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APPLICATION OF NON-DESTRUCTIVE TESTING METHODS TO ASSESS PROPERTIES OF CONSTRUCTION MATERIALS IN BUILDING DIAGNOSTICS

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Abstract

The paper includes:

- **foundations safety and reliability of civil structures,**
- **analysis the effect of the quality and durability of materials on building threats, break-downs and catastrophes,**
- **analysis of testing concrete in elements and in building structures,**
- **analysis of testing of reinforcement in reinforced concrete structures (exp. radiographic testing and electromagnetic testing),**
- **testing walls, steel, wood and plastic of civil structures,**
- **examples of assessments of concrete elements in the structure,**
- **trends in the development of no-n-destructive methods in building industry,**
- **examples of the application of non-destructive methods to assess structural elements.**

Streszczenie

Przedstawiona praca zawiera:

- **podstawy bezpieczeństwa i niezawodności konstrukcji budowlanych,**
- **analizy wpływu jakości i trwałości materiałów na zagrożenia, awarie i katastrofy budowlane,**
- **analizy metod badawczych betonu w elementach i konstrukcjach,**
- **analizy metod badawczych zbrojenia w konstrukcjach żelbetowych (m. in. metody radiograficzne i metody elektromagnetyczne),**
- **badania muru, drewna, stali i tworzyw w konstrukcjach budowlanych,**
- **przykłady oceny elementów z betonu w konstrukcji,**
- **kierunki rozwoju metod nieniszczących w budownictwie,**
- **przykłady zastosowań metod nieniszczących do oceny elementów i konstrukcji.**

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

1. INTRODUCTION

In accordance with international norms and regulations any building materials, products and elements should have specific physical and strength properties to ensure that the required ultimate and serviceability limit states are met in the designed buildings during their whole useful life [1÷14].

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 a 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 [7,12, 13, 14].

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 CIVIL STRUCTURES

For the civil structures 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 building structures or their elements are generally expressed in the form of a following inequality:

$$S_d \leq R_d \qquad (1)$$

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 materials in a given element.

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

$$E_d \leq C_d \qquad (2)$$

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).

Generally, the ultimate limit states and serviceability limit states of civil structures are defined in the basic requirements provided for in national and international regulations.

Characteristic and design values provided for in formulas (1) and (2), cover, apart from strength properties of the materials, also strength properties of auxiliary elements and connections, distribution and dimensions of steel bars in reinforced concrete elements as well as other parameters specified in the basic requirements.

In the structures exploited the characteristic strengths of materials f_k (R) 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 MATERIALS ON BUILDING THREATS, BREAK-DOWNS AND CATASTROPHES

Any changes in quality and durability of materials and in reliability of the building structures critically affect the occurrence of building threats, break-downs and catastrophes. It follows from the long-term analysis of building threats, break-downs and catastrophes which has been carried out in Poland by the Building Research Institute, that the building materials have been a significant factor in the occurrence of building threats, break-downs and catastrophes. Poor quality of materials caused threats, break-downs and catastrophes in various types of building structures and other civil structures or facilities [7].

Kinds of building structures which involved threats, break-downs and catastrophes during the last 40 years in Poland are provided in Fig. 1.

Types of building structures which involved threats, break-downs and catastrophes during the last 40 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.

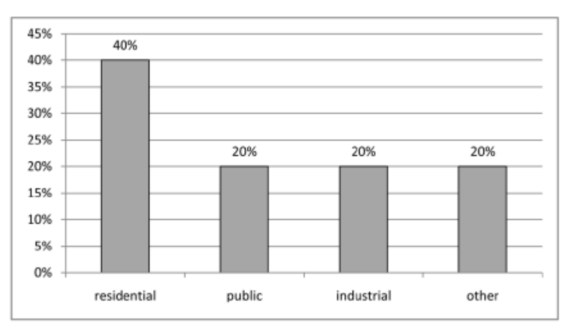

Figure 1.
Percentage of break-downs and catastrophes in the years 1962-2007 broken down into the types of buildings
(The total percentage presented in the diagrams may be less than 100 since not all types were taken into account, or may be more than 100 due to a wide-spread break-down or catastrophe involving more than one type of technology or type of elements.)

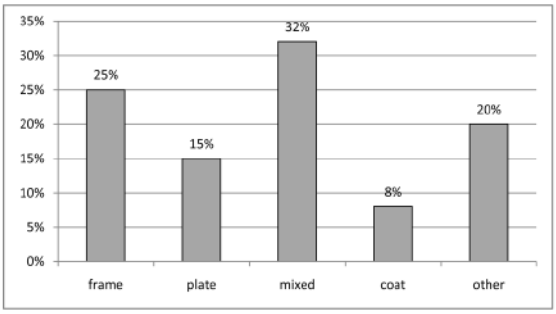

Figure 2.
Percentage of break-downs and catastrophes in the years 1962-2007 broken down into the types of building structures

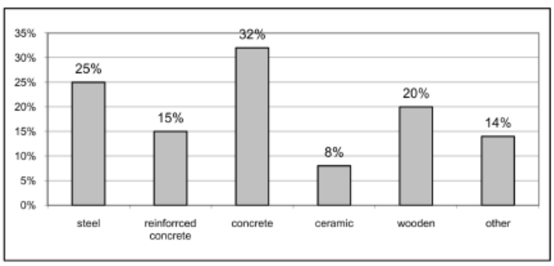

Figure 3.
Percentage of break-downs and catastrophes in the years 1962-2007 broken down into the types of material used

4. GENERAL CHARACTERISTICS OF TESTING METHODS

In Poland, for the purpose of assessing safety and reliability of building structures the non-destructive methods are applied among others to assess the properties of materials and the quality of building 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

Diagnostic in situ testing of concrete in products, elements and structures are carried out mainly to assess: compression 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:

- **sclerometric methods** which are based on the measuring of hardness of near-surface layer of the material;
- **acoustic methods** 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 methods** 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 methods** which use electric and dielectric properties and characteristics of electric field (in the material in its proximity);
- **semi-non-destructive methods** for materials in the structure (e.g. pull-out method);
- **complex methods** using several testing methods.

These are indirect methods based on empirical relationships between the measured physical parameters and the properties of the materials that are being tested for. These methods require that the measuring apparatus and testing equipment be preliminarily scaled.

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

They are assessed through a statistic 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^G_g (R^G_g) and the class of concrete are tested depending o the number of measurings and bore-holes. 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% [15÷19].

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

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÷18].

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 are 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.

4.2. Testing of reinforcement in reinforced concrete structures

To assess the reinforcement in reinforced concrete structures non-destructive and destructive methods are applied. In this case the testing consists in defining quality of individual steel bars in the concrete, distance between the steel bars and surface of the element being tested, as well as the diameter and distance between the bars.

For these purposes the non-destructive methods are used, namely: radiological, eddy current, electric, acoustic, chemical and magnetic methods as well as destructive testing on cut-off samples. Up to date, amongst the radiological methods radiographic methods have showed up to be most useful [8].

Thanks to radiographic testing we can assess reinforcement in complicated structural systems. They require however a complicated apparatus to be applied and a special system of protection to be used against ionizing radiation.

In simple cases of plate and wall elements it is also possible to apply, among others, electromagnetic, ultrasonic, eddy current and thermovision methods.

4.2.1. Radiographic testing

Radiographic testing of the structural reinforcement in reinforced concrete elements is carried out with the use of an apparatus containing sources of gamma or X rays. Until now the most optimal sources of radiation for reinforced concrete radiography have been isotopes Co-60 of high activity, X-ray apparatus of voltage above 200kV and betatrones and microtrones showing radiation energy from 6 to 30 MeV.

When testing civil structures movable sources are used. They include: gammagraphic defectoscopes, X-ray apparatuses and betatrones showing energy of 6 MeV, etc. When interpreting phenomena of absorption and dispersion of ionizing radiation passing through the reinforced concrete elements are being taken into account.

On the basis of the obtained results of testing it has been decided that if the parameters are properly selected the detectability of cavities and steel bars in the concrete itself is sufficient for the construction purposes.

The testing parameters defined in this way enable us to assess the reinforcement bars, cavities and honeycombing in concrete with the accuracy of 2 to 5%.

Fig. 4 shows the example of the radiographic testing of the reinforcement location in the reinforced concrete beam.

4.2.2. Electromagnetic testing

Electromagnetic methods base on the use of phenomena occurring in a magnetic stream created in a specific sonde when it is approached to a ferromagnetic material (e.g. a steel bar). The testing apparatus used to determine the location and dimension of reinforcement are manufactured in many countries. Commonly known electromagnetic devices which are applied include among others: Pachometr, Covemeter, Ferrometr and Femetr.

To assess diameters of bars and the distance from the bars to the surface of the element (the size of cover) special nomogrames and expert minicomputers are built.

The application of electromagnetic methods is limited mainly to the dense location of bars and placement of reinforcement bars in the elements. A correct magnetic testing is impaired by neighbouring bars and complicated systems in and around nodes. In this respect new testing methods and techniques using digital technologies should be developed and improved.

4.3. Testing walls in the structure

To test and assess walls in the building structures various methods are being improved in order to:

- assess strength and durability of bricks, joints and walls with the use of ultrasonic, radiological, sclerometric methods and on the samples taken out of the structure;
- assess structures, cavities, humidity, thickness and corrosion with the use of ultrasonic, radiological, thermovision, electrical and dielectrical methods.

The examples of nomogrames to assess the strength of walls with the use of an ultrasonic method are shown in Fig. 5 and Fig. 6 and the assessment of compressive strength with the use of sclerometric method in Fig. 7.

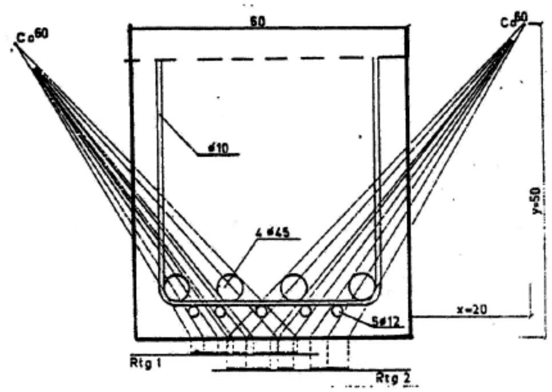

Figure 4.
Assessment of bottom reinforcement in the beam (inside the middle of the span) with the use of radiographic method

4.4. Steel structures testing

In the diagnostics of steel structures the following methods are mainly used:

– ultrasonic, rotary current and radiographic methods as well as testing on cut-off samples – to test strength properties of steel and connections in the structure;
– non-destructive specialist methods and tests on models or cut-off samples – to test elements, steel plates and connections;
– acoustic, ultrasonic, electrical thermovision, electromagnetic and other methods – to test corrosion and protective layers;

Steel elements of building structures are tested with the use of specialist methods and stands enabling a complex assessment of steel elements.

In this respect new specialist testing methods are being developed on the basis of various physical phenomena and computer technologies, which are optimal for specific structures.

4.5. Testing of wood in structures

The testing of wood and connections between elements in the structure are used, among others, to assess:

– strength, homogeneity, humidity – with the use of ultrasonic, radiological, dielectrical methods and specialist testing on the cut-off samples;
– quality of screw, bolt, nail or glue connections – with the use of ultrasonic, thermovision and radiological methods as well as specialist methods on models and cut-off samples;
– corrosion and biological destructions – with the use of chemical methods and on the cut-off samples;

New techniques and methods using computer technologies are being developed.

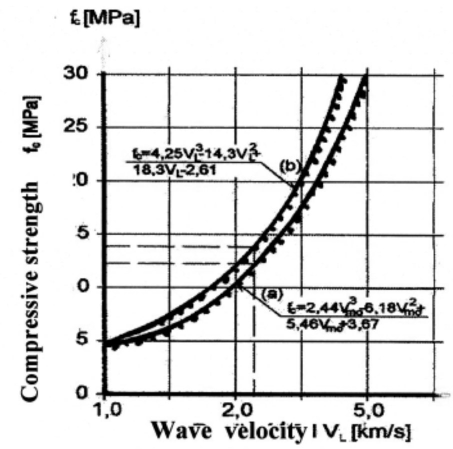

Figure 5.
Examples of nomogrames for assessing strength of a brick (a) and a wall (b) in the structure with the application of ultrasonic methods

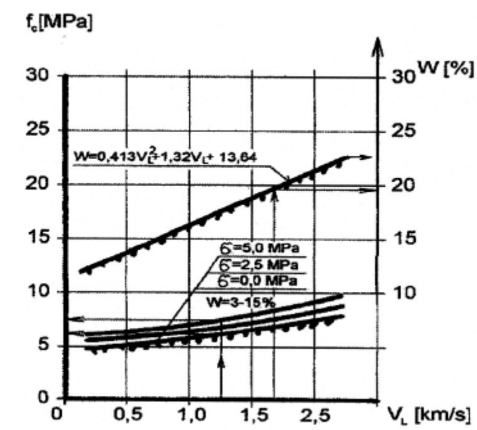

Figure 6.
Examples of nomogrames for assessing strength of a wall showing different levels of humidity (W) with different compressive tensions (σ), with the use of ultrasonic methods

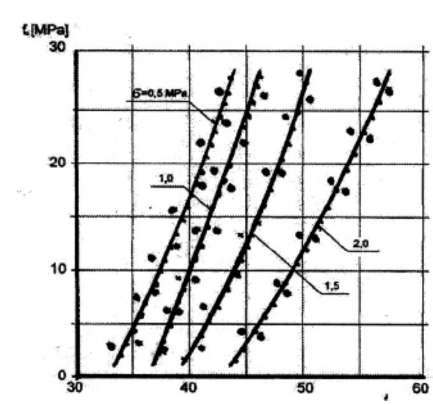

Figure 7.
Examples of relationships to assess strength of bricks in walls depending on tension, with the use of a sclerometric method

4.6. Testing of plastic elements

Plastic elements are tested mainly in order to assess strength, durability, resistance to UV-radiation and high temperatures, quality of connections, chemical and usable properties and radioactivity.

The above testing is carried on directly on elements and on samples or elements taken out of the structure with the use of specialist methods in accordance with technical norms and approvals. New specialist non-destructive testing methods are being developed for specific structures, products and special structural solutions.

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÷18].

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 conditions of exploitation have a material effect on empirical relationships in testing.

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 works involving bore-holes, 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 express in the following formulas:

• for ultrasonic method (Fig. 8)

$$f_c = (1.4 \div 2.7)\,(2.75\,V^2 - 8.12V + 4.8),\ MPa \qquad (3)$$

• For sclerometric method (Fig. 9)

$$f_c = (0.9 \div 1.5)\,(0.0409\,L^2 - 0.915L + 7.4),\ MPa \qquad (4)$$

The application of corrected relationships in accordance with Figures 8 and 9 enable us to significantly improve the accuracy of the assessment of strength and durability in accordance with norms [12÷19].

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 [13] with appropriate adjustments resulting from another statistical relations in line with a draft of PN-EN [19].

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 construction materials and the assessment of their durability in building structures include laboratory testing and "in situ" tests on sites or on the structures in use.

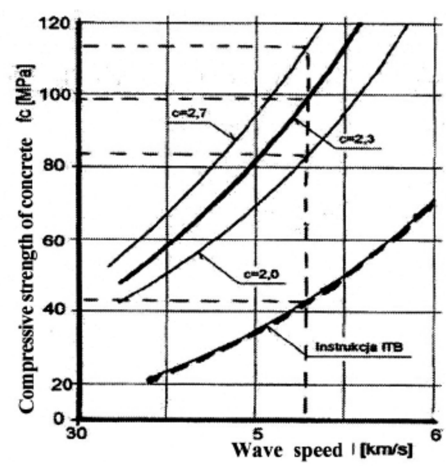

Figure 8.
Empirical relationships for the assessment of high quality concrete strength with the use of ultrasonic method

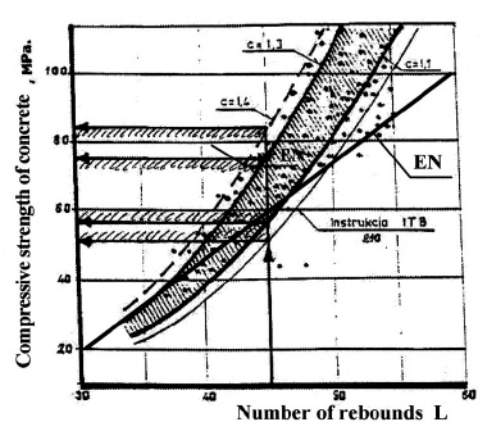

Figure 8.
Empirical relationships for the assessment of high class concrete strength with the use of sclerometric method

The most important testing concerns in respect of the assessment of quality and durability of construction materials with the use of non-destructive methods include the testing of:

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

The testing and inspections of the above listed properties of construction materials 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, ultrasonographic and sclerometric methods to assess strength and structural properties;
– ultrasonographic methods using acoustic waves and acoustic emission methods to assess homogeneity ad structure of materials;
– electric and electrochemical methods to assess humidity and corrosion of materials;
– interferometry method to assess structures of concrete, steel, wood, ceramics, etc.;
– holographic and magnetic methods to assess structures and inclusions in the structural materials;
– radiological methods to assess humidity and weight of materials in the structures;
– radiolocation and thermographic methods to assess structures, and
– eddy 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 materials and their change in time;
– complex methods involving more than one testing method.

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

In the diagnostics of building structures it is necessary to apply non-destructive methods to assess:

- strength and homogeneity of concrete in foundation piles and cavity walls;
- homogeneity of concrete in foundation, walls and slabs;
- location of reinforcement and the concrete structure in connections between reinforced concrete elements;
- connections between steel and wood elements with the use of different types of joints;
- quality of location of reinforcement in the elements exposed to the biggest effort;
- reinforcement in composite walls;
- scratches on reinforced concrete elements;
- corrosion of concrete and steel in structures;
- structural connections in the structures composed of large plate elements;
- strength and structure of brick walls in monuments;
- corrosion and destruction of elements in monuments;
- biological destruction of wooden elements;
- quality of repairs and strengthening of reinforced concrete elements (including underlay), brick, steel and wooden elements;
- humidity and health properties of materials contained in the elements;
- quality of structural and surface protection measures of the elements.

8. CONCLUSIONS

For diagnostic testing of strength, quality, durability of structural materials for the assessment of reliability of limit states of modern civil structures, the non-destructive acoustic, ultrasonic and sclerometric methods are mainly applied in connection with the testing of samples (bore-holes) 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 EU norms [1 -18].

For example, when assessing the strength of concrete the testing has shown material discrepancies between empirical relationships for ordinary concrete (B10 – B37) and the relationships for modern concrete of high quality (B45 – B150).

The proposed correction factors for hypothetical relationships provided in ITB instructions [17, 18] for high quality concrete amount to:

- from 1.4 to 2.7 for ultrasonic methods;
- from 0.9 to 1.5 for sclerometric methods with the use of arrangements made on the basis of norm [19].

In order to improve the accuracy of assessment of limit states in building structures and their durability, correct empirical relationships must be precisely defined (scaling) for the applied testing methods and construction materials. 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 non-destructive methods. These methods are adjusted to the requirements and conditions of the building industry applying new technologies, including without limitation of diagnostic in situ testing, monitoring of structures during exploitation as well as diagnostics and assessment of the structures during repairs, modernization and improvements.

REFERENCES

[1] *Brunarski L.*; Metody badawcze stosowane przy ocenie konstrukcji budowlanych – oszacowanie wytrzymałości betonu in situ (Research methods used in building structures assessment – in situ strength estimation). Mat. Konferencji „Diagnostyka i wzmacnianie konstrukcji żelbetowych". Wyd. ITB, Warszawa, 1994 (in Polish)

[2] *Brunarski L., Runkiewicz L.*; Principles and application examples of non-destructive method testing of concrete structures, Warsaw, Procc. IBT, 1983

[3] *Brunarski L., Runkiewicz L., Krawczyk M.*; On establishing technical parameters in radiographical testing of building structures, Procc. VII IC NDT, Warsaw-Poland, 1973

[4] *Runkiewicz L.*; Wpływ statystycznej analizy wyników badań nieniszczących na ocenę betonu w konstrukcji (Impact of statistical analysis of non-destructive tests results on evaluation of concrete in the structure). Prace ITB, nr 1/81 (in Polish)

[5] *Runkiewicz L.*; Application of radiographical testing to control concrete building construction in Poland, Procc. 3 European Conference on Nondestructive Testing. Florence, 1984

[6] *Runkiewicz L.*; Nondestructive testing of concrete in situ in Poland, Procc. 3 European Conference on Nondestructive Testing, Florence, 1984

[7] *Runkiewicz L.*; Badania konstrukcji "in situ" w rzeczoznawstwie budowlanym ("In situ" structures testing in civil engineering expert consulting). Materiały Konferencyjne „Warsztat Pracy Rzeczoznawcy Budowlanego". Wyd. Politechnika Świętokrzyska, Kielce, 1996 (in Polish)

[8] *Runkiewicz L.*; Radiografia konstrukcji budowlanych z betonu (Concrete structures radiography). Wyd. ITB, Warszawa, 1989 (in Polish)

[9] *Runkiewicz L.*; Wpływ wybranych czynników na wyniki badań sklerometrycznych betonu (Chosen factors influence on concrete sclerometric testing results). Wyd. ITB, Warszawa, 1994 (in Polish)

[10] *Runkiewicz L.*; Diagnostyka i wzmacnianie konstrukcji żelbetowych (Diagnostic and strengthening of reinforced concrete structures). Materiały Sesji Naukowo-Technicznej ITB Warszawa, 1994 (in Polish)

[11] *Runkiewicz L.*; Assessment of the strength of concrete in structures by means of the Schmidts sclerometers, Warsaw, Procc. IBT, 1983

[12] PN-B-03264 Konstrukcje betonowe, żelbetowe i sprężone. Obliczenia statyczne i projektowanie. (Polish Standard, Plain, reinforced and prestressed concrete structures. Analysis and structural design), (in Polish)

[13] PN-EN 206-1 Beton – część 1 Wymaganie, wykonywanie, produkcja i zgodność. (Concrete – Part 1 Specification, performance, production and conformity), (in Polish)

[14] PN-EN 1992 Projektowanie konstrukcji z betonu. (Design of concrete structures), (in Polish)

[15] PN-74/B-06261 Nieniszczące badania konstrukcji z betonu. Metoda ultradźwiękowa. (Polish Standard, Concrete structures non-destructive testing, Ultrasonic method), (in Polish)

[16] PN-74/B-06262 Nieniszczące badania konstrukcji z betonu. Metoda sklerometryczna. Badania wytrzymałości betonu na ściskanie za pomocą młotka Schmidta typu N. (Polish Standard, Concrete structures non-destructive testing, Sclerometric method, Concrete compression strength testing with the use of N type Schmidt sclerometer), (in Polish)

[17] PN-EN 12504-1-4 Badania betonu w konstrukcjach. (Testing concrete in structures), (in Polish)

[18] Instrukcja ITB nr 209 Metoda ultradźwiękowa do badań wytrzymałości betonu w konstrukcji (Building Research Institute Instruction No.209, Ultrasonic method of structural concrete strength testing), (in Polish)

[19] Instrukcja ITB nr 210 Metoda sklerometryczna do badań wytrzymałości betonu w konstrukcji (Building Research Institute Instruction No.210, Sclerometric method of structural concrete strength testing), (in Polish)