A R C H I T E C T U R E C I V I L E N G I N E E R I N G E N V I R O N M E N T
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# NON-DESTRUCTIVE TESTING METHODS TO ASSESS STRENGTH OF CONCRETE IN BUILDING DIAGNOSTICS – THE MAIN AREA OF SCIENTIFIC RESEARCH OF PROFESSOR LEONARD RUNKIEWICZ

Maciej RUNKIEWICZ*

* MSc; Kajima Poland Sp. z o.o., Aleje Jerozolimskie 65/79, 00-697 Warszawa
E-mail address: *maciej.runkiewicz@kajimaeurope.com*

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Abstract

**The paper presents the issues connected with non-destructive testing methods in building diagnostics. These issues are the one of the most important topics covered in the scientific and engineering work of Prof. Leonard Runkiewicz. The paper includes :**

- **foundations of the safety and reliability of civil structures,**
- **analysis of the effect of the quality and durability of materials on building threats, break-downs and catastrophes,**
- **analysis of testing concrete in elements and in concrete structures,**
- **examples of assessments of concrete elements in the structure,**
- **trends in the development of non-destructive methods in building industry,**
- **examples of the application of non-destructive methods to assess structural concrete elements.**

Streszczenie

**W artykule omówiono zagadnienia związane z nieniszczącymi badaniami stosowanymi w diagnostyce obiektów budowlanych. Zagadnienia te są jednym z najważniejszych tematów naukowych i inżynierskich podejmowanych przez prof. Leonarda Runkiewicza. W artykule przedstawiono:**

- **podstawy bezpieczeństwa i niezawodności konstrukcji budowlanych,**
- **analizy wpływu jakości i trwałości betonu na zagrożenia, awarie i katastrofy budowlane,**
- **analizy metod badawczych betonu w elementach i konstrukcjach,**
- **przykłady oceny elementów z betonu w konstrukcji,**
- **kierunki rozwoju metod nieniszczących w budownictwie,**
- **przykłady zastosowań metod nieniszczących do oceny elementów i konstrukcji z betonu.**

Keywords: **Building structures; Concrete; Security; Reliability; Damages; Catastrophic; Non-destructive testing.**

## 1. INTRODUCTION

To assess physical and strength properties in the building diagnostics the non-destructive testing methods are widely used.

The complexity of safety, reliability and durability issues in the conditions of modern building structures exploitation requires specialist testing methods to be continuously developed and improved.

To correctly diagnose and assess the building structures the optimal in situ testing methods must be applied, which enable sufficiently, accuracy of the assessment of limit states of buildings during its whole useful life [2-19]. In accordance with the European Union principles, in general, the properties of construction products, elements and building structures are determined by way of basic requirements determined in the form of technical norms and approvals [6, 13, 15, 16].

The properties of building products, elements and structures enable us, in turn, to assess safety, durability and reliability of civil structures.

## 2. SAFETY AND RELIABILITY OF CONCRETE STRUCTURES

For the concrete to be safe and reliable the limit states of their individual elements and of the entire structures must not be exceeded in the areas of elements, which are mostly loaded or efforted, during their whole anticipated useful life and with certain probability.

The ultimate limit states of concrete structures or their elements are generally expressed in the form of the following inequality:

$$S_d < R_d \quad (1)$$

where:

$S_d$ – functions defining design values of internal forces in considered elements of the structure evoked by computational values of interactions in continuous, transitional and exceptional situations.

$R_d$ – functions defining design load bearing capacity of considered elements (section) of the structure defined for computational strength of construction concrete in a given element.

Serviceability limit states, most frequently relating to deflection, scratching, deformation, vibration, tilting, etc. are expressed in the following inequality:

$$E_d < C_d \quad (2)$$

where:

$E_d$ – deformations, deflections, width of scratch opening, vibrations in building structures, or any other serviceability parameters for characteristic values of interactions, strength of materials and their E-modules as well as acoustic, thermal, health and fire protection parameters, etc.

$C_d$ – values of admissible serviceability limit states of the structure defined most frequently in relevant regulations (norms, technical approvals and ordinances).

In the structures exploited characteristic strengths of concrete $f_k$ should be assumed to be the results of the tests carried out in nature. These should be such values for which the probability that in the construction occurs a lower value is not more than 5% for the specified useful life of the structure. It is required that the assumptions of a computational model to find S and R values which often depends on the quality of materials and connections used refer to the entire anticipated useful life of the structure.

## 3. EFFECT OF THE QUALITY AND DURABILITY OF CONCRETE ON BUILDING THREATS, BREAK-DOWNS AND CATASTROPHES

Any changes in the quality and durability of concrete and in reliability of the building structures critically affect the occurrence of building threats, breakdowns and catastrophes. It results from the long-term analysis of building threats, break-downs and catastrophes which has been carried out in Poland by the Building Research Institute (L. Runkiewicz), that the concrete have been a significant factor in the occurrence of building threats, break-downs and catastrophes. Poor quality of materials caused threats, breakdowns and catastrophes in various types of building structures and other civil structures or facilities [6].

Types of building structures which involved threats, break-downs and catastrophes during the last 50 years in Poland are provided in Fig. 2. Kinds of construction materials due to which the threats, break-downs and catastrophes occurred are provided in Fig. 3.

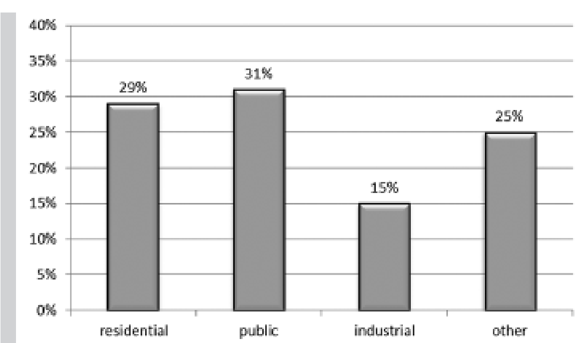


**Figure 1.**
**Percentage of break-downs and catastrophes in the years 1962-2012 broken down into the types of buildings (The total percentage presented in the diagrams may be less than 100 since not all types were taken into account, or may be more than 100 due to a wide-spread break-down or catastrophe involving more than one type of technology or type of elements)**

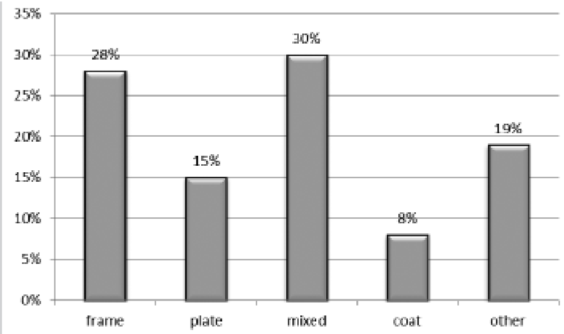


**Figure 2.**
**Percentage of break-downs and catastrophes in the years 1962-2012 broken down into the types of building structures**

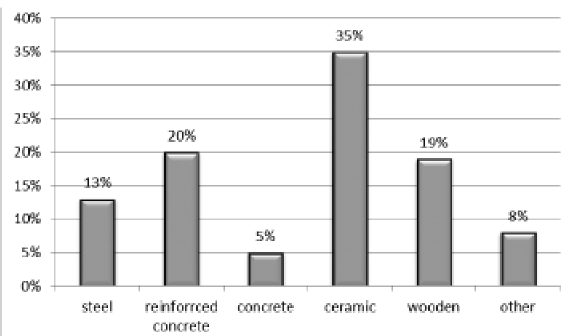


**Figure 3.**
**Percentage of break-downs and catastrophes in the years 1962-2012 broken down into the types of material used**

## 4. GENERAL CHARACTERISTICS OF TESTING METHODS

In Poland, for the purpose of assessing safety and reliability of concrete structures the non-destructive methods are applied among others to assess the properties of materials and the quality of concrete structures. Diagnostic testing and monitoring of building structures with the use of non-destructive methods are being developed, improved and adjusted to relevant conditions.

### 4.1. Testing of concrete in elements and in building structures

Diagnostics and in-situ testing of concrete in products, elements and structures are carried out mainly to assess: compressive strength and tensile strength, homogeneity, size and distribution of honeycombing and cavities in concrete, concrete-concrete connections and steel-wood connections in nods, stiffness, thickness and destruction of elements.

For these purposes mainly non-destructive methods are used, for example:

– **rebound hammer tests** which are based on the measuring of hardness of near-surface layer of the material;
– **acoustic tests** which consist in measuring, among others, speed and other characteristics of propagation of longitudinal and transverse waves in the material (e.g. impact-echo method);
– **radiological tests** which use, among others, the absorption of X-rays and gamma rays passing through the material and their parameters of dispersion and suppression;
– **electric and electromagnetic tests** which use electric and dielectric properties and characteristics of electric field (in the material in its proximity);
– **semi-non-destructive tests** for materials in the structure (e.g. pull-out test);
– **complex tests** using several testing methods.

The strength and homogeneity of concrete in the elements and structures being used are tested mainly with the application of non-destructive acoustic, ultrasonic, rebound hammer, radiological, semi-non-destructive and complex tests.

They are assessed through a statistical analysis of the measuring results on the basis of empirical relationships valid for a given type of concrete in the structure being tested.

The guaranteed compressive strength of concrete $f^{\circ}_{g}$ and the class of concrete are verified depending on the number of measurements of cores. In the statistical analysis the guaranteed strengths are assessed on the basis of empirical relationships valid for specific technologies of concrete. To assess the strength of concrete of medium homogeneity with technically required accuracy (maximum error 20%), the accuracy of the empirical relationship should be such for which a correlation factor for the correlation analysis is bigger than 0.75, or the relative mean square deviation for the assumed hypothetical curve is less than 12% [16-20].

In diagnostic testing the empirical relationships are also determined with certain approximation.

It is commonly known that the empirical relationships between the strength of concrete and the parameters measured with the application of non-destructive methods depend on numerous factors characteristic for the tested concrete in the structure [3-20]. The development of the concrete technology and the application of still new components for its production significantly influences the nature and process of the above relationships and accuracy of assessments.

In this way a number of relationships is worked over which are used for non-destructive control of “in-situ” concrete that are used in the diagnostics of reinforced concrete structures [1-11]. To assess the quality of concrete also various chemical, electric as well as electromagnetic, radiological and acoustic methods should be used and complex methods consisting of several testing methods.

Actually the rules and conditions of the application of the non-destructive testing methods for in-situ concrete structures have been defined by norms PN-EN. They became obligatory in Poland since 01.04.2010.

It seems that those days the most important factors considered when the PN-EN norms are used are: the selection of the most representative places of the structure and proper execution of the ultrasonic or rebound hammer tests.

When the representative places are selected the special attention should be paid to the following issues:

- Satisfactory thickness and stiffness of the tested elements such as: beams, columns, walls, slabs, floors subbases etc,
- Dense and homogenous structure of the concrete in the tested places,
- Damages of the concrete surface.

For the correct interpretation of the results the following issues should be observed:

- Satisfactory number of the tested places,
- Proper selection of the correlation curves for the tested concretes if they have been executed following the individual technology,
- Gathering the cores for the scaling of the non-destructive methods (according to PN-EN),
- Assuming the correction factors after deep consideration,
- Assessment of the guaranteed, characteristic and design values according to the obligatory norms.

The above rules are consistent with the actual norms and instructions [16-20].

Procedures regarding the assessment of the compressive strength using the non-destructive testing methods have been presented in PN-EN 13791:2008. The norm says that these methods may be used as alternative for cores testing, however, they should be treated as the supplementary tests when the number of the cores is limited. Non-destructive methods should be used after completion the scaling based on the cores tests.

The norm describes a number of the methods, however, 3 of them are described in detail [18]:

- Rebound hammer test according to PN-EN 12504-2,
- Ultrasonic pulse velocity test according to PN-EN 12504-4,
- Pull-out test according to PN-EN 12504-3:2005.

Assessment of the homogeneity and strength using the indirect methods is carried out based on the obtained results and using the proper empirical correlations between the measured results and concrete strength. Such correlations – in the actual Polish norms – are not the same for all concrete types. They depend on many parameters resulting from the content and execution technology of the concrete. Various publications present a number correlation curves for the rebound hammer, pull-out and ultrasonic tests, however, they differ too much and it is not possible to set one common regression curve.

### Methods of calibrating with core tests and the assessment of the strength

This procedure requires to have pairs of results: results obtained directly from the core tests and results obtained from the indirect tests (rebound number *L*, pull out force *F* or ultrasonic velocity *V*). There are 2 variants to assess the strength:

a) Alternative 1 – direct correlation with cores. To assess the *f-R* correlation it is required to test at least 18 cores. This method is equal to the precise methods proposed by L. Runkiewicz in norms PN-B and ITB instructions [16, 17, 19, 20].

b) Alternative 2 – Calibration with cores for a limited strength range using established correlation curves. This method is used for the limited range of the strength and using established hypothetical correlation curve, regression curve (including shifting of this curve following the core tests). This method is the equivalent of the simplified method proposed in standards PN-B and ITB instructions [16, 17, 19, 20].

### Alternative 1 (precise method)

As mentioned before there are needed at least 18 pairs of results: 18 results of core tests and 18 results of the indirect tests (carried out in the same places as borings of cores). The defined minimal number of results is required by the norm PN-EN 13791:2008. The correlation curve is obtained based on the *f-L* curve. The correlation curve is found (using analytical method of regression of pairs of results) to fit close to *f-L* curve. Obtained correlation $f_R=f(L)$ can be representative if the pairs of results are uniformly distributed across the range of the concrete strength.

Characteristic compressive strength of the concrete in the structure should be calculated as lower value of the following values:

$$f_{ck,is}= f_{m(n),is}-1.48s, \quad (3)$$

or

$$f_{ck,is}= f_{is,lowest} +4 \quad (4)$$

where:

$f_{ck,is}$ – characteristic compressive strength of concrete in structure,

$f_{m(n),is}$ – mean of the compressive strength values calculated from the correlation eg. *f–L* (for rebound hammer test),

$f_{is,lowest}$ – the lowest measured value of the compressive strength calculated from the correlation eg. *f–L* (for rebound hammer test),

*s* – standard deviation of the compressive strength.

**Alternative 2 (simplified method)**

For the approximate calibration the standards PN-EN 13791:2008 gives the basic curves that constitute the lowest values of the correlated results (correlation of concrete strength $f_{c,cyl}$ and rebound number *L* or pull out force *F* or ultrasonic velocity *V*). These curves relate to $f_{c,cube}$ corresponding to cube samples 150 mm. The assessment of the concrete strength is made by shifting of the basic curve to the correct level defined following the results of cores tests and non-destructive tests.

This method may be used for the assessment of the typical concretes, made of the same materials and in the same way. For the establishing the value $\Delta f$ it is necessary to have at least 9 pairs of the results of the core strength and parameters *R* (*L*, *V* or *F*).

Basic curves are calculated based on the following equations:

- For the rebound hammer test:

$$f_L= 1.25L- 23 \text{ when } 20\leq L \leq 24 \quad (5)$$

$$f_L= 1.73L- 34.5 \text{ when } 24\leq L \leq 50 \quad (6)$$

- For the pull-out test:

$$f_L= 1.33 (F -10) \text{ when } 10\, kN \leq F \leq 60\, kN \quad (7)$$

- For the ultrasonic pulse velocity test:

$$f_V= 62.5 V^2 - 497.5 V +990$$
$$\text{when } 4.0\, km/s \leq V \leq 4.8 \text{ km/s} \quad (8)$$

Standard PN-EN 13791:2008 allows to use another correlation curves if they are based on reliable scientific considerations.

The rule regarding the shifting of the basic curve has been presented in Fig. 4. At any point– where the tests have been carried out – one must calculate the difference of the concrete strength obtained from the cores and the results based on the basic curve. As the next step the mean value of the differences $\delta f_{m(n)}$ from *n* measurements should be calculated.

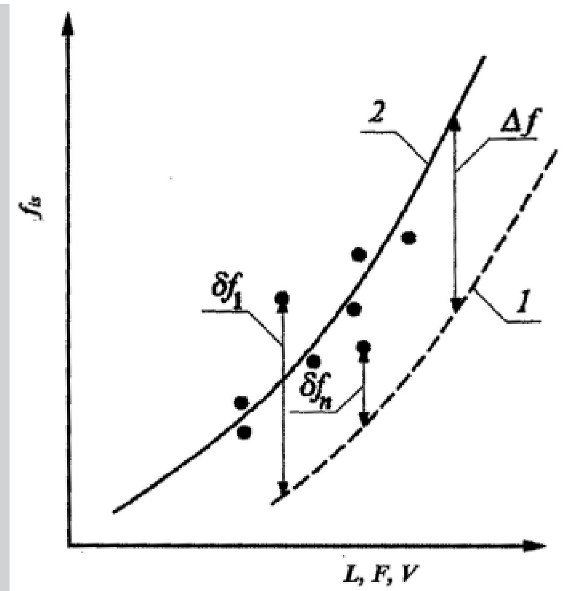


**Figure 4.**
**Shifting of the basic curve. 1 – basic curve, 2 – correlation curve based on the indirect method for the calculation of the concrete compressive strength (for the particular concrete type), $\delta f_{1...n}$ – the difference between the unitary concrete strength based on the cores and the value taken from the basic curve**

$$\delta f = f_{iS} - f_R \quad (9)$$

where:

$f_{iS}$ – concrete strength based on the core tests,

$f_R$ – concrete strength based on basic curve.

The value of the shifting $\Delta f$ of the basic curve depends on the mean difference value $\delta f_{m(n)}$ and the coefficient $k_1$ that depends on the number of paired tests. It should be calculated as follows:

$$\Delta f = \delta f_{m(n)} - k_1 s \quad (10)$$

where:

$\delta f_{m(n)}$ – mean of difference values between the concrete strength based on core tests and based on the basic curve,

$s$ – standard deviation of $\delta f_{m(n)}$ values,

$k_1$ – coefficient taken from the Table 1.

**Table 1.**
**Values of the coefficient $k_1$**

| η | 9 | 10 | 11 | 12 | 13 | 14 | >15 |
|---|---|---|---|---|---|---|---|
| $k_1$ | 1.67 | 1.62 | 1.58 | 1.55 | 1.52 | 1.50 | 1.48 |

After shifting the basic curve the concrete compressive strength can be assessed – first as the strength equivalent to the concrete cubes strength (150x 150x150 mm) and after that – characteristic strength (depending on number of tests).

Pull-out test is not popular enough so there is not reliable Polish basic curve that could be used. There are correlation curves based on testing equipment producer's recommendations and US norm ACI 228.IR. It seems these curves are close to each other and the curve proposed in actual norm gives bigger safety buffer.

For the ultrasonic pulse velocity test the correlation curves proposed by the ITB instruction and the European norm differ significantly. The ITB curve gives bigger safety buffer for the concrete strength over 20 MPa. The European norm correlation curve gives too low values for the concrete strength below 20 MPa. It seems that this curve does represent the reality well.

Actual recommendations require high number n = 9 of the samples that can be used for the correlation of the curves. However, it seems that the value n ≥ 3 should be enough to obtain approximated results.

The parameter proposed by [13] used for shifting the basic curve depends on the coefficient $k_1 \geq 1.48$ calculated as value of the differences $\Delta f$ of the characteristic functions. ITB instruction suggest to treat $\Delta f$ as the upper approximation of the confidence interval for the mean value $\delta f_{m(n)}$.This value is approximated on the level ±0.15 $\delta f_{m(n)}$ in Polish literature but also in US recommendations.

The curve shifting parameter as in PN-EN 13791:2008 gives not only bigger safety buffer but it does not require to calculate relative standard deviation and to use correction factors due to age, humidity etc. of the concrete.

Application of the basic curves relationships (as shown in literature eg. ITB instructions) allows to obtain the shifted basic curve and then to assess the in-situ compressive strength in any place.

Unfortunately the actual regulations do not precise the allowed deviations of the expected values which can be judged as reliable. Some good Polish practices may be used in this area. If we assume that the core strengths represents well the actual concrete structure strength than (even if the number of samples is less than 6) the indirect tests carried out in many places may give good approximation of the strength value. The deviation coefficient of the indirect test results helps to judge if the direct tests may be judged as representative. If they cannot be used as representative than it is necessary to collect another core tests, from the places where rebound hammer tests showed lower compressive strength.

For the assessment of the concrete strength of the precast elements concrete made of the same type of concrete it is recommended to use actual experience demonstrated in Polish norms and instructions regarding guaranteed compressive strength and concrete grades.

For the rebound hammer test the following equations may be used (based on PN-EU):

$$f = 1.25\,L - 23 \text{ when } 20 \leq L \leq 24 \qquad (11)$$

and

$$f = 1.73\,L - 34.5 \text{ when } 24 \leq L \leq 50 \qquad (12)$$

and $f_{min}$ should be calculated as the equivalent of the guaranteed compressive strength as follows:

$$f_{min} = f_c^G = f_m - 1.64\,s_L$$

where:

$f_c^G$ – guaranteed concrete strength for the element,

$f_m$ – mean concrete strength for the element,

$s_L$ –standard deviation of rebound number,

$L_m$ – mean rebound number for the element,

$n$ – number of testing places.

If the hardened concrete of the in-situ concrete structure or the precast concrete is assessed the appendix A to the norm PN-EN 1992-1:2008 says that the coefficient $\gamma_C$ may be reduced by multiplying by 0.85 (in EU it is called conversion coefficient $\eta$). In the same time $\gamma_C$ may have been already reduced due to geometrical deviations of the structure or the deviation of the concrete strength. However the reduced value of the coefficient should not be less than $\gamma_{C,red4}$ whose value – according to Polish Appendix toEC2 should be equalto1.3.

## 5. EXAMPLES OF ASSESSMENTS OF CONCRETE ELEMENTS IN THE STRUCTURE

To assess reliability and limit states of the tested elements and structures (in accordance with formulas 1 and 2) built with the use of modern technologies, non-destructive methods are used in accordance with norms and instructions [7-20].

In the non-destructive testing of concrete, the selection of appropriate correlations is of great significance. As the up-to-date practice shows, empirical relationships (correlations) are extremely differentiated and their incorrect use can lead to the errors even up to approximately 100%. For the modern concrete production, among other things, various additives and admixtures are used. It is stated that the additions, admixtures, age and con-ditions of exploitation have a material effect on empirical relationships in testing (L. Runkiewicz).

For instance, in high quality concrete various new additives that are used materially influence changes in empirical relationships to the assessment of, among others, strength of concrete.

As a result of long-term testing and implementation of works involving cores, it was found out that for the high quality concretes (with additives) class from B40 to B150, the obtained correction factors for typical ITB relationships is expressed in the following formulas:

- for ultrasonic test (Fig. 5):

$$f_c = (1.4 \div 2.7)\ (2.75\ V^2 - 8.12V + 4.8),\ MPa \qquad (13)$$

- for rebound hammer test (Fig. 6):

$$f_c = (0.9 \div 1.5)\ (0.0409\ L^2 - 0.915L + 7.4),\ \text{MPa} \qquad (14)$$

The application of corrected relationships enable us to significantly improve the accuracy of the assessment of strength and durability in accordance with norms [15].

These relations may also change due to a time factor and conditions in which the structure is exploited.

At present, the guaranteed strengths and characteristics of homogeneity of concrete should be defined in accordance with a new norm for concrete [14] with appropriate adjustments resulting from another statistical relations in line with a draft of PN-EN .

## 6. TRENDS IN THE DEVELOPMENT OF NON-DESTRUCTIVE METHODS IN BUILDING INDUSTRY

The new trends in the application of non-destructive methods for diagnostic testing of concrete and the assessment of their durability in building structures include laboratory testing and “in situ” tests on sites or on the structures in use.

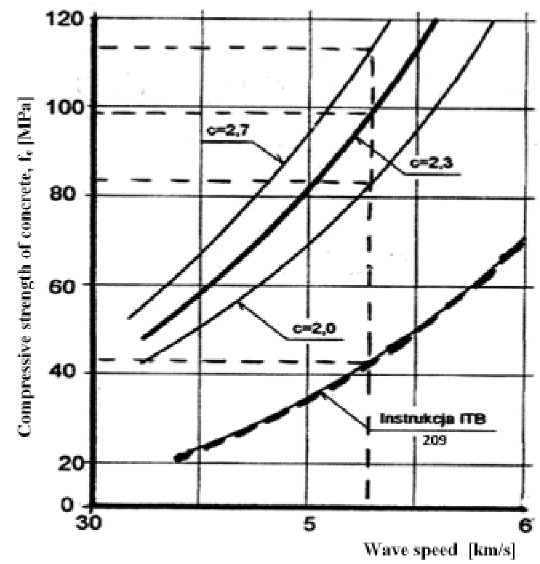


**Figure 5.**
**Empirical relationships for the assessment of high quality concrete strength with the use of ultrasonic method**

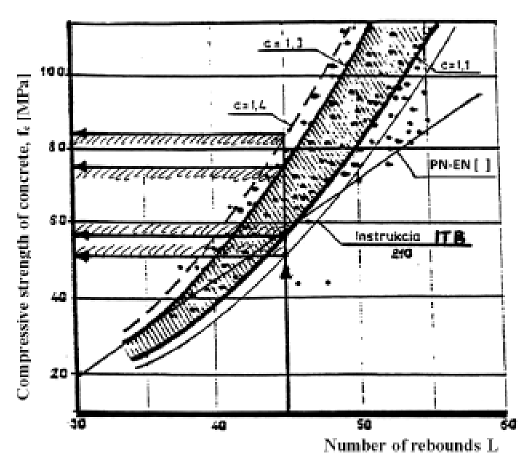


**Figure 6.**
**Empirical relationships for the assessment of high class concrete strength with the use of sclerometric method**

The most important testing, in respect of the assessment of quality and durability of construction concrete with the use of non-destructive tests include the testing of:

– changes of strength and homogeneity of concrete in the structure;
– changes of thickness of structural and finishing elements;
– changes of rheological properties of concrete in the structures;
– changes of structure, porosity, an non-continuity of concrete in structures;
– changes of humidity and its location within the element;
– corrosion of concrete in the building elements;
– quality of concrete and their durability;
– density of concrete and how it changes in time;
– external inclusions, defects and honeycombing in the concrete and connections.

The testing and inspections of the above listed properties of construction concrete in the elements of modern building structures which affect quality, reliability and durability of the structure, the following specialist methods are being improved and developed:

– acoustic, ultrasonic and rebound hammer tests to assess strength and structural properties;
– ultrasonic tests using acoustic waves and acoustic emission methods to assess homogeneity and internal structure of concrete;
– electric and electrochemical tests to assess corrosion of concrete;
– interferometry test to assess structures of concrete;
– holographic and magnetic tests to assess structures and inclusions in the structural concrete;
– radiolocation and thermographic tests to assess structures, and
– strain current and radiographic methods with the use of betatrones and microtrones, computer tomography, radiometric (gamma), electromagnetic resistance, electro-acoustic, spectroscopy, gas transmittance, heat transmission, optical, etc. to assess other selected significant properties of concrete and their change in time;
– complex methods involving more than one testing method [13].

## 7. EXAMPLES OF THE APPLICATION OF NON-DESTRUCTIVE METHODS TO ASSESS STRUCTURAL ELEMENTS

In the diagnostics of concrete structures it is necessary to apply non-destructive methods to assess (L. Runkiewicz):

- strength and homogeneity of concrete in foundation piles and cavity walls of tall buildings;
- homogeneity of concrete in foundation, walls and slabs in buildings, tanks, cooling towers and chimneys;
- location of reinforcement and the concrete structure in connections between reinforced concrete elements of walls, slabs, beams, chimneys, silos, tanks;;
- quality of location of reinforcement in the elements exposed to the biggest effort (in walls, slabs, beams, tanks, cooling towers, towers, core structures etc;
- reinforcement in composite walls of precast structures and frame structures;
- scratches on reinforced concrete elements in beams, walls, silos, tanks, towers;
- corrosion of concrete and steel in structures in tanks, decks, silos, towers, beams, walls;
- structural connections in the structures composed of large plate elements;
- corrosion and destruction of elements in monuments;
- quality of repairs and strengthening of reinforced concrete elements (including underlay) in beams, walls, slabs, tanks, towers, cooling towers, chimneys, post-tensioned girders etc.

Above mentioned structures were the parts of such buildings as apartments, public buildings, skyscrapers, office buildings, hotels, logistic warehouses, retail centers, sport objects, stadiums, swimming pools, waste treatment plants, industrial buildings, storages, telecommunication objects, energy industry objects, power plants, water dams, airports, railway objects, protected buildings, palaces, churches etc.

**Example of the assessment of the concrete strength in the in-situ structure under construction**

Assessment of the concrete strength class has been carried out following the norm. It is the case when number of the samples is less than 15. Summary of the calculations is presented in Table 2.

**Table 2.**
**Strength of the concrete cores based on the destructive method**

| | walls | foundation slab |
|---|---|---|
| Average concrete strength in the structure, $f_{m,is}$ [MPa] | 50.15 | 32.15 |
| Minimum concrete strength in the structure, $f_{is,lowest}$ [MPa] | 46.4 | 31.5 |
| criteria 1: $f_{ck,is}= f_{m,is}$ -7 (n=3 – 6 pcs) | 43.15 | 25.15 |
| criteria 2: $f_{ck,is}= f_{is,lowest} + 4$ | 50.4 | 35.5 |
| Characteristic strength of the concrete in the structure, $f_{ck,is}$ [MPa] | 43.15 | 25.15 |
| Class of concrete compressive strength | C40/50 | C20/25 |

Class of the concrete strength is taken from the norm (Table 1) – it takes into account differences of the strength based on the destruction of samples and in the structure.

Method to calculate the characteristic strength $f_{ck}$ is established in such a way that one result deviating much from the average cannot influence the final result. In the presented case taking into account the low result P1 would not influence the class of strength.

Assessment of the direct correlation of concrete strength and rebound number (rebound hammer test) requires having at least 18 bored cores. Due to the costs of taking such amount of cores it limits this approach.

It is more practical to proceed the way described in the norm (alternative 2). It requires at least 9 bored cores. In the analyzed case just 10 samples has been taken. All have been done of the same concrete (same content however the cement was different). So the basic conditions for the method have been fulfilled – it allows to establish the correlation relationship.

The shift of the regression curve has been calculated according to the norm:

$$\Delta f = \delta f_m - k_1 s = 12.2 - 1.62 \cdot 2.98 = 7.33 \text{ MPa}$$

And the regression curve (after the shift) has been calculated:

$$f_{R,is} = f_R + \Delta f = 1.73 \cdot L_m - 27.2$$

Fig. 7 shows the relations between the rebound hammer test results and destructive method result. The linear correlation between these parameters has been shown as calculated using the smallest squares method (black line no 2, $f_{R,is} = 2.05 \cdot L_m - 34.3$). Correlation according to the norm (red line no 1) has been also shown.

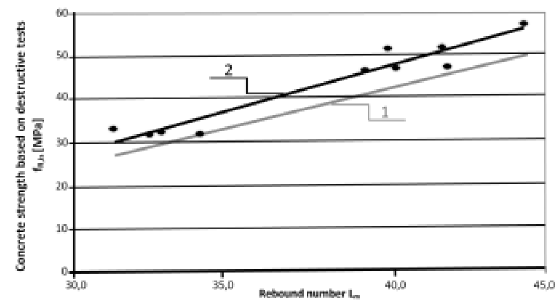


**Figure 7.**
**Correlation between the rebound number and the concrete strength**

Correlation described in norm seems to be on the safe side.

Assessment of the concrete made by rebound hammer test was executed for the random vertical elements and the slab (deck). Essential results are shown in table 3. Characteristic strength (cube samples strength equivalent) has been calculated using relations given in the norm. It means that $f_{ck,is}$ is lower value of the following:

Criteria 1: $f_{ck,is} = f_{m,is} - 1.48 \cdot s$

Criteria 2: $f_{ck,is} = f_{lowest,is} + 4$

**Table 3.**
**Strength of the concrete assessed by the non-destructive method**

| | columns | | | wall | deck |
|---|---|---|---|---|---|
| | axis 2 | axis 9 | axis F | axis Y | slab |
| Mean rebound number, $L_m$ | 43.6 | 42.9 | 43.8 | 37.4 | 41.5 |
| Mean concrete strength according to equation (1), $f_{m,is}$ [MPa] | 48.2 | 47.0 | 48.5 | 37.5 | 44.6 |
| Standard deviation (min. 3.0 MPa), s[MPa] | 3.0 | 3.0 | 3.0 | 3.0 | 4.78 |
| Minimum concrete stregth in the structure $f_{is,lowest}$ [MPa] | 42.9 | 44.6 | 44.6 | 35.9 | 35.1 |
| criteria 1: $f_{ck,is} = f_{m,is} - 1.48 \cdot s$ | 43.8 | 42.5 | 44.1 | 33.0 | 37.5 |
| criteria 2: $f_{ck,is} = f_{is,lowest} + 4$ | 46.9 | 48.6 | 48.6 | 39.9 | 39.1 |
| Characteristic strength of the concrete in the structure, $f_{ck,is}$ [MPa] | 43.8 | 42.5 | 44.1 | 33.0 | 37.5 |
| Class of concrete compressive strength | C40/50 | C35/45 | C40/50 | C30/37 | C30/37 |

The strength of the concrete in the columns was relatively homogenous, however the results were close to the value (43.0 MPa) between two concrete strength classes so the results have been finally assigned to both classes.

The internal structure and homogeneity of the concrete in the columns has been assessed using ultrasonic pulse velocity test.

Table 4 shows results of the concrete strength comparing to the design requirements.

**Table 4.**
**List of the concrete strength results in the structural elements**

| structural element | class of concrete (based on tests) | class of concrete (as designed) |
|---|---|---|
| columns in axis 2 | C40/50 (B50) | C35/45 (B45) |
| columns in axis F | C40/50 (B50) | C35/45(B45) |
| columns in axis 9 | C35/45(B45) | C35/45(B45) |
| wall in axis Y | C30/37 (B37) | C35/45(B45) |
| deck slab | C30/37 (B37) | C30/37 (B37) |
| foundation slab | C20/25 (B25) | C25/30 (B30) |

If the non-destructive tests are carried out independently or other tests they can be mainly used to identify the areas where the strength is lower than the mean. In the analyzed case we can observe it in the external wall axis Y. The correlation analysis allowed to identify that the concrete strength class in this element is one class lower than designed one. It means that additional strength and durability considerations should be done.

Minimal characteristic strength related to class C25/30 is 26.0 MPa, so slightly lower than identified for the foundation slab $f_{ck,is}$ =25.15 MPa so – from the formal point of view – concrete did not achieve its designed value. Following this finding it should be recommended to carry out some strengthening works.

This is the mathematical consequence of the application of the criteria 1. This criteria is very tough for the low number of the cores (less than 6) and it seems to lower the actual class of the concrete. In the analyzed case, after considering the above remarks and notifying that the lowest strength was relatively high $f_{is.lowest}$ = 31.5 MPa it was assessed that the real concrete strength in the foundation slab is satisfactory.

Application of the non-destructive tests for the executed structural elements enabled – after additional statistical analysis – to judge the safety of the structure and to recommend necessary strengthenings.

To avoid situation when the difficult choices have to be done and to improve the reliability of the norm method the number of samples should increase to min. 15. It is often difficult due to high cost. It is then recommended to introduce norm methods – satisfactory from the reliability and safety point of view– also in case of low number of samples.

## 8. CONCLUSIONS

For diagnostic testing of strength, quality, durability of structural concrete for the assessment of reliability of limit states of modern civil structures, the non-destructive acoustic, ultrasonic and rebound hammer tests are mainly applied in connection with the testing of cores as well as other specialist scientific methods justified and adjusted to the construction practice under specific conditions.

The methods and empirical relationships that have been applied in Poland have been compliant with the PN-EN norms [1-20].

For example, when assessing the strength of concrete the testing has shown material discrepancies between empirical relationships for ordinary concrete (B1O - B37) and the relationships for modern concrete of high quality (B45 – B150).

Actually the proposed correction factors for hypothetical relationships provided in ITB instructions for high quality concrete amount to:

- from 1.4 to 2.7 for ultrasonic pulse velocity tests;
- from 0.9 to 1.5 for rebound hammer tests with the use of arrangements made on the basis of norm.

In order to improve the accuracy of assessment of limit states in building structures and their durability, correct empirical relationships must be precisely defined (calibrated) for the applied testing methods and construction concrete. It is also recommended that more than one testing method should be used at the same time.

Diagnostic processes for civil structures being implemented in Poland under new conditions, in compliance with the EU requirements, need to be extensively developed and tested with the use of nondestructive methods. These methods are adjusted to the requirements and conditions of the building industry applying new technologies, including unlimited diagnostic in situ testing, monitoring of structures during exploitation as well as diagnostics and assessment of the structures during repairs, modernization and improvements.

## 9. SUMMARY

Professor Leonard Runkiewicz started to work at the Building Research Institute (ITB) in 1965. In ITB he was mainly involved in the testing methods of building structures, particularly non-destructive sclerometric, ultrasonic, radiological methods, as well as semi non-destructive methods of assessing quality, loading capacity and reliability of engineering structures, analysis and improvement of concrete structure designing and the issues of safety, reliability and diagnostics of existing civil structures.

In this respect he conducted researches, expressed opinions on, and coordinated research works carried on by research and designing centres and organized post-diploma studies in respect of methods of testing and assessment of civil structures during which he also gave lectures. Apart from scientific and research works he organised and was personally involved in research studies in the area of assessment and diagnosis of responsible and complicated structures, including, without limitation, containers and silos, industrial concrete structures as well as facilities in the Paper and Cellulose Plant, Water Power Plants, Petrochemical Plants, Water Supply Plants, Cement Plants, Iron Mills, Motorcar Factories, etc. These mainly included: industrial halls, tanks, towers, masts, chimneys, silos, foundation for machines, as well as buildings, theatres, bridges, viaducts, sports halls, etc. Leonard Runkiewicz prepared over 1000 scientific and design (expert) opinions for existing building structures in the area of general, industrial and special constructions made of reinforced and prestressed concrete, as well as complex and pioneer structures taking into account the structure dynamics.

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