BUDAPEST UNIVERSITY OF TECHNOLOGY AND ECONOMICS
Department of Construction Materials and Engineering Geology

New scientific
results of
PhD THESIS

Rebound surface hardness
and related properties of concrete

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Contents

4. Methodology

5. Hypotheses and new scientific results

1. BACKGROUND

Surface hardness testing is a long established NDT method for the strength estimation of materials. Hardness testing was the first material testing practice from the 1600's in geology and engineering by the scratching hardness testing methods (Barba, 1640; Réaumur, 1722; Haüy, 1801; Mohs, 1812); appearing much earlier than the systematic material testing that is considered to be started in 1857 when David *Kirkaldy*, Scottish engineer set up the first material testing laboratory in London, Southwark (Timoshenko, 1951). The theoretical hardness research was initialized by the pioneering work of Heinrich *Hertz* in the 1880's (Hertz, 1881). Hertz's proposal formed also the basis of the indentation hardness testing methods by Brinell, 1900; Rockwell, 1920; Vickers, 1924 and Knoop, 1934 (Fisher-Cripps, 2000).

Researchers adopted the Brinell method to cement mortar and concrete to find correlations between surface hardness and strength of concrete during the four decades following that Brinell introduced his ball indentation method for hardness testing of metals.

As further developments, dynamic surface hardness testing devices also appeared (Durometer by Albert F. Shore, 1920; Duroskop by Rational GmbH, 1930; spring hammer by Gaede, 1934; pendulum hammer by Einbeck, 1944).

In Switzerland Ernst *Schmidt* developed a spring impact hammer of which handling were found to be superior to its predecessors (Schmidt, 1950) and became very popular in the in-situ material testing due to the inexpensive testing device and its relatively simple use. Nowadays, the Schmidt rebound hammer is still the surface hardness testing device of the most widespread use for concrete. In the rebound hammer *(Fig. 1)* a spring (1) accelerated mass (2) is sliding along a guide bar (3) and impacts one end (a) of a steel plunger (4) of which far end (b) is compressed against the concrete surface (c). The impact energy is constant and independent of the operator, since the tensioning of the spring during operation is automatically released at a maximum position causing the hammer mass to impinge with the stored elastic energy of the tensioned spring. The hammer mass rebounds from the plunger and moves an index rider (5) before returning to zero position. Original Schmidt rebound hammers record the rebound index *(R)*: the ratio of paths driven by the hammer mass during rebound and before impact.

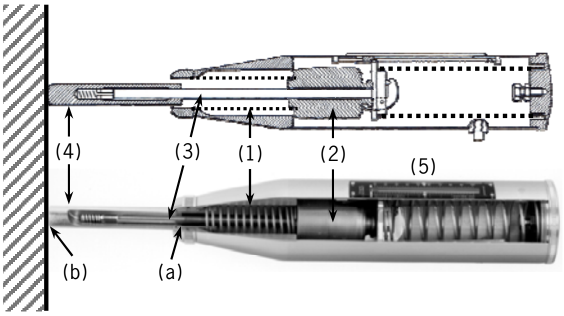

Fig. 1. Structure of the rebound hammer.

The dissipation of the impact energy by the local crushing of concrete under the tip of the plunger makes the device suitable for strength estimation.

The study of hardness is a research topic frequently appearing in the technical literature of physics and material science, nevertheless, the theory of contact mechanics still has several gaps. The topic sometimes induces even a philosophical question: Is hardness a material property at all?

It should be mentioned here that scientific consensus does not exist for the term 'hardness' even for the definition of the word (Fisher-Cripps, 2000).

2. RESEARCH SIGNIFICANCE

Aim of rebound hammer tests is usually to find a relationship between surface hardness and compressive strength to be able to estimate the strength of concrete with an acceptable error. The uncertainty of the estimated compressive strength, therefore, depends both on the variability of the in-situ measurements and the uncertainty of the relationship between hardness and strength.

Based on a comprehensive literature review it was realized that several publications are available in the technical literature concerning experimental results and analyses, however:

- The assessment of statistical parameters based on a considerable collection of rebound index data is missing from the technical literature. Even the current standards and recommendations contain statistical parameters that are obtained by datasets of limited size.
- For the rebound method neither a general theory nor a general empirical formula was developed that can describe the relationship between measured hardness values and compressive strength. Nevertheless, it is deemed in some technical papers that the behaviour is commonly understood. As a result of the diversity of the numerous empirical proposals that can be found in the technical literature some researchers even state that the method is suitable only for assessing the uniformity of strength of concrete.
- Rebound hardness can be related to compressive strength only if a sufficient amount of energy can dissipate in the concrete during the impact. The inventor of the original rebound hammer fitted the impact energy of the hammer to concrete compressive strengths available in the 1950's. The concrete construction technology, however, nowadays uses concretes of higher compressive strengths.
- Due to the lack of scientific consensus the rebound hammer is continuously loosing its role to estimate compressive strength of concrete by itself, e.g. current International and European Standards exclude the use of the rebound method for strength estimation on its own due to the limited accuracy reported. Testing of drilled cores together with the rebound method is suggested for an acceptable reliability.

Above findings highlighted the need of detailed theoretical and laboratory research.

3. OBJECTIVES

Present PhD research intended to investigate the reasons of the concerns about the strength estimation of concrete with the rebound method and provide a comprehensive analysis of the rebound method for a better understanding of the hardness of concrete and its relation to compressive strength.

Three general objectives were aimed to achieve within the framework of present PhD research:

Present PhD research intended to investigate the reasons of the concerns about the strength estimation of concrete with the rebound method and provide a comprehensive analysis of the rebound method for a better understanding of the hardness of concrete and its relation to compressive strength.

Three general objectives were aimed to achieve within the framework of present PhD research:

1) Based on an extensive literature survey and statistical analysis of available in-situ and laboratory test data it was intended to ascertain whether the tendency and the distribution of variability parameters of rebound hardness are similar to that of the compressive strength. Precision statements of available recommendations were intended to be monitored.

2) Based on an extensive literature survey and theoretical considerations the main governing parameters of the rebound hardness were intended to be identified considering properly prepared concretes. After studying general laws related to the rebound index and compressive strength of concrete and detecting their interrelationships a phenomenological model was intended to be developed. For the validation of the developed model parametric simulations, as well as laboratory verification test were intended to be carried out.

3) Based on targeted laboratory experimental studies it was intended to demonstrate which mechanical property can be related to the measured rebound hardness value by comparison of the development rate of the tested properties in time and how the water-cement ratio of concrete and the impact energy of the hardness tester device influence the rebound index.

4. METHODOLOGY

The general methodology of the research covers the following train of thought: based on technical literature data or own considerations setting up a hypothesis, then confirming or disproving the hypothesis (i.e. forming a new scientific result) based on statistical analysis, theoretical considerations or laboratory tests.
Present chapter is structured in accordance with the three main objectives of present PhD research.

4.1 STATISTICAL ANALYSIS

4.1.1 Calculation of repeatability parameters

An extended *repeatability* analysis was made on 8955 data-pairs (own measurements: 2699 laboratory data-pairs, 578 in-situ data-pairs, total 3277 data-pairs) of corresponding average rebound indexes and standard deviations of rebound indexes that were collected from 48 different sources (in which the number of in-situ test areas was 4785 and the number of laboratory test areas was 4170; resulting more than eighty thousand individual rebound index readings. Range of the studied concrete strengths was f_{cm} = 3.3 MPa to 105.7 MPa, and the range of the individual rebound indices was R = 10 to 63. The averages and the standard deviations were calculated by 10 to 20 replicate rebound index readings on the same surface of a concrete specimen during laboratory tests, or at the same test area in the case of in-situ testing. The data were analysed to see the general repeatability (within-test variation) behaviour of the rebound method. Analysis of reproducibility (batch-to-batch variation) was not the aim of the studies. Standard deviation and coefficient of variation was calculated and analysed. The range of the analysed data was from $R_{m,min} = 12.2$ to $R_{m,max} = 59.0$ for the averages and from $s_{R,min} = 0.23$ to $s_{R,max} = 7.80$ for the standard deviations. Coefficient of variation range was found to be as from $V_{R,min} = 0.43\%$ to $V_{R,max} = 31.12\%$.

4.1.2 Goodness of fit tests of repeatability parameters

An extended statistical analysis has been made on the previously detailed database (8955 test areas) to ascertain the probability distribution of the parameters of statistical dispersion of the rebound index (i.e. standard deviation, coefficient of variation, range).
Goodness of fit tests were used to compare test data to the theoretical probability distribution functions. Three tests were run to get the best goodness of fit out of more than 60 different types of distribution functions: Kolmogorov-Smirnov test, Anderson-Darling test and χ^2 test.

4.1.3 Influences on the repeatability parameters

The governing parameters over the changes of the standard deviation, coefficient of variation, range, and studentized range were analysed based on the available database, with the selection of the following possible influencing parameters: the w/c-ratios of the concretes, the age of the concretes, the cement types used for the concretes, the testing conditions of the concretes (dry/wet), the carbonation depths of the concretes and the impact energy of the rebound hammers (N-type original Schmidt hammer with impact energy of 2207 Nmm or L-type original Schmidt hammer with impact energy of 735 Nmm).

4.2 MODELLING

4.2.1. Development of the phenomenological model

The development of the model was induced by the extensive literature survey of the rebound method after the analysis of more than 150 technical publications of the last 60 years.
Deductive principles were followed in the theoretical research. The ideas were based on theoretical considerations, where it was appropriate, while in other cases empirical relationships were considered. General

experimental observations and limitedly available theoretical models were studied for the compressive strength and rebound index. Models were preferred where the degree of hydration was found to be the primary driver of phenomena. Since the mathematical modelling and experimental determination of the degree of hydration do not satisfy the principle of "intended simplicity for practical use", therefore, a simplification was applied; the degree of hydration was characterized by three variables: type of cement, water-cement ratio (w/c) and age of concrete. The randomness of the phenomena were not taken into consideration during the theoretical research by focusing mostly on general laws, that is, the particular influencing parameters were not considered as random variables. Revealing of the possible interrelationships has lead to the hypothesis of a phenomenological model for the compressive strength and rebound index of concrete which was able to generate data points of compressive strength and rebound index for concretes made from a given type of cement, with a given water-cement ratio, at a given age, by means of five general relationships. The generator functions are (all of them can be validated empirically): relationship between the water-cement ratio and compressive strength of concrete at the age of 28 days; development of compressive strength in time; relationship between compressive strength and rebound index of concrete at the age of 28 days; development of carbonation depth in time; relationship between carbonation depth and rebound index of concrete.

4.2.2 Robustness study by parametric simulation

The applicability of the model was tested by parametric simulation; by the preliminary selection of arbitrary function parameters. Series of functions were generated to simulate results that are similar to real experimental observations. Empirical formulations were selected from the technical literature for the generator functions of the model for the parametric simulation.

4.2.3 Model verification with laboratory tests

The intention of the experimental part of the research connected to modelling was to verify the applicability of the developed phenomenological model. Inductive principles were followed, i.e. laboratory tests were carried out under strictly controlled experimental conditions, with the introduction of sufficiently large number of test parameters changed on a wide range, on a large number of specimens. The general performance of the developed phenomenological model was studied by the appropriate graphical representation of the particular observations.

The experimental study was carried out at the Department of Construction Materials and Engineering Geology (BME). The tested 72 concrete mixes were prepared in accordance with present concrete construction needs during the experiments, i.e. slightly over-saturated mixes with different admixtures were designed. Consistency of the tested concrete mixes was constant: 500±20 mm flow provided by superplasticizer admixture. Design air content of the compacted fresh concrete for the tested concrete mixes was 1.0 V%. The specimens were stored in water tank for 7 days as curing. After 7 days the specimens were stored at laboratory condition. Test parameters were:

Water-cement ratio: 0.38 – 0.41 – 0.43 – 0.45 – 0.47 – 0.50 – 0.51 – 0.55 – 0.60
Cement type: CEM I 42.5 N – CEM III/B 32.5 N
Cement content (kg/m^3): 300 – 350 – 400
Mixing water content (kg/m^3): 150 – 165 – 180
Cement paste content (litres/m^3): 247 – 263 – 278 – 293 – 294 – 309
Aggregate-cement ratio: 4.5 – 4.6 – 4.7 – 5.3 – 5.4 – 5.5 – 6.3 – 6.5 – 6.6
Admixture type: accelerator admixtures (3 types)
Age of concrete at testing (days): 7 – 14 – 28 – 56 – 90 – 180

The 72 (9 water-cement ratio × 2 cement types × (3 admixture types + 1 reference mix)) mixes tested at 6 different ages with double repetitions (total number of 864 cube specimens of 150 mm) needed more than 3 cubic metres of concrete prepared and tested in the laboratory exclusively for the verification study. Surface hardness tests were carried out by the N-type Schmidt rebound hammer. Altogether twenty individual readings were recorded with the rebound hammers used in horizontal direction on two parallel vertical sides of the 150 mm cube specimens restrained by 40 kN force into a hydraulic compressive strength tester just before the compressive strength tests (according to EN 12390-3) were carried out. Carbonation depth of concrete specimens was measured by phenolphthalein solution.

4.3 TARGETED EXPERIMENTS

In addition to the model verification experimental study detailed previously, another experimental programme was completed on wide range of compressive strength of normal weight concretes to study the relationships between rebound hardness, compressive strength and Young's modulus of concrete. Concrete was mixed from Danube sand and gravel using CEM I 42.5 N cement. Cement paste volume was kept constant (304 litres/m^3) to be able to study the neat effect of the water-cement ratio, within the same aggregate skeleton. Consistency of the tested concrete mixes was 500±20 mm flow provided by superplasticizer admixture. Design air content of the compacted fresh concretes was 1.0 V%. The specimens were cast into steel formworks and the compaction of concrete was carried out by a vibrating table. The specimens were stored under water for 7 days as curing. After 7 days the specimens were stored at laboratory condition. 150 mm cube specimens and 120×120×360 mm prism specimens were prepared for the experiments. Test parameters were:

Water-cement ratio: 0.40 – 0.50 – 0.65
Cement content (kg/m^3): 315 – 375 – 425
Mixing water content (kg/m^3): 170 – 185 – 205
Aggregate-cement ratio: 4.25 – 4.85 – 5.75
Age of concrete at testing (days): 3 – 7 – 14 – 28 – 56 – 90 – 240 – 1100

For the 3 mixes tested at 8 different ages with double repetitions (total number of 48 cube specimens and 48 prism specimens) 500 litres of concrete was prepared and tested in the laboratory exclusively for present experimental study. Surface hardness tests were carried out by the original Schmidt rebound hammers of L-type and N-type as well as with a D-type Wolpert Leeb hardness tester of low impact energy as an alternative control impact device. The three devices have the same operating principle, i.e. an impact mass is accelerated by a spring toward the surface of the test object and impinges on it at a defined kinetic energy. The masses of the used impact bodies were 380 g for the N-type rebound hammer, 125 g for the L-type rebound hammer, and 5.5 g for the Wolpert Leeb hardness tester that resulted 2207 Nmm, 735 Nmm and 11 Nmm impact energy, respectively. Altogether 20 individual readings were recorded with the Schmidt rebound hammers used in horizontal direction on two parallel vertical sides of the 150 mm cube specimens restrained by 40 kN force into a hydraulic compressive strength tester just before the compressive strength tests (according to EN 12390-3) were carried out. Leeb hardness tests were carried out on the 120×120×360 mm prism specimens, right after the completion of the Young's modulus measurements (according to ISO 6784). Altogether 120 Leeb hardness readings were taken on the moulded side surfaces of each prism specimen.

5. HYPOTHESES AND NEW SCIENTIFIC RESULTS

5.1 STATISTICAL FINDINGS

According to the ACI 228.1R-03 Committee Report, the within-test standard deviation of the rebound index at a *test area** shows an increasing tendency with increasing average of the rebound index and the within-test coefficient of variation has an apparently constant value of about 10% (ACI, 2003) (**test area*: a concrete surface area that is not larger than 10×10 cm where 10 repeated rebound tests are performed by the same operator, with the same device in such a way that no reading is recorded on the same test point more than once) *(Fig. 2.a and b)*.

It can be realized that the information given in *Fig. 2.a and b* is rather limited: number of data points indicated in is only 55 and the range of the analysed rebound index is narrow and restricted to low values; all fall below rebound index of 35.

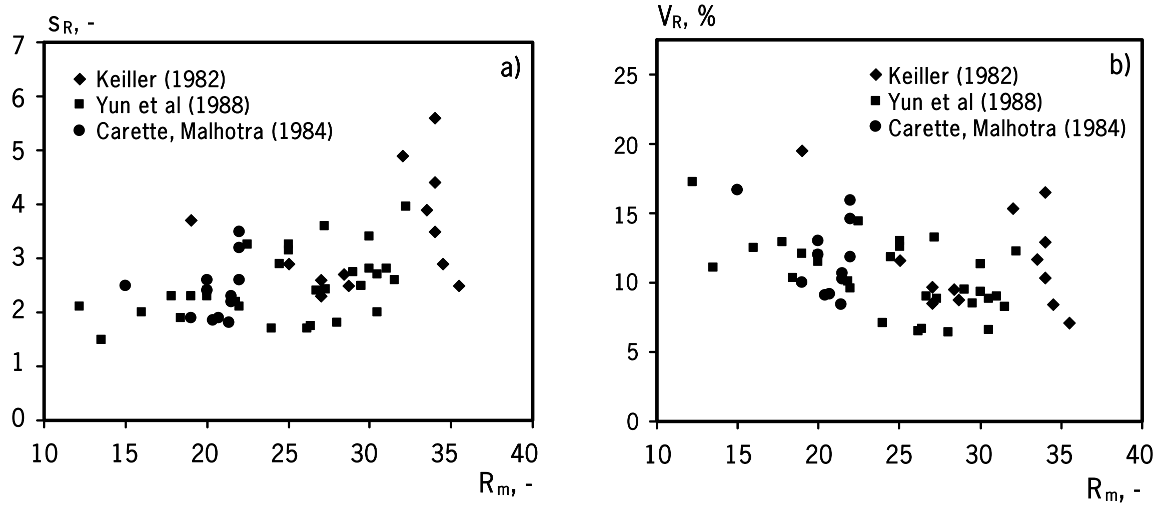

Fig. 2. a) Within-test standard deviation and b) coefficient of variation of rebound index over the average (ACI, 2003).

According to the available technical literature, standard deviation of the compressive strength of concrete does not depend on the average value of the compressive strength, only depends on the quality of the concrete production *(Fig. 3.a and b)* (fib, 1999).

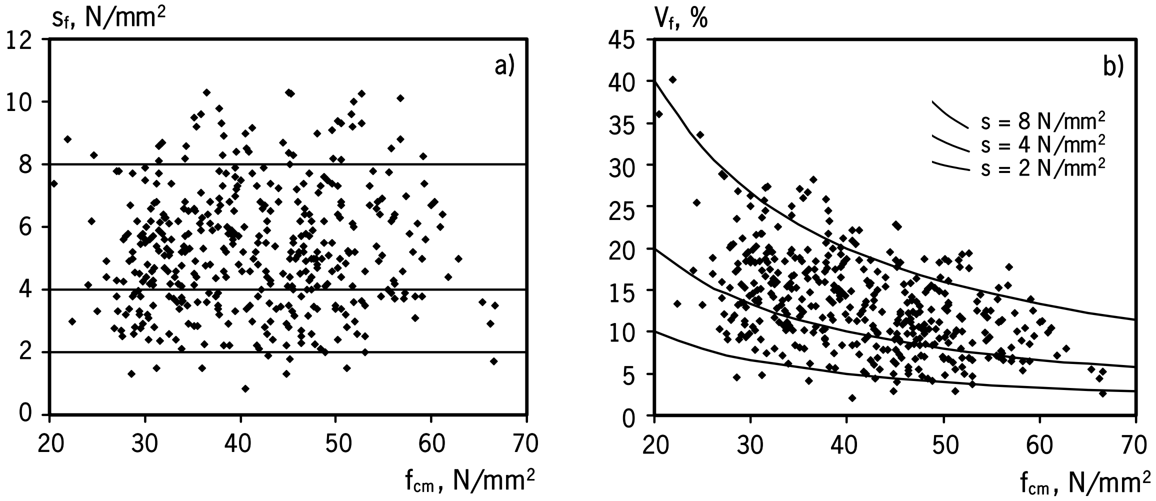

Fig. 3. a) Standard deviation and b) coefficient of variation of concrete compressive strength over the average (fib, 1999).

H1.1: Surface hardness and compressive strength of concrete are interrelated material properties. It is more likely during the production of higher strength concretes that rigorous quality control is performed, therefore, the standard deviation of strength is not expected to increase, but rather to decrease with increasing strength. Therefore, the within-test standard deviation of rebound index is not expected to increase with the average value of the rebound index.

T1.1 [3, 11]: I have demonstrated by the analysis of 8955 test areas (from which 4170 are laboratory and 4785 are in-situ test areas, with total number of individual rebound index readings exceeding fifty thousand) that the within-test standard deviation of the rebound index does not depend on the average value of the rebound index and the within-test coefficient of variation of the rebound index is inversely proportional to the average value of the rebound index (Domain: R = 10 – 63, codomain: 3.3 MPa – 105.7 MPa); implications given in some technical literature do not fit to empirical findings.

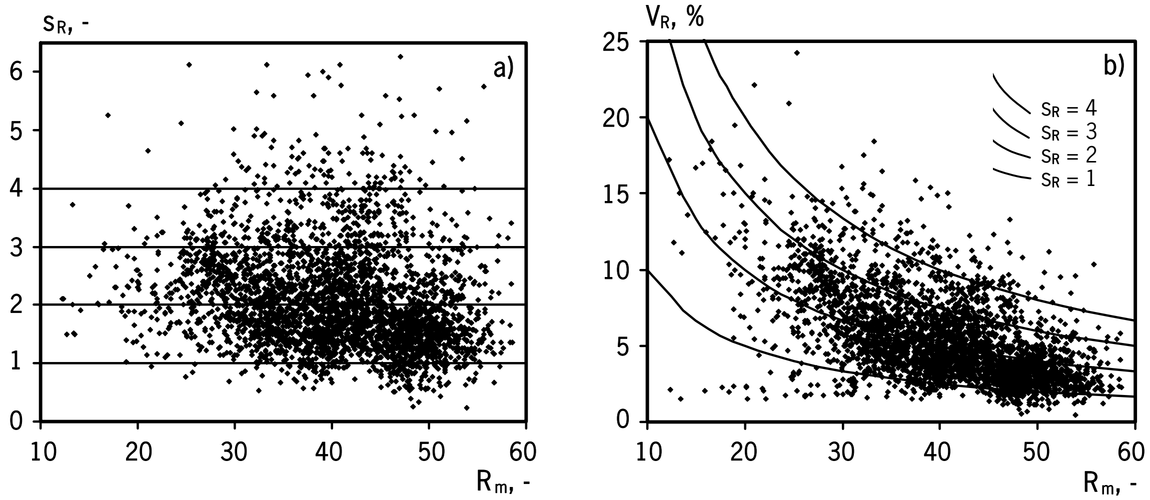

Fig. 4. a) Standard deviation and b) coefficient of variation of rebound index over the average.

The ASTM C 805 International Standard contains precision statements for the rebound index of the rebound hammers (ASTM, 2008). There are two underlying assumptions: (1) the within-test standard deviation of the rebound index has a constant value independently of the properties of the actual concrete and of the actual operator error, and (2) the percentage points of the standardized ranges of N(μ,1) normal probability distribution populations can be applied for the determination of the acceptable range of rebound index readings at test areas. It is given for the precision that the within-test standard deviation of the rebound index is 2.5 units, as "single-specimen, single-operator, machine, day standard deviation". Therefore, the range of ten readings should not exceed 12 units (taking into account a k = 4.5 multiplier given in ASTM C 670 (ASTM, 2003). The multiplier is actually the one digit round value of the p = 0.95 probability level critical value (k = 4.474124) for the standardized range statistic of a N(μ,1) normal distribution population at n = 10 according to Harter, 1960. Dependence of the within-test standard deviation on the average rebound index is not indicated in the standard and no indication is given either about the probability distribution of the within-test standard deviation of the rebound index or its percentile level for which the value is given.

H1.2: The probability distribution of the range (r_R) of ten (n=10) rebound index readings is supposed to follow a normal probability distribution, where $r_R = 12$ at a p = 0.95 probability level if n = 10.

The within-test standard deviation of the rebound index can be supposed to have a normal probability distribution with a mean value of $s_R = 2.5$ for n = 10.

On the other hand, it is demonstrated in the technical literature that the probability distribution of the coefficient of variation of concrete strength follows the log-normal probability distribution and the probability distribution of the concrete strength follows the normal probability distribution (Shimizu *et al*, 2000). Surface hardness and compressive strength of concrete are interrelated material properties. Therefore, it can be supposed that the probability distribution of the coefficient of variation of rebound index readings has a positive skewness.

T1.2 [3, 11]: I have demonstrated by the analysis of 8955 test areas (from which 4170 are laboratory and 4785 are in-situ test areas, with total number of individual rebound index readings exceeding fifty thousand) that the probability distribution of

- the range (r_R) of rebound index readings (based on 8342 test areas) and
- the standard deviation (s_R) of rebound index readings (based on 8955 test areas)
- the coefficient of variation (V_R) of rebound index readings (based on 8955 test areas)

has a positive skewness ($\gamma_r = 1.9432$; $\gamma_s = 1.7064$; $\gamma_V = 2.2472$), therefore, the supposition of having normal probability distribution should be rejected. Implications given in ASTM C 670 do not fit to empirical findings, but the assumption of the positive skewness of the coefficient of variation of rebound index is confirmed.

Goodness of fit (GOF) analysis of sixty different probability distributions has demonstrated that:

- the probability distribution of the range (r_R) of rebound index readings follows a four parameter Burr distribution (a=0.89001; b=4.0809; c=3.755; d=0.41591), of which mean value is $E[r_R] = 4.8068$; the median value is $m[r_R] = 4$; the mode value is $Mo[r_R] = 3.75$; the 95% percentile value is $v_{95}[r_R] = 9$; for the analysed range of $r_R = 1$ to 24. Value of $r_R = 12$ exceeds the experimental values in 98.7% of the cases (*Fig. 5a)*.
- the probability distribution of the standard deviation (s_R) of rebound index readings follows a three parameter Dagum (also referred in the literature as generalized logistic-Burr or inverse Burr) distribution (a=1.7958; b=3.7311; c=1.2171), of which mean value is $E[s_R] = 1.667$; the median value is $m[s_R] = 1.5$; the mode value is $Mo[s_R] = 1.45$; the 95% percentile value is $v_{95}[s_R] = 3.1526$; for the analysed range of $s_R = 0.23$ to 7.80. Value of $s_R = 2.5$ exceeds the experimental values in 88.5% of the cases (*Fig. 5b)*.
- the probability distribution of the coefficient of variation (V_R) of rebound index readings follows a three parameter Dagum distribution (a=2.2255; b=3.1919; c=2.7573), of which mean value is $E[V_R] = 4.4021\%$; the median value is $m[V_R] = 3.8\%$; the mode value is $Mo[V_R] = 3.125\%$; the 95% percentile value is $v_{95}[V_R] = 9.2132\%$; for the analysed range of $V_R = 0.43\%$ to 31.12% *(Fig. 6)*.

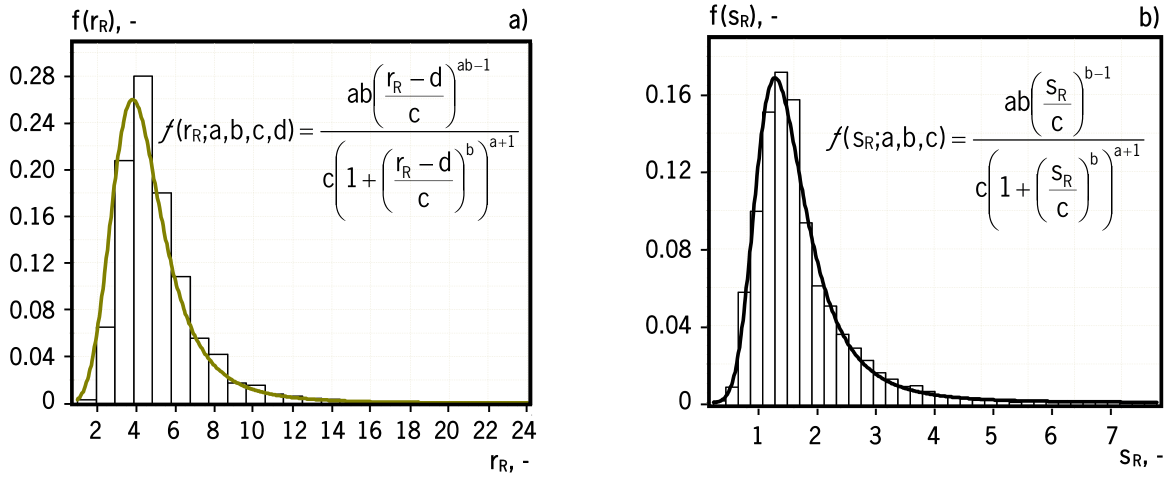

Fig. 5. Relative frequency histogram of the a) range and b) standard deviation of rebound index readings together with the best goodness of fit probability density function (PDF).

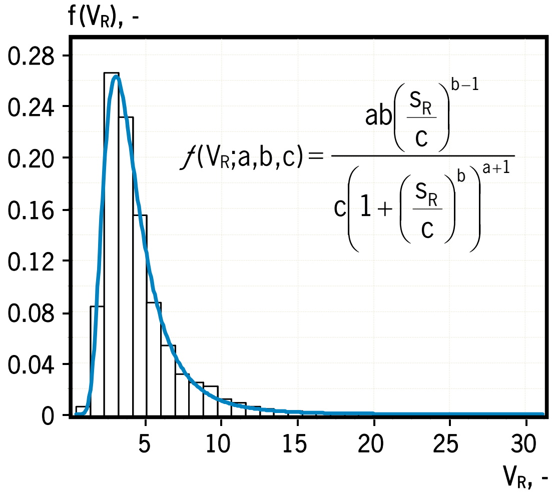

Fig. 6. Relative frequency histogram of the coefficient of variation of rebound index readings together with the best goodness of fit probability density function (PDF).

Goodness of fit analysis of sixty different probability distributions has demonstrated that the probability distribution of the coefficient of variation (V_R) of rebound index readings follows a three parameter Dagum distribution (a=2.2255; b=3.1919; c=2.7573), of which mean value is $E[V_R] = 4.4021\%$; the median value is $m[V_R] = 3.8\%$; the mode value is $Mo[V_R] = 3.125\%$; the 95% percentile value is $v_{95}[V_R] = 9.2132\%$; for the analysed range of $V_R = 0.43\%$ to 31.12% (*Fig. 6)*.

Reliability analysis techniques mostly concentrate on the use of the coefficient of variation for taking into account the variability of different material characteristics, rather than the standard deviation. One may practically select in this view the coefficient of variation as the repeatability parameter for the rebound method, as well. For this purpose, however, the governing parameters over the changes of the coefficient of variation are needed to be known.

T1.3 [3, 11]: I have demonstrated by laboratory and in-situ tests that the magnitude of the within-test coefficient of variation of rebound index readings (V_R) is influenced by the type of cement, the water-cement ratio, the age of concrete, the depth of carbonation and the impact energy of the rebound hammer.

- I have demonstrated on 9 different cement types and 102 different concrete mixes that the average coefficient of variation of rebound index readings (V_R) on concretes prepared by CEM I is lower (~ 3.5 %) than those of prepared by CEM II or CEM III (~ 5.0 %) *(Fig. 7)*. I have demonstrated for CEM I cements that the average coefficient of variation of rebound index readings (V_R) is decreasing by increasing the strength class of the cement. Studied cement types: CEM I 32.5; CEM I 42.5 N; CEM I 42.5 N-S; CEM I 52.5; CEM II/A-S 42.5; CEM II/A-V 42.5 N; CEM II/B-M (V-L) 32.5 N; CEM III/A 32.5 N-MS; CEM III/B 32.5 N-S.
- I have demonstrated on 6 different cement types and 93 different concrete mixes that the average coefficient of variation of rebound index readings (V_R) is decreasing by decreasing the water-cement ratio *(Fig. 8)*. 1-10 % differences can be realized between the coefficients of variation of rebound index corresponding to different water-cement ratios, depending on the age of concrete and impact energy of the device. Analysed range of the water-cement ratio: w/c = 0.35 to 0.65.
- I have demonstrated on 9 different cement types and 102 different concrete mixes that the average coefficient of variation of rebound index readings (V_R) considerably decreases in the first 14 (from ~6 %), reaches a minimum (at ~4 %) at the age of 28 to 56 days and gradually increases afterwards (to ~5 %) *(Fig. 9a)*. Analysed range: 1 to 1100 days of age.
- I have demonstrated on 30 different concrete mixes that the average coefficient of variation of rebound index readings (V_R) is increasing by an increasing carbonation depth of concrete *(Fig. 9b)*. Analysed range of carbonation depth: x_c = 2.2 to 22.8 mm, and the corresponding coefficients of variation of rebound index were found to be ~3 % and ~8 %, respectively. Analysed range of compressive strength of concrete: f_{cm} = 42.6 to 91.7 MPa.
- I have demonstrated for CEM I cement type that the average coefficient of variation of rebound index readings (V_R) is higher for the lower impact energy when concretes tested before the age of 56 days (can reach up to 14-17 %). After 56 days of age the differences gradually disappear in time (*Fig. 8)*. Analysed range of the water-cement ratio: w/c = 0.40 to 0.65. Analysed range of age: 3 – 1100 days. Analysed range of impact energy: 735 Nmm and 2207 Nmm.

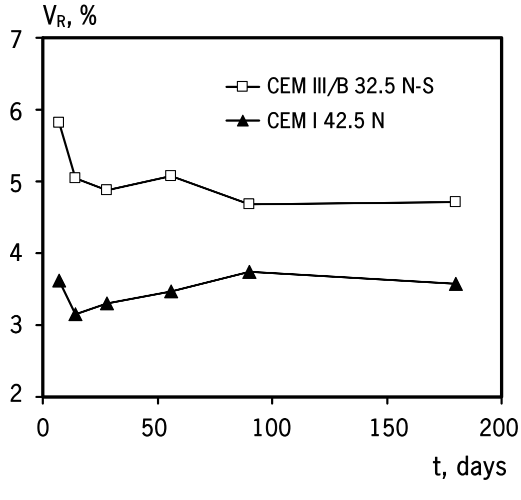

Fig. 7. Influence of the type of cement on the coefficient of variation of rebound index.

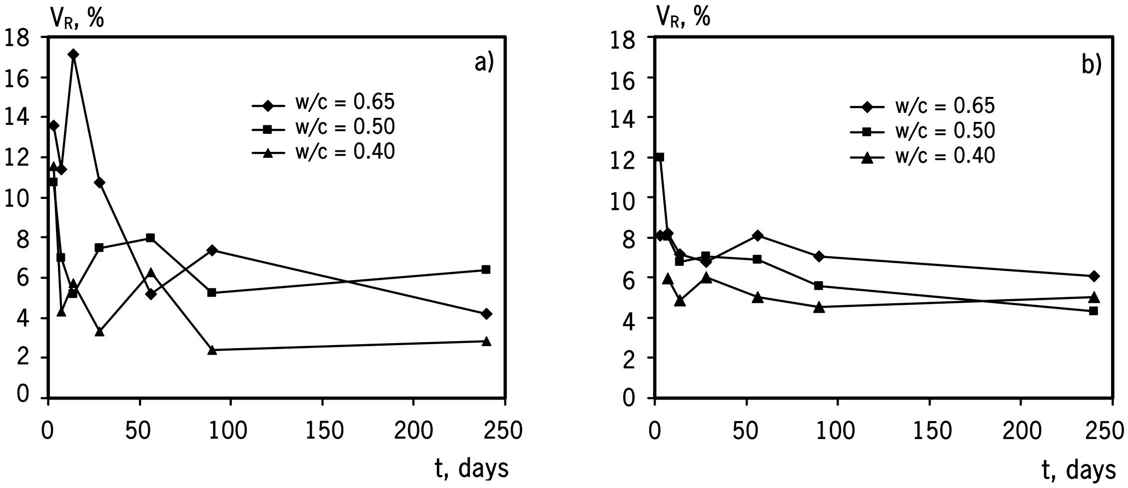

Fig. 8. Influence of the water-cement ratio and the impact energy a) 735 Nmm, b) 2207 Nmm on the coefficient of variation of rebound index in time.

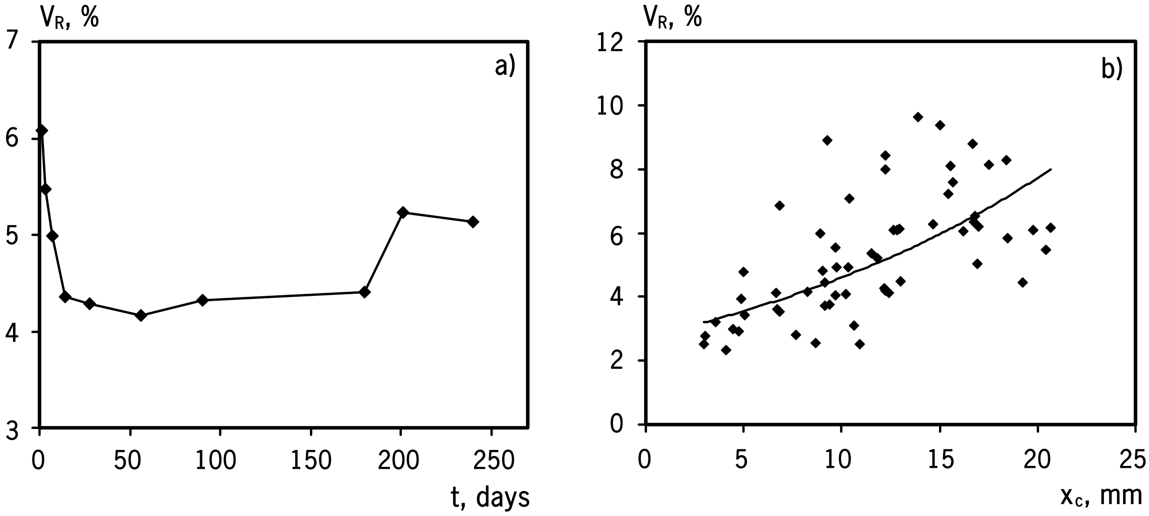

Fig. 9. Influence of the a) age and the b) average depth of carbonation on the coefficient of variation of rebound index.

5.2 MODELLING OF REBOUND HARDNESS

Aim of Schmidt rebound hammer tests is usually to find a relationship between surface hardness and compressive strength of concrete with an acceptable error. The hardness testing devices have been developed for in-situ testing of concrete based on the observation that the surface hardness of concrete can be related to the compressive strength of concrete.

The existence of only empirical relationships was considered in the earliest publications (Anderson et al, 1955; Kolek, 1958) and also recently (Bungey at al, 2006; Kausay, 2013).

For the rebound method no general theory was developed that can describe the relationship between measured hardness values and compressive strength.

It should be also highlighted that researchers usually do not separate the experimental data by different influencing parameters in the graphical representations of the corresponding rebound index vs. compressive strength results – that was typically experienced over the last 60 years.

Numerous empirical relationships between compressive strength and surface hardness of concrete are available in the technical literature, but usually based on very simple laboratory tests, i.e. mainly univariate regression curves are available (*Fig. 10)*. Only a few extensive studies can be found that consider multiple influencing parameters together with detailed parameter analysis (Herzig, 1951; Borján, 1981; Tanigawa et al, 1984).

H2.1: Compressive strength and surface hardness of concrete are only partially determined by the same physical characteristics or chemical processes and these can vary over time in particular cases. It is not expected that a single univariate function exists between the compressive strength and the rebound index (either in an R_m-f_{cm} or an f_{cm}-R_m coordinate system) with a confidence interval that is suitable for engineering applications.

T2.1 [2, 11, 12]: I have demonstrated based on an extensive literature review – after studying the results of more than 150 literature references – as well as on own laboratory and in-situ test results that it is not possible to find – and during the last more than 60 years it did not happen – a single univariate function between the compressive strength and rebound index that would provide an R_m-f_{cm} or an f_{cm}-R_m relationship with a confidence interval suitable for engineering applications.

Based on the published R_m - f_{cm} relationships the following conclusions can be drawn:

- The most accepted function form is the power function.
- Concrete strength estimation for a given rebound index is found to be published in a ±40 to 60 N/mm^2 wide range, i.e. it is possible to find estimated strengths for different concretes with 40 to 60 N/mm^2 strength differences corresponding to the same rebound index.
- The validity of a literature proposal should be restricted to the testing conditions and the extension of the validity to different types of concretes or testing circumstances is impossible.
- The R_m-f_{cm} basic curve suggested by the current European Standard testing practice (EN 13791:2007) does not always give a conservative estimation, in certain cases a negative shift of 6-8 N/mm^2 would be needed (which cannot occur according to the standard) (Fig. 10).
- The remarkable diversity of the proposed curves (Fig. 10) implies the need of the two- or more variable regression techniques to reveal the most important influences on the hardness behaviour.

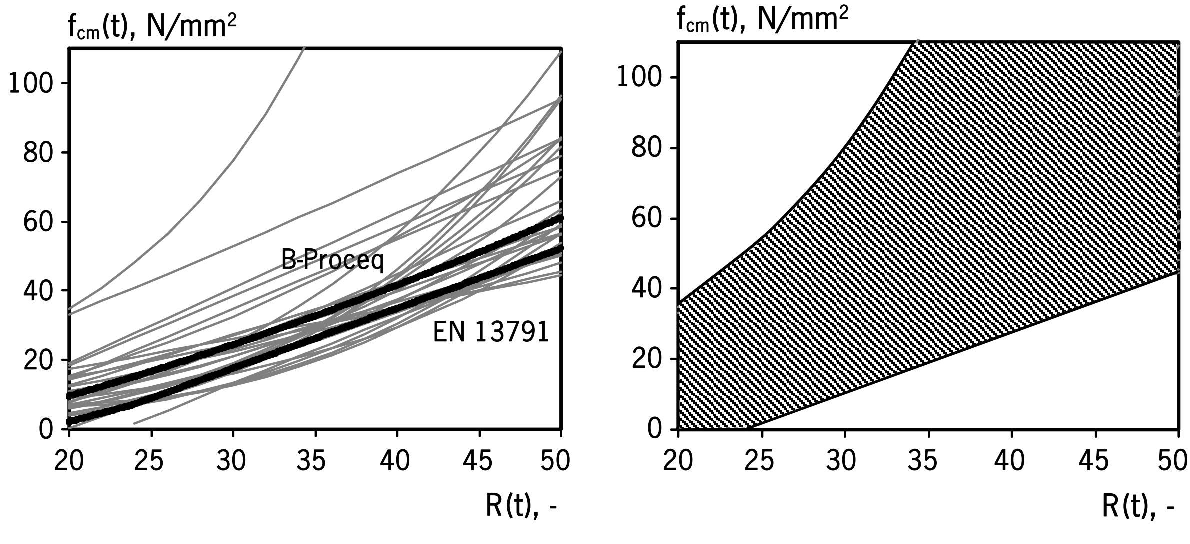

Fig. 10. Empirical curves for the rebound index vs. compressive strength relationship of concrete and their overall range found in the technical literature.

Surface hardness and compressive strength of concrete are depending on several parameters (e.g. type of cement, amount of cement, type of aggregate, amount of aggregate, compaction of structural concrete, method of curing, quality of concrete surface, age of concrete, carbonation depth in the concrete, moisture content of concrete, mass of the structural element, temperature and state of stress) therefore, univariate regression between hardness and strength may lead to completely misleading results and can hide the real driver of the relationship.

H2.2: The following observations can be summarised for hardened concrete in view of the water-cement ratio and the age of concrete according to own experimental results as well as technical literature data:

- average compressive strength of concretes of 28 days of age can be formulated for different cement types as exponential functions of the water-cement ratio (e.g. Ujhelyi, 2005),
- average compressive strength of concretes at any age can be formulated in a simplified way (i.e. independently of the water-cement ratio) for different cement types as exponential functions of the average compressive strength of concretes at 28 days of age (e.g. CEB-FIP Model Code 1990); in fact, the strength development of concretes depends on the water-cement ratio (e.g. Washa, Wendt, 1975),
- carbonation depth of concretes at any age can be formulated in a simplified way as functions of age, water-cement ratio and type of cement (e.g. Papadakis et al, 1992),
- rebound hardness development in time for identical composition concretes stored under identical conditions can be formulated (e.g. Kim *et al*, 2009),
- relationships between the rebound hardness and the depth of carbonation of concretes can be formulated (e.g. JGJ, 2001),
- relationships between the rebound hardness and the compressive strength of concretes can be formulated for concretes of the same age that are prepared with identical cements and stored under identical conditions.

The existence of a series of multivariate functions can be hypothesized based on the above findings which functions can give an explicit relationship between the average rebound index $R_m(t)$ and average compressive strength $f_{cm}(t)$ of concrete of arbitrary age. The independent variables of the functions are the degree of hydration for the cement paste (that is determined by the water-cement ratio, the age, the type of cement and the curing/environmental conditions), and variables accounting for the amount of the cement and the aggregate, the degree of compaction and the testing conditions.

T2.2 [2, 6, 9]: I have demonstrated that a series of multivariate functions can be constructed which give an explicit relationship between the average rebound index $R_m(t)$ and the average compressive strength of concrete $f_{cm}(t)$. I have demonstrated that a simplified version can be a series of bivariate functions with two independent variables: the water-cement ratio and the age of concrete. I have demonstrated by a parametric simulation that the simplified model is robust and suitable to describe experimental results. I have verified the model by a laboratory test of 864 concrete cube specimens of 150 mm made of two cement types (CEM I 42.5 N and CEM III/B 32.5 N), with a range of water-cement ratio of 0.38 to 0.60 and age of concrete at testing of t = 7 to 180 days.

5.2.1 Composition of the model

The generation scheme of the model as well as the symbolic shapes of the individual functions given by Eq. (1) to Eq. (5) can be studied in *Fig. 11*.

The formulation of the model includes the following experimental relationships:

A) The compressive strength of concrete at the age of 28 days can be described by an exponential function of the water-cement ratio (Eq. 1).

$$f_{c,28} = a_1 \cdot exp\left\langle a_2 \cdot (w/c)^{a_3} \right\rangle \qquad \text{Eq. (1)}$$

with $a_1 > 1$, $a_2 < 0$, $0 < a_3 < 1$

B) The development of the compressive strength of concrete with time can be followed by an exponential function of time (Eq. 2).

$$f_c(t)/f_{c,28} = exp\left\langle a_4 \cdot (1 - (28/t)^{a_5} \right\rangle \qquad \text{Eq. (2)}$$

with $0 < a_4 < 1$, $0 < a_5 < 1$ and both parameter a_4 and a_5 is a function of ***w/c***.

C) An empirical relationship of a power function can be assumed between the strength of concrete and the rebound index at the age of 28 days (Eq. 3).

$$f_{c,28} = a_6 \cdot R_{28}^{a_7} \qquad \text{Eq. (3)}$$

with $a_6 > 0$, $a_7 \geq 1$

D) The development of the carbonation depth in concrete with time can be described by models based on *Fick*'s law of diffusion (Eq. 4).

$$x_c = \left(a_8 \cdot (w/c) - a_9\right) \cdot t^{a_{10}} \qquad \text{Eq. (4)}$$

with $0 < a_8 < 1$, $0 < a_9 < 1$, $0 < a_{10} < 1$

E) Carbonation of concrete results an increase in the surface hardness that can be assumed to be modelled by a power function of the carbonation depth (Eq. 5).

$$R(t)/R_{28} = \frac{1}{1 + a_{11} \cdot x_c^{a_{12}}} \qquad \text{Eq. (5)}$$

with $a_{11} < 0$, $a_{12} > 0$

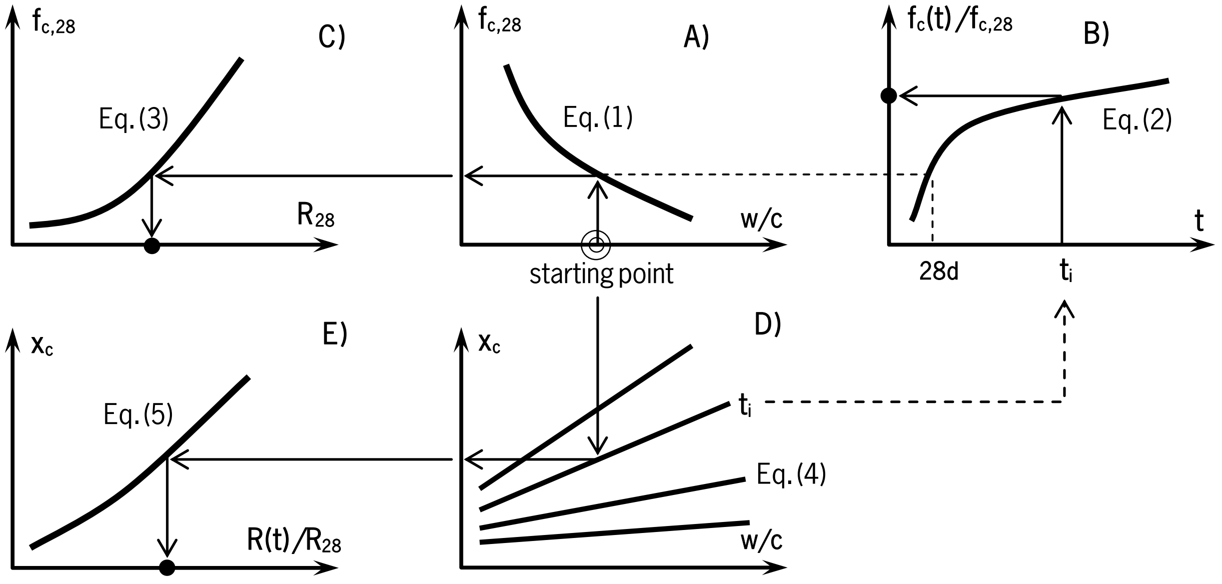

Fig. 11. The generation scheme of the phenomenological model.

The model can provide corresponding compressive strength, $f_c(t)$ and rebound index, $R(t)$ values for any water-cement ratio at any age of concrete (t) *(Fig. 12a):* the output of the model is a set of curves corresponding to different water-cement ratios at different ages of the concrete. The shape and curvature of the individual curves are depending on the actual values of the twelve empirical constants a_1 to a_{12} covered in Eqs. (1) to (5).

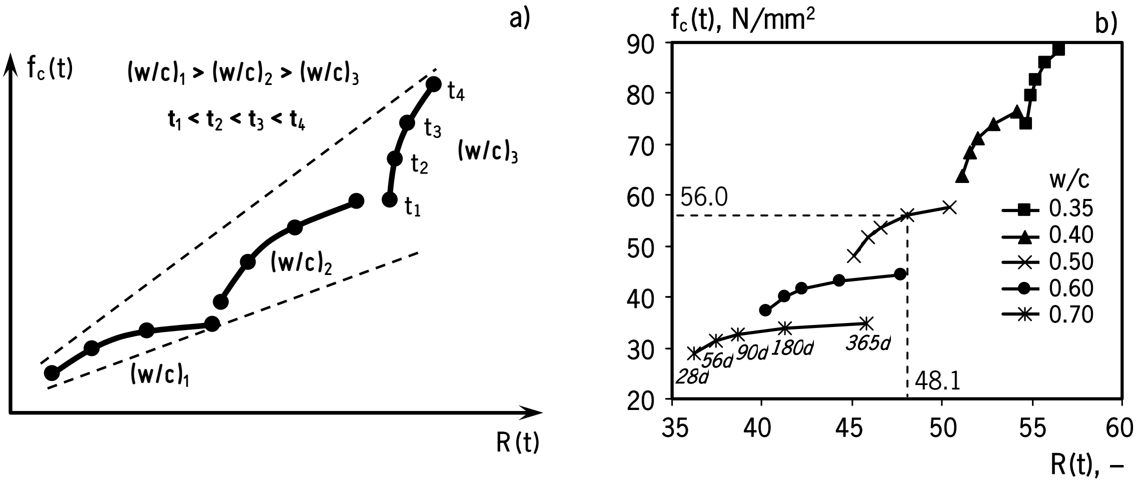

Fig. 12. a) Typical schematic $f_c(t)$ vs. $R(t)$ response as an output of the model; b) Parametric simulation by the model.

5.2.2 Parametric simulation by the model

The following empirical formulations were selected from the technical literature for the generator functions of the model for the parametric simulation by the model.

For the water-cement ratio vs. compressive strength of concrete at the age of 28 days (for cement type of CEM I 42.5 N) the empirical formula of *Ujhelyi* is selected due to the assumptions made by *Ujhelyi* and *Popovics* (2006):

$$f_{c,28} = 406 \cdot exp\left\langle -3.30 \cdot (w/c)^{0.63} \right\rangle \qquad [\mathrm{N/mm^2}] \qquad \text{Eq. (6)}$$

Development of the compressive strength in time depends on the type of cement and the water-cement ratio (Washa, Wendt, 1975; Wood, 1991) (see H3.2 hypothesis). Models available usually neglect the influence of the water-cement ratio.

For the parametric simulation the proposal of the CEB-FIP Model Code 1990 (CEB, 1993) is selected for the development of compressive strength in time, neglecting the influence of the water-cement ratio:

$$f_c(t)/f_{c,28} = exp\left\langle 0.25 \cdot (1-(28/t)^{0.50} \right\rangle \qquad \text{Eq. (7)}$$

Rebound index vs. compressive strength relationships at the age of 28 days are generally non-linear. For the parametric simulation the proposal of Proceq SA (manufacturer of the *Schmidt* rebound hammers) (Proceq, 2003) is selected for the rebound index vs. compressive strength relationships at the age of 28 days:

$$f_{c,28} = 3.07 \cdot 10^{-2} \cdot R_{28}{}^{1.952} \qquad [\mathrm{N/mm^2}] \qquad \text{Eq. (8)}$$

Development of the depth of carbonation in concrete with time can be described reasonably well by models based on *Fick's* law of diffusion. For the parametric simulation the model of *Papadakis et al* (1992) is selected for the carbonation depth of concrete. Its generalized form for the development of the carbonation depth in time is:

$$x_c = \psi 0.35 \rho_c \frac{w/c - 0.30}{1 + \frac{\rho_c}{1000} w/c} f(\mathrm{RH}) \cdot \left(\left(1 + \frac{\rho_c}{1000} w/c + \frac{\rho_c}{\rho_a} \mathrm{a/c} \right) C_{\mathrm{CO_2}} \frac{23.8}{44} 10^{-6} t \right)^{0.50} \qquad [\mathrm{mm}] \qquad \text{Eq. (9)}$$

In Eq. (9) the parameter f(RH) can be taken according to the results of *Matoušek* (1977). If one accepts f(65% RH) = 0.45, C_{CO2} = 800 mg/m^3, ρ_c = 3150 kg/m^3 and ρ_a = 2650 kg/m^3 then Eq. (9) can be simplified and rearranged and can be rewritten as:

$$x_c = (0.50 \cdot (w/c) - 0.14) \cdot \sqrt{t} \qquad [\mathrm{mm}] \qquad \text{Eq. (10)}$$

Limits of use of application for Eq. (10) are $0.35 < w/c < 0.65$ and $4.50 < a/c < 6.50$. It means that cement content c = 290 kg/m^3 to 420 kg/m^3 is to be assumed. For different relative humidity (RH ≠ 65%) and CO_2 concentrations Eq. (9) applies.

Surface hardness of concrete can be considerably changed by carbonation (Kim et al, 2009). Therefore, the influence of carbonation should be taken into account in the evaluation of rebound surface hardness tests. For the parametric simulation the proposal of the Chinese Standard JGJ/T23-2001 is selected for the influence of carbonation depth on rebound index (JGJ, 2001):

$$R(t)/R_{28} = \frac{1}{1 - 0.067 \cdot x_c^{1.0}} \qquad \text{Eq. (11)}$$

The limit of use to apply Eq. (11) is $x_c < 6.0$ mm.

A result of the parametric simulation can be studied for five different water-cement ratios in *Fig. 12b*. For one point on the series of the curves (indicated with dashed lines in *Fig. 12b* as an example the following details are given. Starting value for water-cement ratio is $w/c = 0.50$ and the age of concrete is $t = 180$ days.

Based on formulae covered by Eq. (6) to (11) the numerical results can be calculated as follows:

By Eq. (6): $f_{c,28} = 406 \cdot exp\langle -3.30 \cdot 0.50^{0.63} \rangle = 48.13$ N/mm^2

By Eq. (7): $f_c(180) = 48.13 \cdot exp\langle 0.25 \cdot (1 - (28/180)^{0.50} \rangle = 56.0$ N/mm^2

By Eq. (8): $R_{28} = 5.96 \cdot 48.13^{0.512} = 43.35$

By Eq. (10): $x_c(180) = (0.50 \cdot 0.50 - 0.14) \cdot \sqrt{180} = 1.48$ mm

By Eq. (11): $R(180) = 43.35/(1 - 0.067 \cdot 1.48) = 48.11$

It can be realized that the model gives a realistic formulation for the time dependent behaviour of the rebound surface hardness of concrete. It can be clearly observed that the consideration of the data points as one group of data would not be acceptable; however, an appropriate selection of the parameters can generate a transparent and reliable series of curves that follow the real material response.

5.2.3 Experimental verification of the model

The experimental programme made possible a detailed verification study to be carried out on a wide range of compressive strengths and ages of concrete at testing. Typical results are introduced in *Fig. 13* corresponding to concrete specimens prepared with CEM I 42.5 N cement. *Fig. 13* represents test results for only 104 specimens.

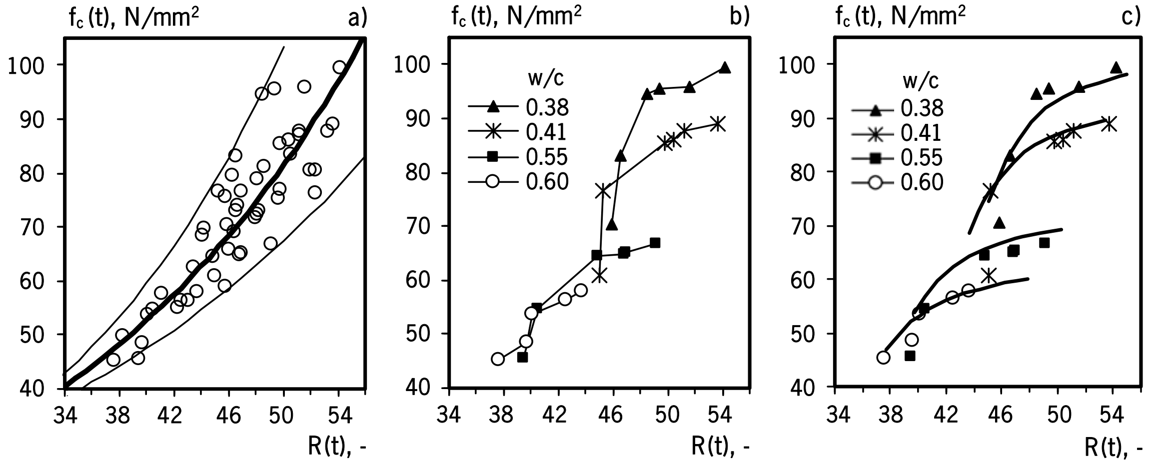

Fig. 13. Experimental verification of the model on concrete cube specimens prepared with CEM I 42.5 N cement; a) data in non-separated representation, b) data separated by the applied water-cement ratios, c) data represented together with the fitted model.

The following observations can be emphasized:

1) An apparently coherent population of data is resulted if one does not differentiate water-cement ratios and ages of concrete in the graphical representation of test data *(Fig. 13a)*. A completely misleading trend of results is realized and an apparent power function or exponential function relationship can be the output of a regression analysis (usually with considerably good correlation coefficients that may further ratify the misleading direction of the analysis). In *Fig. 13a* 52 data points are indicated as the pair-averages of the 104 specimens (covering 9 different water-cement ratios and 6 different ages of concrete at testing). Regression curve of an exponential function is also indicated. The correlation coefficient was found to be $r^2 = 0.84$ for this false relationship.

2) A heteroscedastic behaviour of the rebound index vs. compressive strength data pairs is realized if one does not differentiate water-cement ratios and ages of concrete in the graphical representation of test data *(Fig. 13a)*. It can be studied in *Fig. 13a* that the distance between the lower and upper limit curves corresponding to the increasing rebound index values is increasing with the increase of R(t) that can result the heteroscedasticity (i.e. increasing standard deviation in strength for increasing rebound index).

3) The real performance appears only if one separates the rebound index vs. compressive strength data pairs by the water-cement ratio *(Fig. 13b)*. For the sake of better visualisation only 4 curves are represented in *Fig. 13b* from the 9 different water-cement ratios studied. It can be realized that the apparently coherent population of data comes loose to separate monotonic curves for the different water-cement ratios.

4) It can be seen in the real performance that rebound index vs. compressive strength relationships are sensitive (but not uniformly) to the water-cement ratio applied *(Fig. 13b)*. The gradients and directions of the responses clearly indicate the influence of the capillary pores of different water-cement ratios on the strength development and carbonation depth development differences. It can be postulated that the water-cement ratio dependent strength development and carbonation depth development behaviour of concretes gives the complete explanation of the observed results. Results of the verification study confirmed that the most

significant influencing parameters are the water-cement ratio, the type of cement and the age of the concrete. Further parameters have much less pronounced influences; as it was presumed.
5) The application of the model is reasonable for the rebound index vs. compressive strength data *(Fig. 13c)*. A suitable fit of the empirical parameters of the model can result an acceptable numerical reproduction of any experimental data. The detailed verification study demonstrated the applicability of the model for CEM I 42.5 N and CEM III/B 32.5 N cements on a wide range of water-cement ratios and ages of concrete at testing.

5.3 RESULTS OF THE TARGETED EXPERIMENTS

During static indentation hardness tests plastic deformation is normally associated with ductile materials (e.g. metals). Brittle materials (e.g. concrete) generally exhibit elastic behaviour, and fracture occurs at higher deformations rather than plastic yielding. Pseudo-plastic deformation is observed in brittle materials beneath the point of an indenter, but it is a result of *densification*, where the material undergoes a phase change as a result of the high value of compressive stress in a restrained deformation field beneath the indenter (Swain, Hagan, 1976). The softening fashion of the pseudo-plastic material response with increasing volume of the material is considerably different from that can happen to metals during plastic deformation (where the volume of the material is unchanged during yielding) (Tabor, 1951).
During dynamic hardness measurements the inelastic properties of concrete may be as important as the elastic properties due to the softening fashion of the material response. The value of the rebound index depends on energy losses due to friction during acceleration and rebound of the hammer mass and that of the index rider, energy losses due to dissipation by reflections and attenuation of mechanical waves inside the steel plunger; and energy losses due to dissipation by concrete crushing under the tip of the plunger.

H3.1: Comparison of the relative values of the rebound hardness and mechanical properties (compressive strength and Young's modulus) of concrete (represented as values related to a value of a particular age) may promote to find a relationship between the rebound hardness and a particular mechanical property. The measures of the rebound hardness testing devices are supposed to be sensitive not only to the strength but also to the stiffness of the concrete and influenced by the impact energy of the device.

T3.1 [2, 4, 7]: I have demonstrated by laboratory tests that the impact energy of the device determines – through the obtained hardness characteristic – the mechanical property which can be associated with the hardness value. The measures of the rebound hardness testing devices are sensitive not only to the strength but also to the stiffness of the concrete and influenced by the amount of impact energy of the device. It means that the lower the impact energy of a dynamic hardness tester is, the more likely the hardness value can be related to the Young's modulus (the deformation of concrete is rather elastic), particularly in case of small water-cement ratios; and the higher the impact energy of the dynamic hardness tester is, the more likely the hardness value can be related to the compressive strength (during the test larger portion of the strain energy dissipates), particularly in case of high water-cement ratios.

Laboratory test results indicated that the development of the relative value of rebound indices of L- and N-type Schmidt rebound hammers in time approach the development of the relative value of compressive strength in time for high water-cement ratio (w/c = 0.65), and approach the development of Young's modulus in time for low water-cement ratio (w/c = 0.40), independently of the age of concrete at testing. For medium water-cement ratio (w/c = 0.50) an intermediate trend is observed. The development of the Leeb hardness in time coincide the development of Young's modulus of concrete in time (related to the value of either 7 or 28 days of age), over the complete range of the tested water-cement ratios (w/c = 0.40 – 0.65), independently of the age of concrete at testing (*Fig. 14)*.
Very low impact energy is introduced to the tested surface in the case of the Leeb hardness tests and the material response is mostly governed by the elastic properties of the tested material.

The Schmidt rebound hammers apply much higher impact energy (both the L-type and the N-type devices), therefore, the material response was found to be inelastic in a much more pronounced way; highly depending on both the actual strength and stiffness of the concrete.

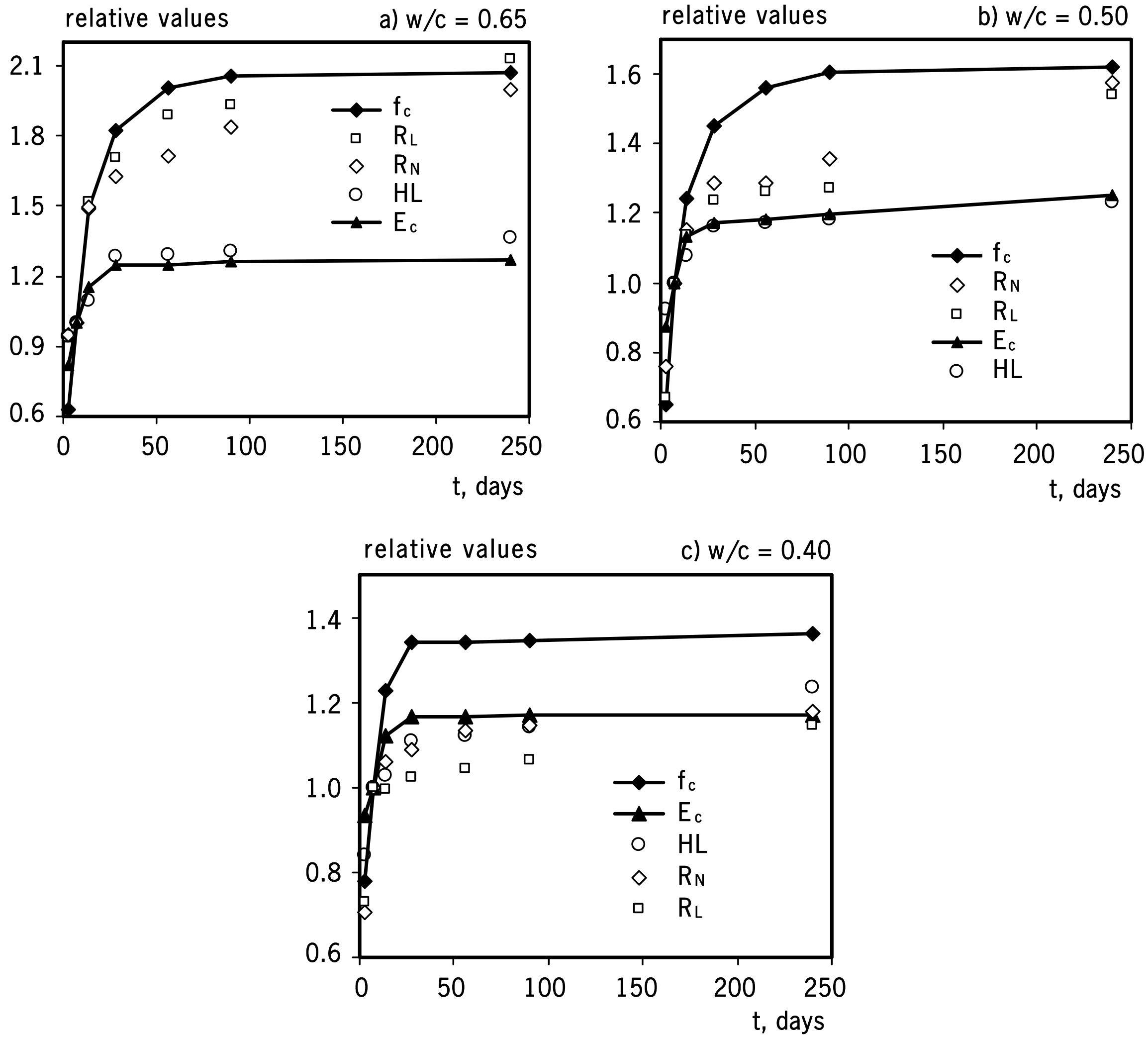

Fig 14. Relative values (related to 7 days) of the tested parameters in the function of time for water-cement ratios w/c=0.40, 0.50, 0.65.

In the technical literature the role of cement type in the development of compressive strength (i.e. compressive strength values at a certain age related to the value obtained at 28 days of age) is highlighted and widely accepted (e.g. CEB, 1993). It is not fundamental evidence, however, that the development of compressive strength of concretes depends on the water-cement ratio. The suggestion of CEB-FIP Model Code 1990 (CEB, 1993) neglect the effect of water-cement ratio *(Fig. 15)*.

H3.2: After analysing the available technical literature data it is demonstrated by 20 to 50 years long laboratory tests (e.g. Washa, Wendt 1975; Wood, 1991) that the development of the relative compressive strength of concrete in time depends on the water-cement ratio, in addition to the applied cement type. It can be supposed that the development of the relative rebound hardness in time also depends on the water-cement ratio.

T3.2 [2, 4, 7]: I have demonstrated by laboratory tests that the development of the relative values of the rebound hardness of concrete (related to the value of 28 days of age) are influenced by the water-cement ratio. The influence is more pronounced with the increase of the maturity of concrete due to the effect of carbonation in case of high water-cement ratios.

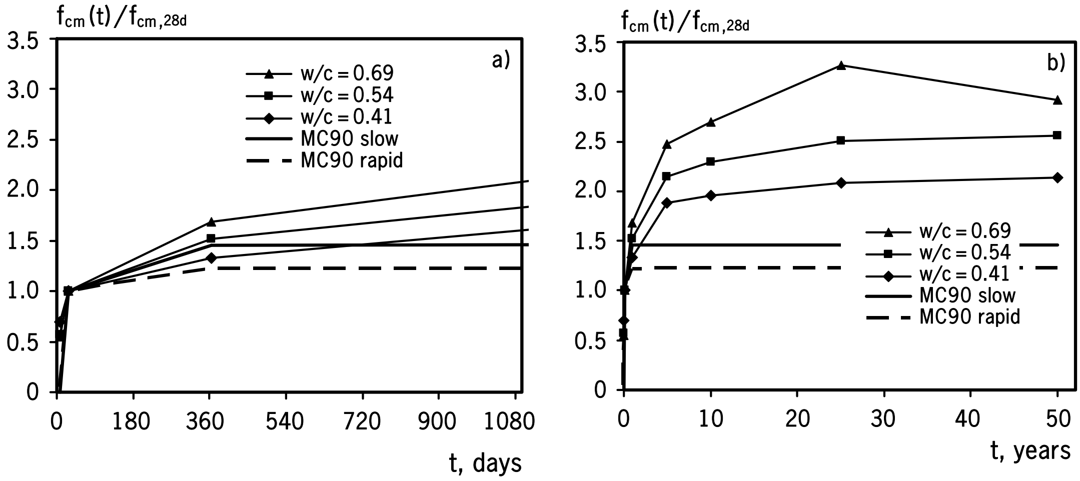

Fig 15. Compressive strength in time according to (Washa, Wendt, 1975) together with the suggestion of (CEB, 1993), related to the values obtained at 28 days of age; a) short-term representation, b) long-term representation.

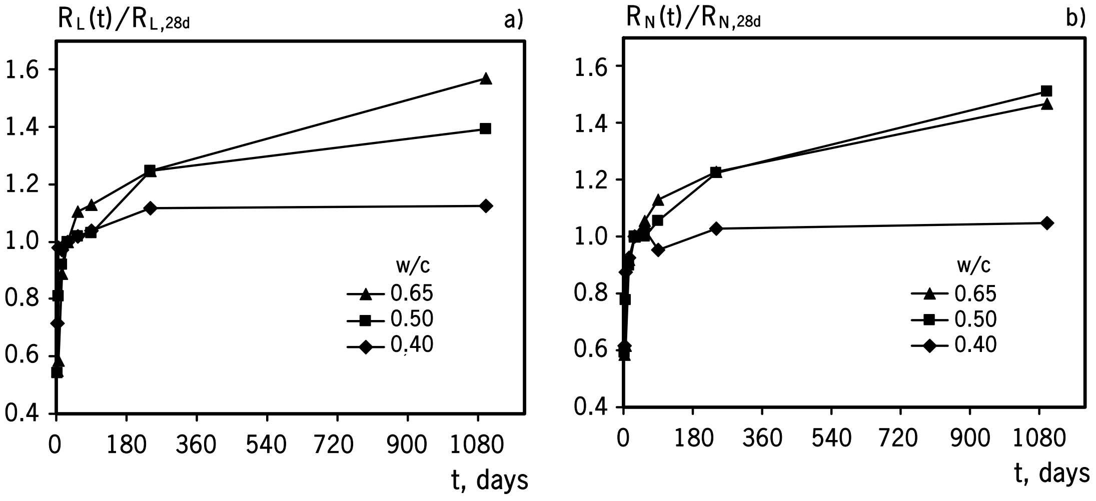

Fig 16. Water-cement ratio dependency of the rebound index (provided by both L- and N-type rebound hammers) in time.

6. THEORETICAL AND PRACTICAL BENEFITS

According to both International and European Standards the use of the rebound method for strength estimation on its own is not suggested. The concept of e.g. EN 13791 considers that the mechanical properties determined indirectly by non-destructive methods are influenced by large number of parameters therefore the compressive strength of structural concrete can be estimated with the maximum possible reliability only by the standard approach, at the moment. However, it should be added that testing of structures are excluded where at least 9 cores are not possible to be drilled. This relatively large number of cores restrain the practical use of the rebound method.Findings of present PhD study may help to take some steps toward a better fundamental understanding of the rebound hardness of concrete, as well as to point out both future application possibilities and practical limits:

- It is needed to be declared that a relationship exists between the rebound hardness and the compressive strength of concrete as it was expected, but an univariate relationship does not exist.
- The introduced phenomenological model consisting of a series of curves governed by the degree of hydration can reasonably describe the relationship. The transparency of the model offers further promising development, however, provides also in its present form the long time missing fill to the gap of knowledge appeared in the last 60 years. The shape and variable tangent of the series of curves in the graphical representation of the developed model can explain the large scatter of the numerous proposals found in the technical literature, as well.

- Variability parameters of the rebound index have similar tendency over the average rebound index as that of the compressive strength, which observation can be a further demonstration of the existence of a relationship between the two material properties.
- The development of the relative values of the rebound index in time is similar to that of the compressive strength, however, users should consider that rebound hammers provide rebound index connected to the Young's modulus for high strength concretes and the Young's modulus could not predict compressive strength for mature concrete.

Result were published in international referred journals in 2011-2013, they were welcome and one of them received independent citations. In 2012 author of present study received an invitation to join the RILEM Technical Committee ISC (Non destructive in situ strength assessment of concrete) from its chair, Prof. Denys Breysse. He considered the contribution beneficial for the TC based on the developed model.

7. OUTLOOK AND FUTURE WORK

The theoretical considerations covered in the development of the phenomenological model were confirmed by the extensive experimental verification. However, further studies are needed for the ratification of the model for practical applications. The model provides a clear and transparent explanation to the rebound surface hardness of concrete in its introduced form. The observations predict that the general scheme of the model allows an extension of the model also for concretes older than 180 days. It was found that the predictions made by the model are far more accurate than that was available earlier by simple regression analyses. On the other hand, the number of the empirical constants included in the model may result a challenging parameter fitting work before any practical application. Further types of concretes should be studied in the future to be able to find simplification possibilities. Typical form of generating functions should be clarified and the limits of the practical application should be determined. It is to be highlighted, however, that the main purpose of the development of the model was to provide a better understanding of the rebound surface hardness of concrete and to explain the experimental findings. Author is working on further developments and hope that the model can be successfully used in practice in the future.

Future aim of the research is to extend the model towards a reliability engineering direction by the application of random variables in the model to become more useable for the practice.

8. ACKNOWLEDGEMENTS

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