RELIABILITY OF NONDESTRUCTIVE CONCRETE TESTS*

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Nondestructive concrete tests are aimed at determining mechanical characteristics, in particular, strength of concrete by tests on erected structures without the least impairment of their intended use.

Nondestructive methods indicate the response of concrete to certain physical effects, throwing light to concrete properties other than in tests to failure.

Results of nondestructive tests may be directly used for characterizing concretes, but it is better to classify concretes by strength values assessed from empirical relationships between mechanical and physical characteristics. It is conventional to apply a direct empirical relationship between ultimate strength and nondestructive characteristics. Results of either destructive or nondestructive tests being differently affected by several factors, these latter are only stochastically related to ultimate strength values.

This fact imposes evaluation of the reliability of nondestructive methods or of strength assessment, involving, of course, the reliability of tests to failure.

Reliability of nondestructive strength assessment will rely below on the analysis of stochastic relations, involving each of the property systems and their stochastic relation as well as the describing relationship. It will be kept throughout in mind that both kinds of tests aim at assessing a third characteristic, the *building resistance to mechanical effects*, thus, both are indirect tests.

1. Criticism to published strength assessment methods

Significance of nondestructive test methods can be appreciated by the number of sampling spots. A unit in the set is either adequate or it is not, according to some qualification method.

Ratio of inadequate units in the set is the refuse ratio p. Not more than n samples can be taken from the set. The probability that the sample of n units taken from a set of refuse ratio p contains no refuse hence the set

* Abridgment of the Candidate's Thesis by the Author [1]

qualified as satisfactory is expressed by values for $k = 0$ of the function of binomial distribution. Some probability percentages for different refuse ratios and sample numbers are seen in Table 1. The high sample number needed for a reliable strength assessment is practically possible only with nondestructive test methods.

Table 1

Adequate qualification probabilities

(Percentages of binomial distribution $P_k = 0$)

n	p			
	0.001	0.1	0.5	0.9
1	99.9	90	50	10
2	99.8	81	25	1
3	99.7	73	13	
5	99.5	59	3	
10	99	35	10^{-1}	
20	98	12		
50	95.1	$5 \cdot 10^{-1}$		
100	90.5			
1 000	36.8			
10 000	$4.5 \cdot 10^{-3}$			

The evenness of the concrete quality is still often expressed in terms of statistical characteristics of nondestructive test results. Statistical characteristics calculated from different nondestructive tests may lead to contradictory results since nondestructive test results differ by orders of magnitude, resulting in different variational coefficients.

Also characteristics obtained by physical relationships from nondestructive test results are often applied to characterize concretes. Initial conditions of these physical relationships are missing in case of concretes where independent variables have values varying in wide ranges between points. Besides, also the relationships involve empirical constants.

Stochastic relationships are directly plotted by fitting mean curves to points defined by nondestructive characteristics and strength values by means of regression analysis even if its conditions are missing.

In regression analysis, the best fitting function is obtained by trial and error. Thus, course of the function depends on the sampling circumstances, a random event.

Position of empirical curves is affected by factors of concrete technology, differently affecting nondestructive characteristics and strength values. The effects of different concrete technology factor levels are reckoned with in standards by applying multipliers higher or lower than unity on the reference curve of the instrument type in establishing the empirical relationship of the structure. This procedure does not fit all nondestructive test methods.

Individual test results deviate from function values read off the mean curve. Deviations underlie residual standard deviation, reckoned with in nondestructive strength assessment by plotting a threshold curve at the given risk level, in knowledge of the distribution of residual deviations. Strength values are read off this threshold curve. 100% of the results are assessed at a neglect on the safety side, using a threshold curve of low, e.g. 5% probability.

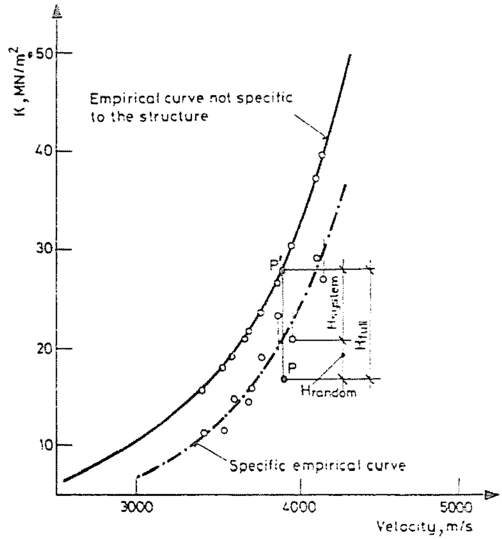

Fig. 1. Interpretation of full, systematic and random error

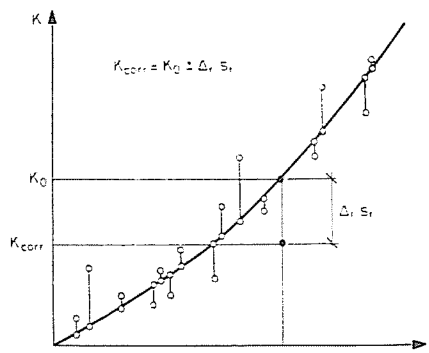

Fig. 2. Reckoning with the real residual deviation

Any measurement is affected by systematic and random errors. In measuring the nondestructive characteristics and the strength values, distinction is made between systematic and random errors.

The former may be eliminated by calibration, and the latter by repeated measurements. In plotting and applying relationship functions, no distinction is made between systematic and random errors. Systematic errors are due to the application of an empirical relationship referring to other than the tested structure. Neither the random errors are properly reckoned with by applying one-sided risk.

2. The research method

To evaluate the reliability of nondestructive concrete tests, several test series have been made at the *Department of Building Materials, Technical University, Budapest*, concerned with the effect of influencing factors. As a conclusion, an extended, comprehensive test was made [2].

Effects of interactions, multiple interactions between nine concrete technology factors have been examined in full experimental arrangement. 24 tests cubes have been made from 48 concrete mixes of different dosages each, cured in different ways. Test adjustments numbered 1152.

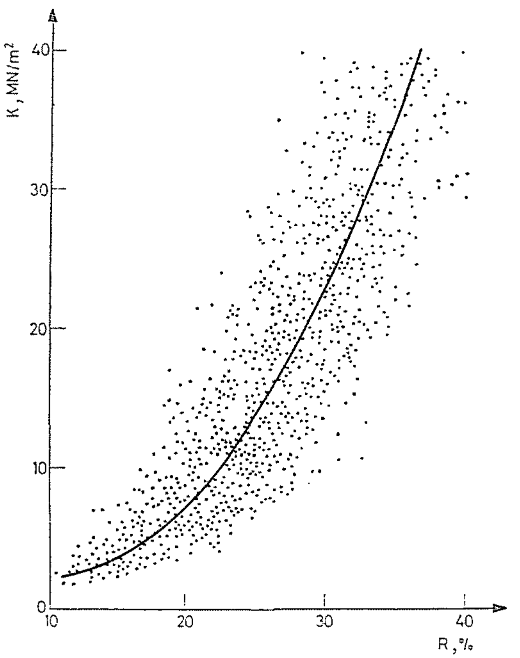

Fig. 3. Curve of strength assessment by the Schmidt hammer method for the complete experiment

Factor analysis of the complete test has led to the construction of ultrasonic and *Schmidt-hammer* strength assessment function fields.

Statistical description of the function field created new bases for the nondestructive strength assessment [3].

3. Recent conclusions, theorems

The outlined conclusions refer to a nondestructive strength assessment method more reliable than the previous ones [4].

Factors influencing the reliability of the existent and the new methods have been submitted to a deep-going analysis.

Theorem 1

Fundamental physical relationships between nondestructive characteristics do not suit concrete quality estimation. Nondestructive strength assessment has to rely on stochastic relationships between ultimate strength and nondestructive characteristics.

Namely:

Initial conditions such as the assumed homogeneous isotropy of concrete are by far not met because of distinct dimensional and mechanical characteris-

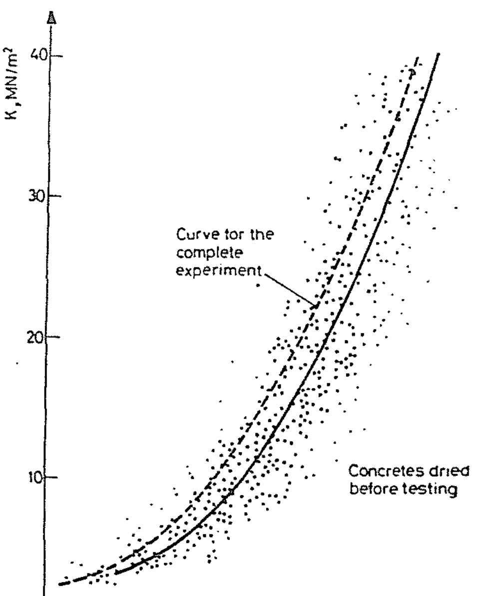

Fig. 4. Strength assessment curve for dry concretes

tics of the components. Variables in physical relationships differ in the concrete for each point, as a rule, and actually are inaccessible to measurement.

Theorem 2

Regression analysis does not suit for expressing stochastic relationships as functions. Reliable functional relationships may be obtained by e.g. the empirical approximation of quantile functions.

Namely:

Regression analysis, a mathematical model considering values of one variable as exact, and of the other as a random variable features neither of the variables in nondestructive strength assessment.

Deviation between the functions obtained by exchanging the variables depends on the test program. The residual deviation varies along the function itself. From the aspect of practical application the regression analysis has the drawback to deliver an empirical curve steeper ascending than the quantile curve, resulting in an increased standard deviation of strength assessment.

The quantile function passes through points defined by equal probability levels of variable distribution functions, minimizing the residual deviation simultaneously with respect to both variables. Its initial conditions are met. No a priori condition needs to be specified in plotting an approximate quantile curve. With increasing number of measurements, the deviation between the theoretical and the approximate quantile curves tends to zero.

Theorem 3

Residual deviations are wrongly referred to the characteristics curve of the instrument type. Namely in this case the deviation has a systematic and a random component, thus, it is not a real residual deviation.

Residual deviation must not be referred to else but a specific empirical function for a structure or product, to be considered effective residual deviation. The effective residual deviation may be reckoned with by applying random corrections.

Namely:

Application of threshold curves plotted from individual measurement results is principially wrong in itself. A reference curve for a wide range of concretes where data resulted from the effect of a wide range of concrete technology factors is a correct one. If an engineering structure were examined by selecting at random a result from the fundamental set, the known method were correct for this one.

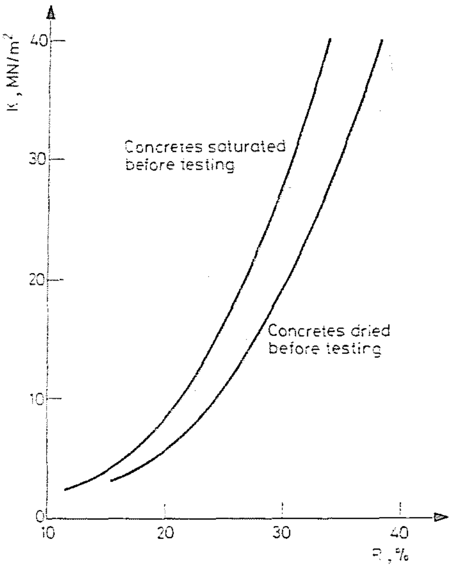

Fig. 5. Effect of moisture on strength assessment curves

A set of measurement results for a given engineering object can only be a part set of the fundamental set. Thus, probability of elements of a part set is not equal to the probability of the result assessed with respect to the threshold curve. Deviation between the unknown specific empirical curve for the structure and the threshold curve applied for the estimation causes a systematic error in the results for the engineering structure.

The effective residual deviation has to be reckoned with at a given, presumed risk level referred to the specific empirical curve, but else than by means of one-sided threshold values. Individual values deviate at random from the specific curve. Individual strength estimations corrected for random effects are given by:

$$K_{corr} = K_0 \pm \Delta_r s_r$$

where K_0 — strength assessment of max. probability read off the specific curve;

s_r — residual standard deviation;

Δ_r — correction factor for determining the residual deviation determined from random numbers taken from a set of normal distribution.

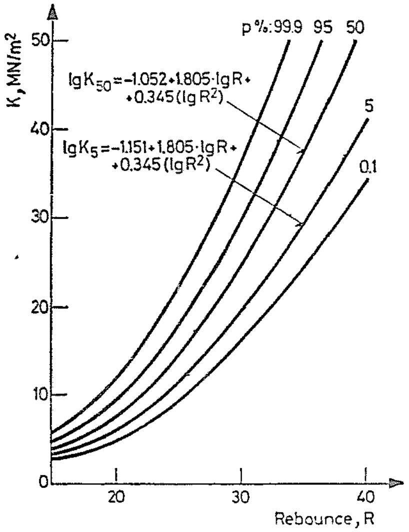

Fig. 6. Function field for strength assessment by the Schmidt hammer method

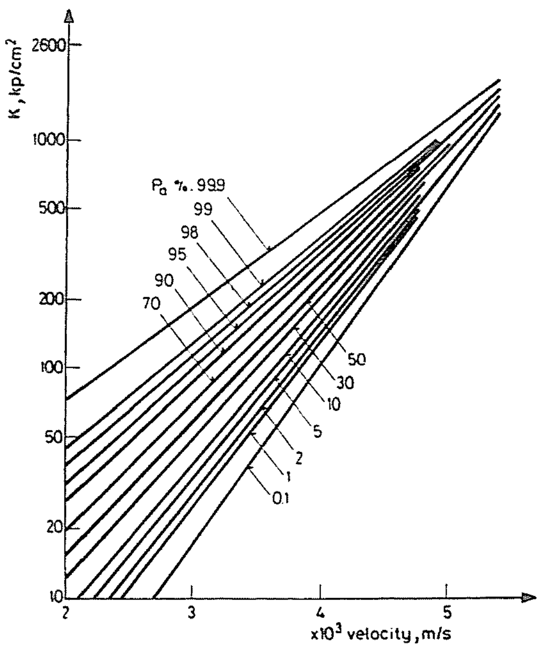

Fig. 7. Function field for ultrasonic strength assessment

Theorem 4

The empirical curve field for non-destructive instrument types is advisably produced by combining concrete technology factors, by the factor analysis of a planned experiment of complete test arrangement. Our research involved plotting of strength assessment function fields for ultrasonic [5] and *N*-type *Schmidt-hammer* instruments.

Namely:

Elements of the quantile curve field represent different combinations of the adjustment levels of concrete technology factors. Coincidence of several adversities leads to lower-level curves, and that of several favourable effects

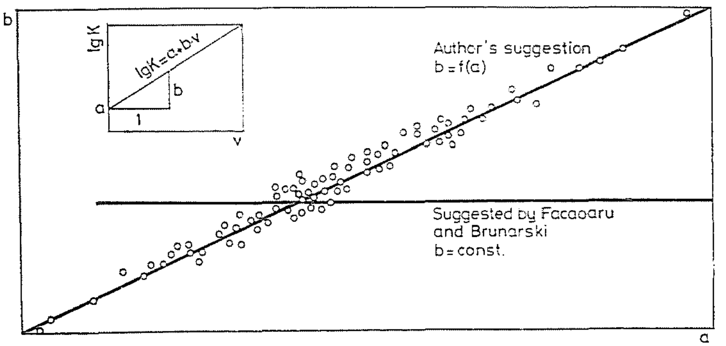

Fig. 8. Wrong assessment due to factor multipliers (comparison of ultrasonic strength assessment models)

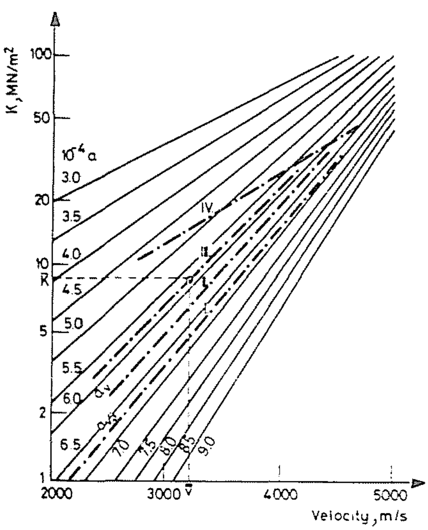

Fig. 9. Strength assessment methods (ultrasonic)

yields curves at a higher level. Effects of favourable and unfavourable effects have their share in determining the position of intermediate curves. This empirical model is closer to reality than any other arbitrary mathematical model, since it handles not only variables but also their function as random variables.

Theorem 5

Modifying effect of concrete technology factors must be taken into consideration by correcting the strength value read off the fundamental curve by means of factor effect multipliers.

Namely:

Specific empirical curves derived from the fundamental curve by a series of multiplications are untrue, since factors are interacting.

The suggested method permits uniform, contradictionless treatment of various strength assessment methods [6].

Summary

Evaluation of the reliability of non-destructive strength assessment has to take into consideration that non-destructive strength assessment is an indirect test to estimate the resistance of engineering structures to mechanical effects, just as are tests to failure.

Variables of the non-destructive strength assessment are considered as random variables, and so are relationship functions of the variables. After a criticism to published strength assessment methods, a short description is given of the research the five statements of reliable non-destructive strength assessment conditions have been deduced from.

The procedure has been successfully applied in practice.

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