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ASSESSMENT OF THE CONCRETE COMPRESSIVE STRENGTH USING NON-DESTRUCTIVE METHODS

BY

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Abstract. The ultrasonic pulse velocity (UPV) and the rebound hammer (RH) are the most utilized non-destructive methods in determining the compressive strength of concrete. In most of the cases, if only one method is used, the results that are obtained are not accurate enough. Thus, the experimental programs that have been conducted in this filed, have proved that the optimum approach consists in applying both methods and correlating the results in order to obtain reliable values for the compressive strengths. The combined method that consists in both UPV and RH tests, is known as SonReb approach. The non-destructive test results obtained by UPV and RH are applied in the compressive strength assessment for concrete elements, using empirical mathematical equations based on linear regression models.

The first part of this paper focuses on presenting the general principles of UPV and RH methods, detailing their particularities and limitations. In the second part of the paper, a case study is presented, aiming to verify nine mathematical models which are commonly applied in the assessment of the compressive strength of concrete. The results that were calculated based on the equations of the mathematical models have been compared to the real values of the corresponding compressive strengths, obtained through laboratory

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compressive destructive tests. The comparative analysis concluded that the SonReb method provides the most accurate results, when compared to the single methods.

Keywords: concrete compressive strength; ultrasonic pulse velocity; rebound hammer; mathematical models; comparative study.

1. Introduction

The compressive strength assessment of concrete elements is frequently necessary for this type of structures during their life cycle, even from the early stages of erection, when doubts may arise concerning the quality of the execution or, even more frequently, during the service stage, when some of the designed performance requirements are not fulfilled anymore (Breysse, 2012). The available methods, which can be applied for obtaining this parameter, can be first divided, based on their impact upon the investigated element. Thus, destructive and non-destructive methods are available. The destructive methods involve either local damaging the construction element or coring samples of concrete which are later tested under laboratory conditions. The most important disadvantage which characterizes the destructive methods refers to the necessity of closing down the specific activities which are undertaken inside the building and in repairing the elements that have been damaged during the testing stage. Under these circumstances, the non-destructive methods represent a viable alternative, especially for those constructions in which the interruption of their specific activities is not possible.

Obtaining the compressive strength for concrete elements based on the results delivered by non-destructive methods is a complex process which can be affected by different factors. For this reason, a very important step in designing a feasible investigation plan consists in evaluating the five characteristic stages (McCann & Forde, 2001): visual inspection, damage identification and analysis (if it exists), obtaining information from the technical documents, selection of the suitable non-destructive method and testing approach. Also, the most important factors that strongly influence the selection of the appropriate non-destructive testing method are (McCann & Forde, 2001): the required depth of penetration into the structure, the vertical and lateral resolution for the investigated element, the contrast in physical properties between the target and its surroundings, the signal to noise ratio and the historical information concerning the methods used in the construction of the structure. The evaluation of each factor, improves the process of selecting the suitable non-destructive method and, consequently, increases the accuracy of the results (Pucinotti, 2015). The most important advantages implied by the use of non-destructive methods refer to the short duration of investigation, lower costs when compared to those specific to the destructive tests and the possibility of applying the testing methods without closing down the specific activities (Malhotra, 1976).

The ultrasonic pulse velocity (UPV) and the rebound hammer (RH) are among the most utilized non-destructive test methods which are both used for quality evaluation and concrete mechanical characteristic assessment (Malhotra and Carino, 2004). The studies carried out in this field (Breysse, 2012; Kheder, 1999; Huang *et al.*, 2011; Qasrawi, 2000; Erdal, 2009) concluded that the use of a single non-destructive method for determining the compressive strength of concrete is not providing results with a reliable accuracy. Thus, at least two methods should be used and the results shall be combined by applying suitable mathematical models (Facaoaru, 1961; Breysse, 2012).

2. NDT Methods for Assessing the Compressive Strength of Concrete

The ultrasonic pulse velocity (UPV) and the rebound hammer (RH) are the most utilized non-destructive methods in determining the compressive strength of concrete. The degree of applicability and the accuracy of the results that are obtained by applying each non-destructive method are influenced by a set of factors. Usually, these factors refer to the environmental conditions during the testing process, to the physical characteristics of the concrete which is investigated and to the mathematical model that is applied in order to calculate the values of the compressive strengths.

2.1. Ultrasonic Pulse Velocity (UPV) Method

The ultrasonic pulse velocity is a non-destructive method generally used for checking the quality of the concrete elements (existence of voids, cracks, honey combs), but also for the assessment of its compressive strength. The method is described in the Romanian standards C26:1985, SR EN 12504-4:2004 and in the international standards respectively, ASTM C597:2009 and BS 1881-203:1986. The device that is used for this method is the ultrasonic pulse velocity tester. The testing procedure is based on measuring the ultrasonic pulse propagation time between two transducers (from a transmitter to a receiver), which are placed at a previously established distance. Once the propagation time is measured, the velocity can be calculated by applying eq. 1. Based on the values of this physical parameter, important appreciations can be formulated with respect to the quality, uniformity, damage extent and to the compressive strength of the investigated concrete element.

$$v = \frac{L}{T}, \tag{1}$$

where: v is the ultrasonic pulse velocity, [m/s] or [km/s]; L – the distance between the transmitting and receiving transducers, [m]; T – the ultrasonic pulse propagation time, [s].

The quality and the accuracy of the data which is recorded during the UPV test can be influenced by some factors which are presented in Table 1 (Breysse, 2012). By analyzing the impact of each factor, it has been concluded that the most important ones refer to the constituents and to the damage extent of the concrete element.

Based on the experimental investigation conducted by Whitehurst (1951), Agunwamba & Adagba (2012) have developed a correlation between the ultrasonic pulse velocity and the quality of the concrete element which is investigated (having the density of 2,400 kg/m^3). The correlation is presented in Table 2.

Table 1
Influencing Factors for UPV Method

<table>
<tr><td rowspan="6">Constituents of concrete</td><td rowspan="2">Aggregate</td><td>Size</td><td>Average influence</td></tr>
<tr><td>Type</td><td>High influence</td></tr>
<tr><td rowspan="2">Cement</td><td>Percentage</td><td>Moderate influence</td></tr>
<tr><td>Type of cement</td><td>Moderate influence</td></tr>
<tr><td rowspan="2">Other constituents</td><td>Fly ash content</td><td>Average influence</td></tr>
<tr><td>Water/cement ratio</td><td>High influence</td></tr>
<tr><td colspan="3">Humidity degree / Moisture content</td><td>Average influence</td></tr>
<tr><td colspan="2" rowspan="3">Other factors</td><td>Reinforcements</td><td>Moderate influence</td></tr>
<tr><td>Age of concrete</td><td>Moderate influence</td></tr>
<tr><td>Voids, cracks</td><td>High influence</td></tr>
</table>

Table 2
Ultrasonic Pulse Velocity – an Index for Concrete Quality Assessment

Concrete quality	Ultrasonic pulse velocity (m/s)
Excellent	Over 4500
Good	3500 – 4500
Doubtful	3000 – 3500
Low	2000 – 3000
Very low	Under 2000

2.2. Rebound Hammer (RH)

The rebound hammer method represents one of the most utilized non-destructive procedures and it consists in measuring the surface hardness of the concrete element which is investigated. This testing method is described in the Romanian standards C26:1985, SR EN 12504-2:2012 and, also, American standard ASTM C805:2008. This procedure is commonly applied for concrete quality evaluation (uniformity, voids) and also, for evaluating the concrete compressive strength. The Indian standard IS 13311-2:1992 provides a correlation between the rebound number (RN) and the investigated concrete quality, presented in Table 3. The method is simple to apply, assume low costs and provides quick results.

Table 3
Rebound Number – an Index for Concrete Quality Assessment

Average Rebound Number	Concrete quality
Above 40	Very good concrete
30 – 40	Good concrete
20 – 30	Fair concrete
Below 20	Poor concrete

This type of test is performed by using a rebound hammer which triggers a mobile mass to the surface of the concrete element. After the impact, a part of the induced energy is consumed as deformation, while the remaining energy produces the rebound effect. The latter, characterizes the hardness of the concrete surface and gives the rebound number, which is recorded by the device.

The correlation between the rebound number and the concrete compressive strength is influenced by several factors, each of them having specific influence. These factors are presented in Table 4 (Breysse, 2012).

Table 4
Influencing factors for RH method

Constituents of concrete	Aggregate	Size	Average influence
		Type	High influence
	Cement	Percentage	Moderate influence
		Type of cement	Moderate influence
Humidity degree / Moisture content			Average influence
Contact surface properties		Carbonation degree	High influence
		Smoothness degree	Average influence
		Formwork type and curing conditions	Average influence
Other factors		Temperature	Moderate influence
		Voids	High influence

2.3. The Combined Method - Sonreb

The combination of the UPV and RH methods was developed by Facaoaru (1961). The main advantage derived from combining the results, consists in obtaining a complete characterization of the material. Thus, the compressive strength of the concrete is obtained by combining the values at the exterior side of element, on a depth of about 2,...,3 cm, obtained by using the RH method, with the ones characterizing the inner part of the element, provided by applying the UPV method.

By taking into account the recordings of both UPV and RH tests, the outcomes of the combined method can be influenced by all before mentioned factors (Arioz *et al.*, 2009). Nevertheless, the results of the combined method, can be differently influenced under the action of the same factor, which will finally lead to an improved accuracy in the assessment of the concrete compressive strength, based on the development of a self-correction mechanism for the induced error.

However, the research programs that have been conducted in the area of combined non-destructive test methods for concrete, have concluded that, when certain specific characteristics of the element / material are known (water-cement and aggregate-cement ratios, age, density), the accuracy of the results can be improved (Kheder, 1999; Huang *et al.*, 2011; Tanigawa *et al.*, 1984). Also, when using the ultrasonic pulse velocity method, the assessment of the concrete compressive strength is strongly influenced by the type and dimension of the aggregates used in the concrete mix. Thus, it was suggested that correction factors should be developed (Trtnik *et al.*, 2009).

3. Regression Models Proposed for Assessing the Compressive Strength of Concrete

Many research groups have focused on identifying the most appropriate closed-form mathematical models which can be applied in the assessment of the compressive strength of concrete, by using the results of the UPV or/and RH methods. The experimental programs that were conducted in this filed also consisted in destructive tests, aiming to calibrate the mathematical models which were previously proposed for the non-destructive results.

The mathematical models proposed so far can be classified based on the number of the variables that are used in the closed-form equations. Thus, single and multiple variable models have been proposed. The single variable models use one set of recordings given by a non-destructive test, while the multiple variable ones involve the use of at least two sets of non-destructive results and also, in some cases, knowing some properties that refer to the constituents of the concrete (water/cement/aggregate ratio, concrete age, carbonation degree, density and type and aggregate dimension).

For most of the concrete elements that are investigated, the information regarding the properties of the constituents are limited or non-existent. Thus, the most efficient mathematical models are the ones that are only based on the variables resulted from the non-destructive tests. Table 5 presents some of the most common mathematical models, based on the linear regression principle, that are used in the assessment of the concrete compressive strength. The variables that are considered in these models are only based on the results of the UPV and RH testing methods.

Table 5
Mathematical Models for Concrete Strength Assessment

Eq. no. (Code)	Proposed equations	Author, year
1 (K1)	$f_c = 1.2 \times 10^{-5} \times UPV^{1.7447}$	Kheder, 1999
2 (K2)	$f_c = 0.4030 \times RN^{1.2083}$	Kheder, 1999
3 (Q1)	$f_c = 36.72 \times UPV - 129.077$	Qasrawi 1, 2000
4 (Q2)	$f_c = 1.353 \times RN - 17.393$	Qasrawi 2, 2000
5 (E1)	$f_c = -0.0177 \times RN^2 + 2.0481 \times RN - 19.303$	Erdal, 2009
6 (T)	$f_c = 0.745 \times RN + 0.951 \times UPV - 0.544$	Tanigawa *et al.*, 1984
7 (K3)	$f_c = 0.0158 \times UPV^{0.4254} \times RN^{1.1171}$	Kheder, 1999
8 (E2)	$f_c = 0.42 \times RN + 13.166 \times UPV - 40.255$	Erdal, 2009
9 (H)	$\sqrt{f_c} = 1.26 + 0.00015 \times RN^2 + 0.035 \times UPV^3 + 0.8024$	Huang, 2011

4. Comparative Case Study

The comparative case study which is presented in this paper focuses on determining the validity of the nine mathematical models that are listed in Table 5. The compressive strength results obtained by applying the mathematical models are compared with those resulted from destructive testing, on a number of 20 cubic laboratory prepared specimens, having the dimensions of 150 × × 150 × 150 mm. The numerical values that are used in this comparative study are taken from the experimental program that has been conducted by Nikhil and his collaborators (Nikhil *et al.*, 2015).

Thus, in Table 6 the first three columns present the results of the non-destructive methods and the values of the compressive strengths obtained by laboratory destructive tests, while the following 9 columns present the compressive strengths obtained by applying the mathematical models.

Table 6
Input Data and Predicted Compressive Strengths

Input data (Nikhil *et al.*, 2015)			Predicted compressive strengths								
RN	UPV (km/s)	Effective compressive strength (MPa)	UPV	RN	UPV	RN	RN	SonReb (UPV + RN)			
			Single-Variable eq.					Multi-Variable eq.			
			K1	K2	Q1	Q2	E1	T	K3	E2	H
23	3.620	16.8	9.41	7.81	.85	3.73	8.44	0.03	7.13	7.07	4.46
24.8	3.718	17.4	0.34	9.51	.45	6.16	0.60	1.47	8.85	9.11	5.63
25.2	3.906	18.1	2.17	9.89	4.35	6.70	1.07	1.94	9.59	1.76	8.01
26.8	3.789	19.6	1.02	1.42	0.06	8.87	2.87	3.03	0.72	0.89	6.60
27.6	4.003	20.1	3.13	2.20	7.91	9.95	3.74	3.82	1.92	4.04	9.55
27.4	4.112	20.5	4.24	2.01	1.92	9.68	3.53	3.78	1.99	5.39	1.24
29.6	3.964	21.4	2.74	4.16	6.48	2.66	5.81	5.28	3.60	4.37	9.13
31.8	4.003	23.8	3.13	6.34	7.91	5.63	7.93	6.95	5.67	5.80	9.88
33	3.998	25.6	3.08	7.55	7.73	7.26	9.01	7.84	6.74	6.24	9.91
32.2	4.112	26.9	4.24	6.75	1.92	6.17	8.29	7.36	6.33	7.41	1.64
29.2	4.049	28.9	3.60	3.76	9.60	2.11	5.41	5.06	3.45	5.32	0.37
29.8	4.109	29.6	4.21	4.36	1.81	2.93	6.01	5.56	4.14	6.36	1.38
30.4	4.112	30.3	4.24	4.95	1.92	3.74	6.60	6.01	4.69	6.65	1.48
32.4	4.129	31.2	4.42	4.95	2.54	6.44	8.47	7.52	6.56	7.72	1.94
31.2	4.219	32.4	5.36	5.74	5.84	4.82	7.37	6.71	5.70	8.40	3.40
31.8	4.199	33.1	5.15	6.34	5.11	5.63	7.93	7.14	6.20	8.39	3.09
33.6	4.112	35.8	4.24	8.16	1.92	8.07	9.53	8.40	7.62	8.00	1.76
34.2	4.159	36.9	4.73	8.77	3.64	8.88	0.04	8.89	8.30	8.87	2.62
35.8	4.259	38.4	5.78	0.40	7.31	1.04	1.33	0.18	0.09	0.85	4.59
39.8	4.159	40.2	4.73	4.55	3.64	6.46	4.17	3.06	3.53	1.22	3.21

For each mathematical model, the values of the compressive strengths have been statistically interpreted. Hence, for each set of results, the root-mean-square error (RMSE), the mean-absolute percentage error (MAPE) and coefficient of determination have been computed. The statistical results are presented in Table 7.

Table 7
Statistical interpretation of the predicted compressive strengths

Statistical interpretation	UPV	RN	UPV	RN	RN	SonReb (UPV + RN)			
	Single-Variable eq.					Multi-Variable eq.			
	K1	K2	Q1	Q2	E1	T	K3	E2	H
RMSE, [MPa]	7.091	4.731	9.191	4.92	4.335	4.882	4.902	4.588	8.558
MAPE, [%]	9.245	3.646	1.077	3.252	4.821	6.383	3.089	3.352	2.269
R^2	0.909	0.965	0.79	0.595	0.974	0.965	0.961	0.969	0.828

For each type of method, the predicted values of the compressive strengths have been compared with the effective ones. The results are presented in Figs. 1,...,3. In the first two graphical representations (Figs. 1 and 2) are illustrated the variation of the compressive strengths based on applying the single variable equations. The third graph (Fig. 3) presents the variation of the compressive strengths obtained based on the multiple variable mathematical models.

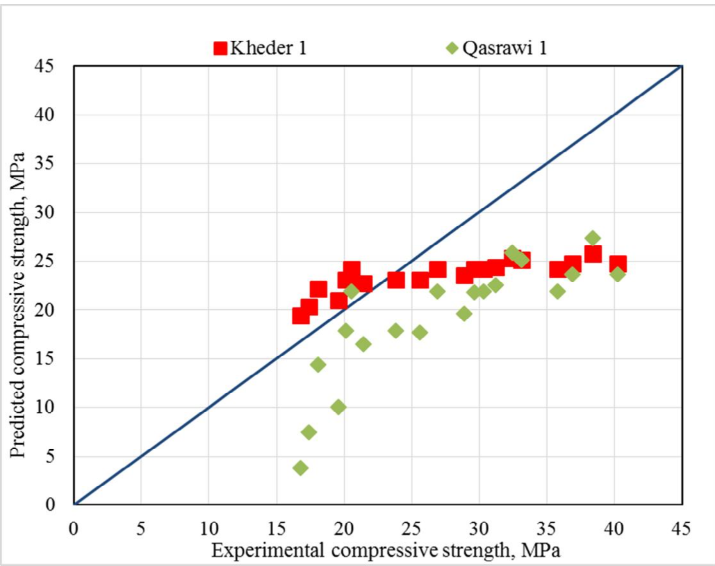

Fig. 1 – UPV vs concrete compressive strength.

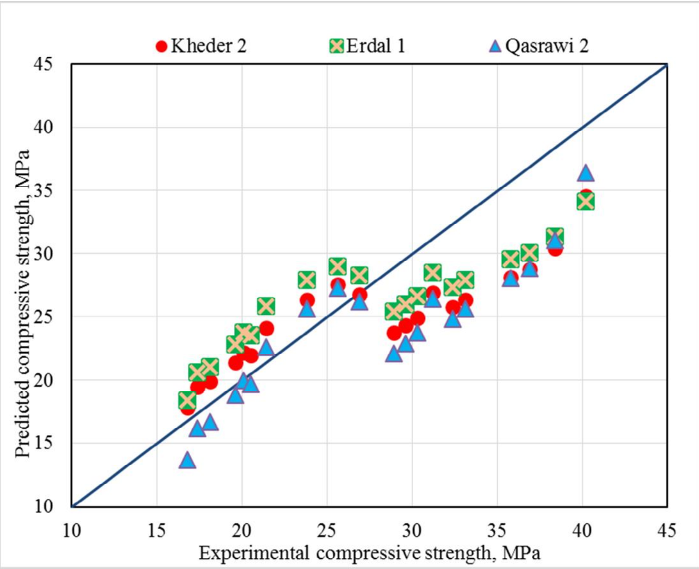

Fig. 2 – RH vs concrete compressive strength.

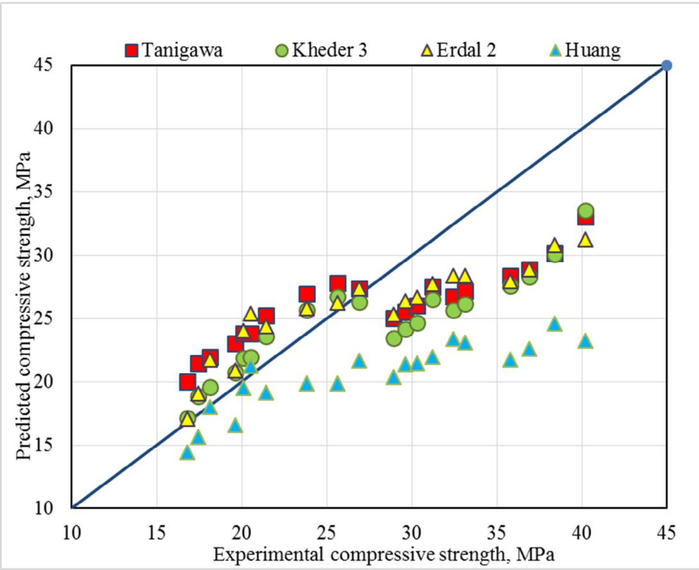

Fig. 3 – SonReb vs concrete compressive strength.

5. Conclusions

This paper presents two of the most used non-destructive testing methods for the assessment of concrete compressive strength, the ultrasonic pulse velocity (UPV) and the rebound hammer (RH). Each of the two methods have a high degree of applicability, delivering results close to the real ones. However, the accuracy of the predicted compressive strength can be affected by a set of factors that depend on the inherent properties of the material and on the service conditions.

A consistent number of research groups have focused on identifying and proposing suitable mathematical models that can be used for assessing the compressive strength of the concrete. Thus, until now, a number of mathematical equations have been proposed, based on the linear regression principle, which involve the use of non-destructive testing results (ultrasonic pulse velocity and rebound number). These models can be classified in single and multiple variable.

This paper presents 9 mathematical models, commonly applied in the assessment of the compressive strength of concrete, that are only using the results of the UPV and RH non-destructive methods. The case study focuses on checking the validity and the accuracy of each mathematical model by comparing the predicted compressive strengths with the effective ones, previously obtained by destructive laboratory tests. For each closed-form equation, the predicted values have been statistically interpreted and graphically compared to the effective ones.

By analyzing the graphs presented in Fig. 1 and 2 it can be concluded that, for the single variable mathematical models, the closest compressive strength results are obtained applying the equations proposed by E1 and K2. The higher degree of accuracy of these models, E1 and K2, is also confirmed by the values of the coefficient of determination, R^2. The model K1 offers results close to the real ones only for the specimens with the compressive strengths ranging between 20-25 MPa, the model Q1 considerably under-estimates the entire set of values, while the model Q2 provides results close to the real ones only for the range between 10-27 MPa.

By analyzing the graph presented in Fig. 3, which presents the results obtained by applying the multiple variable mathematical models (provided by the SonReb method), it can be concluded that equations T, K3 and E2 lead to good results, with compressive strength values close to the experimental ones. Also in this case, the higher degree of accuracy is confirmed by the values of the coefficient of determination, R^2. The model H is an exception for this case because it under-estimates the results for specimens having the compressive strength higher than 20 MPa.

Based on the comparative study of the 9 proposed mathematical models, it has been shown that closest values of the predicted compressive strengths are obtained by applying the multi-variable equations.

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EVALUAREA REZISTENŢEI LA COMPRESIUNE A BETONULUI UTILIZÂND METODE NEDISTRUCTIVE

(Rezumat)

Metoda impulsului ultrasonic (UPV) şi cea bazată pe recul (RH) sunt cele mai des utilizate metode nedistructive pentru determinarea rezistenței la compresiune a betonului. De cele mai multe ori, rezultatele obținute prin utilizarea unei singure metode non-invazive nu sunt caracterizate de un grad ridicat de acuratețe. Din acest motiv, cercetările efectuate în acest domeniu au demonstrat că abordarea optimă constă în aplicarea simultană a celor două metode şi corelarea rezultatelor pentru a obține valori ale rezistenței la compresiune apropiate de cele reale. Combinarea celor două metode, viteza impulsului ultrasonic şi cea bazată pe recul, este cunoscută în literatura de specialitate sub denumirea de SonReb. Rezultatele încercărilor nedistructive de tip UPV şi RH sunt utilizate la determinarea valorilor rezistențelor la compresiune a elementelor din beton, cu ajutorul unor modele matematice empirice bazate pe principiul regresiei liniare.

În prima parte a acestei lucrări sunt prezentate principiile generale ale metodelor UPV şi RH, detaliindu-se particularitățile şi limitările specifice. În partea a doua a lucrării este prezentat un studiu de caz ce constă în verificarea a nouă modele matematice utilizate la aproximarea rezistenței la compresiune. Rezultatele calculate

prin aplicarea modelelor matematice au fost comparate cu cele obținute prin încercări distructive. Studiul comparativ demonstrează că metoda SonReb furnizează rezultate cu un grad mai ridicat de acuratețe, comparativ cu cele rezultate din aplicarea unei singure metode nedistructive.