by ultrasound' technical guidelines (in Hungarian).

Table 1. Standards for the determination of longitudinal ultrasonic pulse velocity in concrete[1]

Country	*Designation*	*Year*
Belgium	NBN 15-229	1976
Brazil	ABNT 18:04.08.001	1983
Bulgaria	BDS 15013-80	1980
Czech Republic	CSN 731371	1981
DDR	TGL 33437/02	1983
Denmark	DS 423.33	1984
Germany	Draft. Same as ISO/DIS 8047	1983
Hungary	MI 07-3318	1994
International	ISO/DIS 8047	1983
Mexico	NOM-C-275-1986	1986
Poland	PN-B-06261	1974
RILEM	NDT 1	1972
Rumania	C-26-72	1972
Russia	GOST 17624	1987
Scandinavia	NT BUILD 213	1984
Spain	UNE 83-308-86	1986
Sweden	SS 137240	1983
United Kingdom	BS 1881: Part 203	1986
USA	ASTM C 597	1983
Venezuela	COVENIN 1681-80	1980
Yugoslavia	JUS U.M1.042	1982

The comparison and analysis of the standards are followed by a critical evaluation. The evaluation is necessarily subjective; nevertheless, it is hoped that it will help improve the use of the ultrasonic pulse velocity method and contribute to the improvement of future specifications.

REVIEW OF THE METHOD

The pulse velocity determination specified in all standards is based on the same principle. Pulses of longitudinal, elastic stress waves are generated by an electro-acoustical transducer that is held in direct contact with the surface of the concrete under test. After traversing through the concrete, the pulses are received and converted into electrical energy by a second transducer. Most standards describe three possible arrangements for the transducers:

The transducers are located directly opposite each other (direct transmission).

The transducers are located diagonally to each other; that is, the transducers are across corners (diagonal transmission).

The transducers are attached to the same surface and separated by a known distance (indirect transmission).

Direct transmission is the most sensitive, and indirect transmission the least sensitive. The velocity, v, is calculated from the distance, l, between the two transducers and the electronically measured transit time, t, of the pulse as $v = l/t$.

This common principle is expressed in somewhat different ways among the standards of various nations. There are also differences in how the standards discuss the factors that affect pulse velocity in concrete, such as reinforcement, temperature, humidity, size and shape of the specimen, etc. These differences have been discussed in a previous paper.[2]

SPECIFICATIONS FOR STRENGTH ASSESSMENT

The most common application of pulse velocity measurement is the assessment of concrete strength. This is usually done with the help of a calibration (or correlation) curve, or a formula representing the curve, for a given concrete.

According to the *British standard*, at least three cube specimens from each batch should be taken in the case of molded specimens for the purpose of generating a calibration curve. The pulse velocity should be measured across the cube between the molded faces in direct transmission mode. For each specimen, there should be at least three measurements spaced between the top and bottom. The variation between the measured transit times of single test specimens should be within $\pm 5\%$ of the mean value of the three measurements. The mean pulse velocity and mean strength obtained from each set of three nominally identical test specimens provide the data to construct the calibration curve. A curve produced in this way relates only to concretes of identical composition, which are produced, cured, and tested in a similar way.

For the case of generating a calibration curve from cored specimens, zones of different material quality should be located within the structure where the cores should be taken.

The procedure recommended by the *RILEM specification* is similar to the British Standard.

The *ASTM standard* does not contain a detailed procedure for strength assessment. Nevertheless, it gives warning that the 'results obtained by the use of this test method should not be considered as a means of measuring strength'.

The *DIN/ISO standard* also does not contain any procedure for the assessment of concrete strength from pulse velocity measurement. Rather, it is given in the *DafStb Recommendations*. This states that the concrete strength can be assessed within a structure if a calibration curve is experimentally established from samples taken from the structure. Specifically, zones of low, medium, and high pulse velocities should be established within the structure. In these zones, locations should be selected where transit time measurements may be performed. Three to five individual transit time measurements should be carried out in each location. Cores should then be taken from the same locations and tested to obtain the compressive strength. If the core diameter is 100 mm, at least three cores should be taken from each zone. If the diameter is 50 mm, at least six cores should be taken from each zone. These cylinder strengths should then be converted to cube strengths. The related pulse velocities and compressive strengths can be plotted in a system of coordinates. A *linear* function is recommended for the pulse velocity vs strength relationship. The coefficients of this equation can be determined by standard linear regression. For this, formulae and numerical examples are presented in the Recommendations. An additional formula is presented for the confidence limits of this regression, the low branch of which is the limit below which only a specified percentage of concrete strength results would fall.

According to the *GOST standard*, the relation between the velocity of ultrasonic longitudinal pulses in the concrete and the strength of the concrete can be established for the given concrete either in the form of 'pulse velocity vs strength of concrete' or 'transit time vs strength of concrete'. Standard 200 mm cubes are tested ultrasonically, after which the compressive strength is determined on the same cubes in the standard, destructive manner. The calibration curve is therefore established. Separate relationships should be established for each different concrete class. Fifteen cubes should be tested for each class.

The relationship between pulse velocity and strength may also be applied, through the use of a conversion coefficient, when the structure is tested with the *indirect* transmission mode. At least six prisms, 100 × 100 × 200 mm in size, should be tested to establish the conversion coefficient. The transit times are measured with both direct and indirect transmission modes, and the conversion coefficient is calculated as

$$K = \frac{1}{n} \sum_{i=1}^{n} K_i \qquad (1)$$

where K_i is the value of the conversion coefficient determined from the results of the tests of ith sample:

$$K_i = \frac{v_i}{v_{i\text{sur}}} \qquad (2)$$

where v_i and $v_{i\text{sur}}$ are mean values of the pulse velocities in the ith sample with direct and indirect transmissions, respectively. The strength of concrete within a structure may then be estimated using the indirect transmission mode from the correlated pulse velocity–strength relationship; the related pulse velocity is

$$v = K \frac{l}{t_{\text{sur}}} \qquad (3)$$

where t_{sur} = the transit time with indirect transmission, μs l = the path length in mm. The mathematical form recommended by GOST for regression of the strength vs pulse velocity relationship is either linear or exponential. The linear form is recommended when the strength range is narrow:

$$R_c = a_0 + a_1 v \qquad (4)$$

when $R_{max} - R_{min} < 2R_{ave}(60 - R_{ave})/100$. For wider strength range, an exponential function is recommended, as follows:

$$R_c = b_0 e^{b_1 v} \quad (5)$$

where

R_c = the mean value of compressive strength of tested samples, MPa
R_{max} and R_{min} = maximum and minimum values, respectively, of compressive strength of tested samples, MPa
v = longitudinal pulse velocity
a_0, a_1, b_0 and b_1 = regression coefficients
e = base of natural logarithm

The Russian standard also presents standard regression formulae for the determination of parameters a and b in eqns (4) and (5) along with numerical examples.

The *Slovak standard* proposes several categories for the development of the strength vs pulse velocity relationship:

(i) Specific, narrow correlations may be developed that are valid within the range of one concrete class. To construct this relationship, at least three or four points are needed. Each of these points should represent the mean value from tests six specimens.

(ii) Broad correlations may also be developed which cover the range of two or more concrete classes. Five or six points are needed for each class. Each point should represent at least six specimens.

(iii) Universal relationships may also be used which cover many concrete classes having different concrete qualities. At least 50 specimens should be tested for each concrete class. The recommended method of characterization of this relationship is with the coefficient α (eqn (6)).

(iv) Finally, guided relationships for concrete classes, which are relevant to the structure in question, may be used. At least 25 specimens should be tested for each class. Here again the coefficient α is recommended for characterization.

To determine the coefficient α for the last two categories, it is necessary to obtain

(i) either at least nine specimens from the same concrete cured in the same way as the concrete in the investigated structure, or

(ii) cores taken from the structure. Specifically,

at least three cores for a concrete volume smaller than 10 m^3

at least six cores for a concrete volume smaller than 50 m^3

at least nine samples for a concrete volume greater than 50 m^3.

The coefficient α is then obtained from the equation

$$\alpha = \frac{\sum_{i=1}^{n} R_{ci}}{\sum_{i=1}^{n} R_{cei}} \quad (6)$$

where

R_{ci} = the strength of concrete determined by the destructive test of the sample
R_{cei} = the compressive strength assessed on the sample by the ultrasonic method, and
n = the number of tested samples.

The transit time must be measured at least at three locations, at different heights on the sides of the cube. The fluctuation of the pulse velocities should not be greater than 5% of the average value of the tested cube.

In addition to the linear and exponential functions mentioned in eqns (4) and (5), the following regression equations are recommended by the STN and the RILEM standards:

$$R_c = a_0 + a_1 v + a_2 v^2 \quad (7)$$

and

$$R_c = b_0 v_1^b \quad (8)$$

where the symbols are the same as in eqns (4) and (5).

The Slovak standard also states that calibration curves for other types of strength (prism strength, flexural strength, splitting tensile strength, and direct tensile strength) can be established in a similar way.

The *Hungarian specification* is the only one that provides formulae with specific numerical coefficients for the calculation of strength. The method of calculation depends on which concrete characteristics are measured:

(i) pulse velocity alone,

(ii) pulse velocity and other characteristics of concrete including cement type, maximum particle size of aggregate, aggregate grading, water–cement ratio, cement content; extent of compaction, curing conditions, and moisture content,

(iii) pulse velocity and additional strength tests on cores or molded specimens. For instance, the formula for case (ii) is

$$\log R_{200} = 2.407 - (6.8 - \Sigma\Delta)10^{-4}(5760 - v) \quad (9)$$

where

R_{200} = calculated strength of concrete for 200 mm cube, MPa
v = effective pulse velocity, m/s
$\Sigma\Delta$ = sum of modifying parameters that depend on the characteristics of the concrete.

Numerical values are also given in the specification for the Δ values. For instance, $\Delta = 0$ when the maximum particle size is 32 mm, and 0.5 when it is 16 mm. As another example, $\Delta = 0$ when the cement content is 200 kg/m^3, and 0.3 when it is 400 kg/m^3.

For case (iii), the term $(6.8 - \Sigma\Delta)$ is substituted by a coefficient calculated by linear regression from the supplementary strength results.

SPECIFICATIONS FOR ASSESSMENT OF CONCRETE PROPERTIES OTHER THAN STRENGTH

Uniformity of concrete

For the determination of concrete uniformity, the British and RILEM standards recommend the use of a grid of measuring points which uniformly covers the appropriate volume of concrete. The number of individual test points depends upon the size of the structure, the accuracy required, and the material variability of the concrete. The non-uniformity is indicated by the variation of the pulse velocities obtained from different points.

It is possible to express the material homogeneity numerically through the use of a statistical parameter, such as the standard deviation or the coefficient of variation of the pulse velocity measurements. In the cases where the path length is the same throughout the survey, the measured transit time may be used to assess the concrete uniformity without the need for conversion to velocity.

Detection of defects

Defect detection is based on the observation that voids, flaws, etc. increase the transit time of the ultrasonic pulses. According to the British standard, only trained and experienced personnel may perform such measurements and interpret the results. Even so, only a defect greater in size than about 100 mm is detectable with longitudinal ultrasonic pulses. Cracks are practically undetectable, especially if they are filled with fluid. Pulse attenuation measurements may give more information, but the description of this test is not given. Additional description is given in the British Standard about the following items:

Detection of large voids or cavities.

Estimation of the depth of a surface crack.

Estimation of the thickness of a layer of inferior quality.

The RILEM specification discusses the same items, but several of the formulae differ from the British formulae.

Determination of changes in concrete properties with time

The British standard recommends that changes in the properties of concrete which occur in time be determined by repeated measurements of pulse velocity at different ages with the same transducers in the same position. The pertinent RILEM specification is very much the same, except RILEM prefers the flexural resonance vibration test for laboratory investigations.

Determination of the dynamic elastic constants

The BS, RILEM, and STN standards provide the following equation for the calculations of the dynamic modulus of elasticity:

$$E_d = \rho v^2 \frac{(1+\mu_{cu})(1-2\mu_{cu})}{1-\mu_{cu}} \quad (10)$$

where

E_d = dynamic modulus of elasticity, MN/m^2
ρ = density, kg/m^3
μ_{cu} = dynamic Poisson's ratio
v = longitudinal pulse velocity, km/s.

For laboratory specimens, the ratio E_d/ρ may be obtained from the results of a longitudinal resonance test, as

$$\frac{E_d}{\rho} = 4n^2l^2 10^{-6} \qquad (11)$$

where

n = resonant frequency, Hz
l = length of test specimen, m.

The STN standard also presents a formula for the calculation of the dynamic shear modulus G_{cu}:

$$G_{cu} = \rho v_t^2 10^{-6} \qquad (12)$$

where v_t = velocity of the transversal vibration in m/s.

The dynamic Poisson's ratio μ_{cu} can also be calculated from eqn (10) if the values of E_d and μ are known. Additionally, the STN standard presents other pertinent formulae:

$$\mu_{cu} = 0.5\left(\frac{E_d}{G_{cu}} - 2\right) \qquad (13)$$

or

$$\mu_{cu} = 0.5\left(\frac{v_L^2}{v_t^2 k^2} - 2\right) \qquad (14)$$

where

$$k^2 = \frac{1-\mu_{cu}}{(1+\mu_{cu})(1-2\mu_{cu})}$$

The other symbols are the same as before.

COMPARISON OF SPECIFICATIONS

Most of the examined ultrasonic standards were issued about ten years ago or earlier. This may indicate a lack of progress in ultrasonic testing of concrete.

The BS and RILEM standards closely resemble each other, although the British standard is longer. This extra length is due to numerous formulas and tables, and detailed explanation. The STN and GOST standards also resemble each other. The reasons for these similarities are probably geographic and/or political. The Hungarian specification of 1994, for instance, no longer shows any dependence upon the Russian specifications.

The ASTM standard does not provide detail about strength assessment or other applications. Other standards describe the calculation of concrete strength from pulse velocity and the assessments of other concrete properties, such as elastic constants, defect detection, and determination of concrete uniformity.

OBJECTS TO EXISTING STANDARDS

Several standards use the term 'measurement' of pulse velocity, or an equivalent to it. This is not exactly correct because only the transit time and the distance between the two transducers are *measured* directly. The pulse velocity is *calculated* from these two direct measurements. However, this misnomer does not cause much confusion.

There is no *theoretical* relationship between the strength of a material and the pulse velocity. Thus, it is not objectionable that only empirical, fitted calibration curves are available for concrete for this purpose. It is objectionable, however, how loosely some of the theoretical formulae, offered for other applications, are treated in several of the standards. For instance, the formulae for the calculations of the elastic constants from pulse velocity are theoretically sound. However, these formulae were derived for linearly elastic, homogeneous materials; concrete is neither linearly elastic nor homogeneous. Therefore, the application of these formulae is not necessarily valid for concrete. Several standards recognize this shortcoming; for instance, it is pointed out both in ASTM and BS that the E value obtained by eqn (10) should not be used for establishing compliance of the modulus of elasticity of field concrete with that assumed in design. The use of eqn (13) is also doubtful for the same reason. Also, a combination of values obtained by the resonance frequency method, such as eqn (11), with values obtained by pulse velocity measurement is not a good practice.

The writers feel that striving for linearity of the formulae for the sake of simplicity has lost its significance. With the advancement of computers the use of any nonlinear formula, with its wider limits of validity, is as simple as that of a linear formula.

From an engineering point of view, a more serious objection against the analyzed standards is the lack of adequate warning concerning the pitfalls of the assessment of concrete properties from longitudinal pulse velocity. Most standards list a handful of potential applications of this ultrasonic test, frequently through the use of formulae. Although it is implied in several of them that the results of the applications are doubtful, none of the standards rate these applications according to their reliability. This is unfortunate because the impression is given that the pulse velocity test is equally suitable for all these applications, which is not the case.[3,4] In fact, the best, and perhaps the only reliable applications of the longitudinal pulse velocity test are for checking the uniformity of concrete without reinforcement, and monitoring the changes in a concrete over time. Strength estimation is possible only within a $\pm 20\%$ accuracy, and even this level of accuracy can be achieved only under strict laboratory conditions with an established calibration curve. This unsatisfactory performance is not improved with supplementation of the pulse velocity test with other tests, such as the rebound hammer test.[5] The other applications of pulse velocity (defect detection, crack depth measurement, etc.) are even less reliable.

The present state of ultrasonic concrete testing clearly needs improvement. The first step in this direction may be to present a warning in the standards about the uncertainties of the assessments based on the presently used longitudinal pulse velocity method. Further improvement should come from a better understanding of the theory of ultrasonic pulse propagation in concrete. This may lead to the utilization of surface and other guided waves, wave features other than the velocity, and advanced signal processing techniques.[6,7] Unfortunately, these writers do not know of any standards dealing with such tests for concrete. A possible exception may be the future edition of EN-ISO 8047 where, reportedly, annexes are planned on 'Factors affecting pulse velocity measurements' and 'correlation of pulse velocity and strength'.

CONCLUSIONS

Seven out of the eight specifications analyzed provide more detail about the applications of pulse velocity for testing concrete than ASTM. In a sense, the lack of the applications in ASTM is acceptable since it has been established that the accuracy of many of the applications for testing concrete, including strength assessment and defect detection, is unacceptably low. Therefore, it is recommended that future standards rate the reliability of the applications of the longitudinal pulse velocity for the users.

Based on the presented analysis, an example for such rating, admittedly subjective, is the following:

The most reliable application of longitudinal pulse velocity in concrete testing is monitoring changes in the concrete over time.

Checking the uniformity of a concrete mass can also be done with acceptable reliability, although here the presence of reinforcement can cause uncertainties.

Strength estimation is a distant third in the rating even when a good calibration curve is available. Without such curve the estimation becomes guesswork.

The determination of the elastic constants of a concrete from longitudinal pulse velocity is not as reliable as that for homogeneous elastic materials. More importantly, these 'dynamic' constants are not applicable directly for engineering purposes.

Defect detection with longitudinal pulse velocity is the least attractive. It is easy to produce misleading results with it with dangerous and expensive consequences.

Ultrasonic testing of concrete needs improvement. This improvement could come from the use of surface and other guided waves, features other than longitudinal pulse velocity, advanced signal processing techniques, etc., and related standardization.

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